# Prediction of the Erector Spinae Muscle Lever Arm Distance for Biomechanical Models

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
May 5, 2013

Keywords: Erector Spinae Muscle Lever Arm, MRI, Musculoskeletal Morphology



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Abstract

Low Back Pain (LBP) remains the U.S.'s most significant and costly injury. Improved biomechanical modeling of the lumbar spine may allow better evaluation of LBP risk. To calculate the forces acting on the spine, accurate biomechanical model inputs are required. However, some biomechanical modelinputs are limited by assumptions. One of the most vital model inputs, the mechanical lever arm of the erector spinae muscle mass, (ESMLA), is typically approximated using a fixed value (5 cm or 2 inches) to simplify biomechanical models. This assumption decreases the sensitivity and applicability of models as well as their credibility. The objective of this study was to develop regression models to estimate the ESMLA distance based solely on (1) easily measured subject variables (gender, age, height, and weight) and (2) some additional anthropometric variables (i.e., lean body mass, sitting height, shoulder width). This will allow currently available biomechanical models to incorporate subject specific parameters and should improve model predictions and risk estimations. In addition to the ESMLA distances at several inter-vertebral disc levels in the lower lumbar region, other morphological parameters of musculoskeletal structure such as the cross-sectional areas (CSA) of the erector spine muscle mass (ESMM) and the inter-vertebral disc (IVD) are investigated. Regression models were also developed for the CSA of the ESMMs at each IVD levels.

Magnetic Resonance Images (MRI) were used in this study. They were obtained from (1) a hospital database and (2) a newly conducted study at the Auburn MRI Research Center. The ESMLA distances and the CSA measurements were measured from axial oblique MRI scans by using architectural design software. Measurements were then statistically investigated to determine the relationships between the measurement and subject variables (characteristic and anthropometrics).

Results indicate that the ESMLA distance and ESMM size can be easily and reliably estimated using subject variables. The results of the present study found that using a fixed ESMLA value could cause errors be as great as 20%. The average error percentage of using the fixed value was 8%. Using an empirically derived average value for a IVD level and gender could cause approximately 5% error in ESMLA distances. On the other hand, using regression models suggested in the present study yielded smaller error percentages. For example, the average error was approximately 4.3% for regression models that had easy to measure anthropometric variables (i.e., height and weight). Regression models that had more predictive variables (i.e., ankle, wrist, and knee indexes), however, can provide much smaller prediction errors. The average absolute residual percentage was 2.15% for the L3/L4 level, 2.39% for the L4/L5 level, and 3.67% for the L5/S1 level. The advantage of using regression equations is that smaller prediction errors in ESMLA distances result in smaller error in spinal loading calculations, especially for extreme subjects.

# Acknowledgments

I would like to express my heartfelt gratitude to Dr. Richard Sesek, Dr. Robert Thomas, Dr. Sean Gallahger, and Dr. Jerry Davis, who helped me throughout the completion of this dissertation with their support and technical expertise. They have always guided me in the right direction and opened their doors to my questions. I also appreciate Drs. Thomas Denney, Ronald Beyers, and Nouha Salibi from Auburn University MRI Research Center for their tremendous help. I could not conduct this study without their helps. I am thankful to the participants in our study that made this dissertation possible. My love and thanks go to my fiance and my family members, who have all helped get me to where I am today. Their understanding and encouragement supports me as I proceed forward. I would like to express special thanks to the Ministry of National Educational of Republic of Turkey for providing me a scholarship. It would not have been possible without their generous financial support.

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Chapter 1

# INTRODUCTION

## 1.1 Low Back Pain (LBP): Epidemiology, Cost, and Risk Factors

### 1.1.1 Epidemiology of LBP

Musculoskeletal disorders (MSDs) are the leading cause of disability in the United States and represent 48 percent of all self-reported chronic medical conditions (BMUS, 2011). According to the U.S. Department of Labor's Bureau of Labor Statistics, there were 1,191,100 workplace injuries and illnesses requiring time away from work in 2010 (BLS, 2011). Twenty-nine percent of these nonfatal occupational injuries and illnesses involving days away from work were MSDs, often referred to as "ergonomic" injuries (BLS, 2011). A total of 346,400 MSDs were recorded in 2010, yielding a rate of 34 cases per 10,000 full-time workers (BLS, 2011). The median days away from work, a key measure of the severity of the injury or illness, was 11 days for MSDs, higher than the median day, for all days away from work cases (8 days) (BLS, 2011). Apparently, MSDs are more severe with longer recovery time than other workplace injuries.

Low Back Pain (LBP) is one of the common MSDs and is highly prevalent in the United States. More than 44.4 million healthcare visits were due to back pain in 2006 (BMUS, 2011). Between 75% and 85% of the U.S. population will experience at least one episode of back pain some form at some point during their lifetime according to the American Association of Orthopaedic Surgeons (AAOS, 1999) and up to 15% of those who experience back pain become chronic (Liebenson, 1996). Low back pain is among the most common physical conditions requiring medical care and affecting an individual's ability to work and manage the daily activities of life. Although rarely life-threatening, back disorders are a major cause of pain, disability, and societal cost. According to the National Health Interview Survey, more than 28.8% of adults age 18 and older reported experiencing LBP in the past 3 months during 2010 (NCHS, 2012a). The 10-year-trends for low back pain for males, females, and both genders are given Figure 1.1.

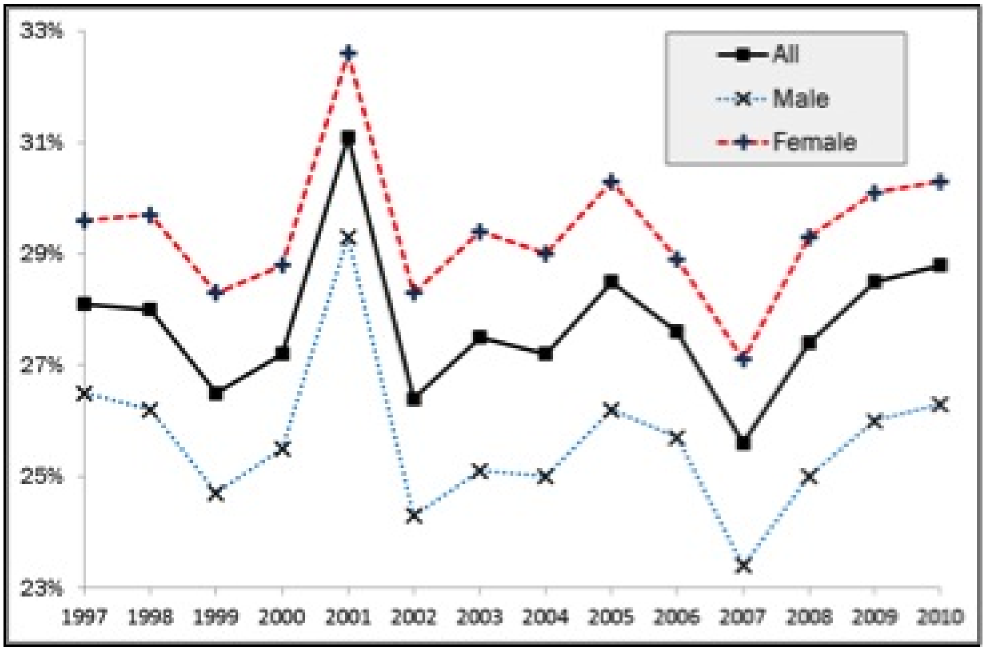



Figure 1.1: Low back pain among adults 18 years of age and over, by selected characteristics: United States, selected years 1997-2010 (National Health Interview Survey, NCHS, 2012a)

In 2007, 27 million U.S. adults 18 years of age and over reported having back problems (Soni, 2010). In occupational settings, nearly half (45.4%) of 346,400 MSDs in 2010 were related to LBP, and back injuries required a median of 7 days to recuperate (BLS, 2011). Even though, the median days away from work for back injury cases (7 days) was the shortest duration compared to other body part injuries (shoulder, 21 days; abdomen, 20 days; arm, 15 days; wrist, 18 days; leg, 16 days; and multiple body parts, 15 days), the higher incidence and prevalence rate of back injuries makes them more severe compared to other body parts.

### 1.1.2 Cost of LBP

LBP is a major burden to society in terms of health, economics, and socioeconomics since it affects not only patients but also their families, employers, and society in general (van Tulder, Koes, and Bombardier, 2002). The economic burden of LBP to society, due to the large number of work days lost by a small percentage of patients with chronic LBP, expensive medical costs, and productivity losses is enormous (Maetzel and Li, 2002). The study by Maetzel and Li (2002) reported that LBP resulted in approximately 149 million lost work days per year, and 68.5% of them were work-related (or 101.8 million lost work days per year). Approximately 2% of the American workforce is compensated for back injuries each year (Hashemi, Webster, and Clancy, 1998; Andersson, 1999), and one fourth of all workers' compensation claim cases are due to LBP (Hashemi *et al.*, 1998).

Based on the Agency for Healthcare Research and Quality (AHRQ) Household Component of the Medical Expenditure Panel Survey data provided by the Center for Financing, Access, and Cost Trends, the mean expenditure per person for the treatment of LBP was $1,589 ($1,146 for an ambulatory visit and $446 for prescription medications) in 2007 (Soni, 2010). The total cost for a patient with LBP can be calculated by summing direct costs (medical care expenditures, work compensation claim costs including indemnity and administrative costs) and indirect costs (time away from work, disability payments, and diminished productivity). By considering both direct and indirect expenses for back pain, it is estimated that total annual cost for back pain is between $20 billion and $50 billion in the United States (Frymoyer and Durett, 1997; Deyo and Weinstein, 2001; Maetzel and Li, 2002; NINDS, 2003; Pai and Sundaram, 2004; Soni, 2010). It should be noted that actual cost estimates for LBP can vary depending on the costing methodology and the estimation of indirect costs (Maetzel and Li, 2002).

The actual statistics regarding LBP might be much more severe than the data revealed by BLS. Data reported might not grasp the whole scenario as not all workers will file a claim or they will continue to work with LBP. Moreover, some cases might not be covered by worker compensation cost. Therefore, the prevalence of LBP might be greater than the reported occupational injury statistics.

### 1.1.3 Risk Factors Associated with LBP

In occupational settings, LBP is highly prevalent among workers performing manual material handling (MMH) tasks. Force, repetition, posture, and duration are the major factors that directly affect the risk of low back injury (Cole and Grimshaw, 2003; Chaffin, Andersson, and Martin, 2006). Heavy loads result in larger compressive forces on the spine and tensile forces on tendons and ligaments (Merryweather, Loertscher, and Bloswick, 2009; Gallagher and Heberger, 2013). The posture in which the task is performed can increase or decrease the magnitude of forces loading tissues (Marras and Granata, 1997). Frequency and duration are also major determinants of LBP development (Marras, Parakkat, Chany, Yang, Burr, and Lavender, 2006). Risk factors for LBP can be categorized as individual factors (e.g., age, physical fitness, muscle strength, and smoking), psychosocial factors (e.g., stress, anxiety, mood, cognitive functioning, and pain behavior), and occupational factors (e.g., awkward posture, duration, heavy load lifting, frequency, and vibration) (van Tulder *et al.*, 2002; Manek and MacGregor, 2005). The likelihood of low back pain increases with physical demands, including manual lifting, bending, twisting, and whole body vibration (Waddell and Burton, 2001).

A number of factors such as force, repetition, posture, and duration may increase the risk of chronic LBP, but no single factor seems to have a strong individual impact (van Tulder *et al.*, 2002). Interactions between risk factors or combinations of risk factors can change the magnitude and severity of both the injury and healing processes (Gallagher and Heberger, 2013). The magnitude of the load and the time of exposure were found to be positively related with LBP prevalence (de Looze, Visser, Houting, Rooy, van Dieen, and Toussaint, 1996). However, the time (exposure duration, frequency, and loading cycle) is often ignored in biomechanical models. van Dieen and Oude Vrienlink (1994) claimed that the magnitude of peak loads alone is not a good criterion to evaluate risks for damage, as the time aspects are ignored. For example, if the load is reduced, it is possible that workers will simply work faster, resulting in the loss of the advantage gained by load reduction (de Looze *et al.*, 1996). Light weight or frequent bending without a load also shows an increase in the risk for LBP (Frymoyer, Pope, Costanza, Rosen, Goggin, and Wilder, 1980). Gallagher and Heberger (2013) systematically reviewed the current literature to explain the interaction effect of force and repetition on musculoskeletal tissues. They concluded that the interaction effect may be due to a fatigue failure process which is logarithmic in nature, meaning a small increase in the level of imposed stress might result in a large decrease in the number of cycles required for failure of a tissue.

## 1.2 Erector Spinae Muscle Mass Lever Arm (ESMLA) in Biomechanical Models

### 1.2.1 Definition of the ESMLA

The erector spinae muscle (ESM) group in the low back region consists of three muscles: from medial to lateral, the spinalis thoracis, longissimus thoracis, and iliocostalis lumborum (Figure 1.2). These three muscles of the spine are basically responsible for extension of the spine when acting bilaterally and lateral flexion of the spine when acting unilaterally. The multifidus, a deep back muscle in the transversospinalis group, is also responsible for extension of the vertebral column. The lateral border of the multifidus with the longissimus is often not distinct enough to see without refinements in the procedure; thus, it is very difficult to distinguish the lumbar multifidi from the ESM in magnetic resonance imaging (MRI) or computed tomography (CT) scans (Stokes, Rankin, and Newham, 2005). Since the main purpose of biomechanical back models is to estimate forces and moments at the lumbar inter-vertebral discs (IVD) while an individual is performing a task (e.g., lifting, lowering, pushing, and pulling), it is logical and essential to combine the erector spinae muscles (the iliocostalis lumborum, longissimus thoracis, and spinalis thoracis) with the multifidi. In this dissertation, the whole structure consisting of erector spinae muscles and multifidi is grouped and referred to as the erector spinae muscle mass (ESMM). Moreover, the lever arm associated with ESMM is designated as the erector spinae muscle mass lever arm (ESMLA).

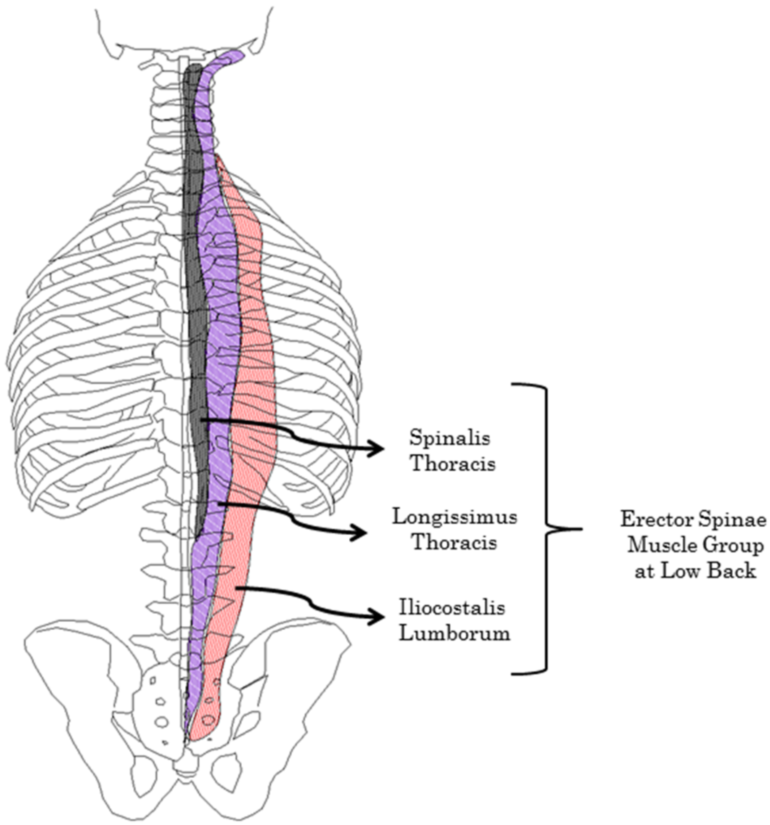



Figure 1.2: Erector spinae muscles
Redrawn from Dr. Kenneth Bo Foreman's Anatomy for Engineers lecture notes, 2010

The psoas major, quadratus lumborum, and latissumus dorsi are other muscles in the low back region. However, they are excluded from this study since their functions do not directly impact the lower back region during typical "sagittal" lifting tasks, the location of greatest concern for LBP. They do have some degree of contribution to risk associated with lifting/lowering and standing tasks, but their contributions are not considered in this study. Contributions from these muscles as compared to the benefit of improving ESMLA estimates are assumed to be relatively minor for most lifting tasks.

### 1.2.2 Biomechanical Models

Biomechanical models are widely used in ergonomics to understand and calculate forces and moments (also called torques) on body parts, joints, and specifically the inter-vertebral discs (IVD). Accurate inputs for biomechanical models are important for calculating forces and moments. More accurate biomechanical estimates might lead to a better risk estimation, and therefore, more efficient preventive actions might be established to minimize the likelihood of typical occupational injuries such as work related LBPs. In many biomechanical (or mathematical) torso models, the lever arm of the erector spinae muscle group, one of the model inputs, is assumed to be a fixed number (5 cm or 2 inches) for all people (Chaffin, 1969; Poulsen, 1981; McGill and Norman, 1985 and 1987a; Kumar, 1988; Ayoub and Mital 1989; Garg, 1997; Merryweather *et al.*, 2009). This assumption decreases the sensitivity and applicability of biomechanical torso models.

### 1.2.3 Importance of the ESMLA in Biomechanical Models

Forces and moments are among the major criteria used to evaluate a task in terms of ergonomics, safety, and efficiency. If forces and moments exceed the maximum capacity (and/or submaximal repetitive loading capacity) of a tissue, it is likely to contribute to occupational injuries (Cole and Grimshaw, 2003; Cole, Grimshaw, and Burden, 2004). Therefore, measuring the erector spinae muscle lever arm of an individual with higher accuracy is vital for closely estimating actual exposures. Accurate measurements require effective, sensitive, and reliable measuring techniques. However, measuring techniques/protocols for the erector spinae muscle mass lever arm (ESMLA) distance have not been well defined in the literature and differ tremendously among researchers. For example, some researchers used simple visual techniques (Tracy, Gibson, Szypryt, Rutherford, and Corlett, 1989) to determine the dimensions of the erector spinae. This will lead to inherent error in calculating forces and moments.

Knowing the ESMLA distance is important because it directly impacts the calculation of forces and moments loaded on the inter-vertebral discs. In the literature, the ESMLA distance is typically assumed as 5 cm (2 in) for simplicity (Morris, Lucas, and Bresler, 1961; Vincent, 1991); however, some research has shown that it can vary from 3.8 cm up to 7.2 cm (Hansen, Zee, Rasmussen, Andersen, Wong and Simonsen, 2006; McGill and Norman, 1987a), which is a relatively large range. The change in the ESMLA distance will affect the need for extensor muscle force and thus the magnitude of compression forces in the lumbar spine in loading (Tveit, Daggfeldt, Hetland, and Thorstensson, 1994). For example, a subject with a 3.8 cm ESMLA distance could be exposed to nearly twice the force related to muscle tension as a subject with a 7.2 cm ESMLA distance given a similar L5/S1 moment to counteract and all other factors being equal.

The simplest biomechanical models require a manual calculation procedure that considers forces and distances of force applications. An example for the mechanical effects of a load held in the hands on the L5/S1 inter-vertebral disc is shown in Figure 1.3. Even though body weight, height, joint angles, and body segment link lengths are required for calculation of forces and moments, they are ignored in this example. The purpose of this example is to explain the effect of the ESMLA distance. An individual is assumed to hold a 10 kg box (98.1 N) in a sagittally symmetric and upright standing posture. The distance of the load to the center of the L5/S1 inter-vertebral disc is 20 cm. Therefore, a moment of 19.62 Nm applies on the inter-vertebral disc. A positive (counterclockwise) moment of 19.62 Nm must be generated by the ESMM to be able to maintain the holding task in equilibrium. The ESMM has to create a 392.4 N force to sustain the posture and perform the task if the ESMLA distance is assumed to be 5 cm.

However, as previously mentioned literature indicates that the ESMLA can vary from 3.8 cm to 7.2 cm (Hansen *et al.*, 2006; McGill and Norman, 1987a). Individuals whose ESMLA distance is smaller than 5 cm will have to produce more force at the ESMM for the same holding task (for example, 258.2 N for a 3.8 cm ESMLA distance). With no

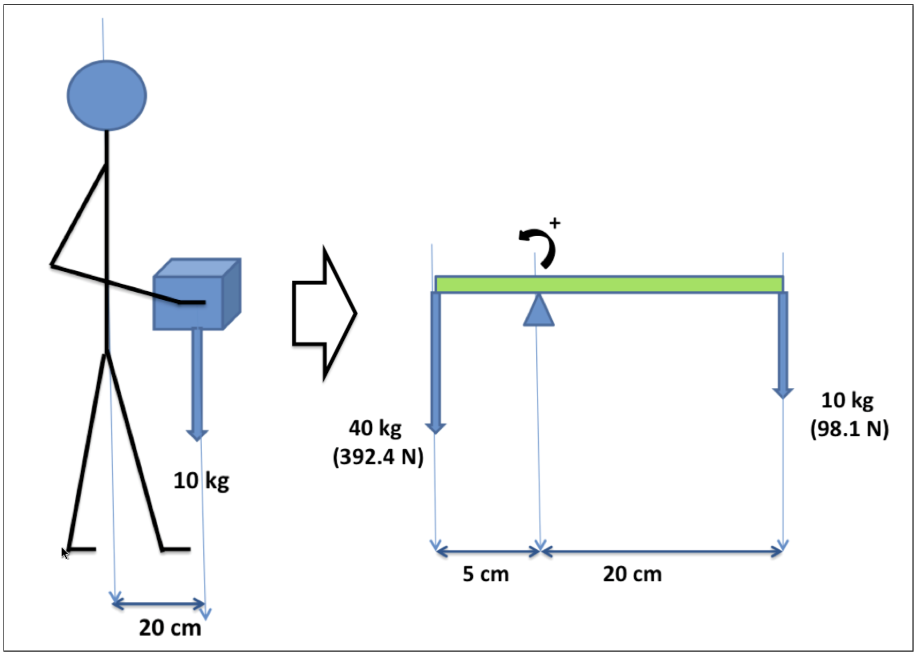



Figure 1.3: An example to explain the effect of the magnitude of the ESMLA distance

change to other factors, individuals whose ESMLA distance is larger than 5 cm will require less muscle force and therefore produce less compression force at the ESMM for the task (for example, 136.3 N for a 7.2 cm ESMLA distance). This simple calculation demonstrates that individuals who have a smaller ESMLA distance are at a higher level of low back compressive force for a given external load. To calculate a safe lifting weight, an accurate (and reliable) ESMLA distance should be used.

Chaffin, Andersson, and Bloswick (1985), McGill and Norman (1987a), and Chaffin, Redfern, Erig, and Goldstein (1990) indicated that simplifying assumptions about the moment arm distances of the muscles relative to the spinal motion segments could cause errors as great as 40% in predictions of the spinal forces. Therefore, estimating the ESMLA distance with minimum error could improve the calculation of forces and subsequent risk associated with MMH tasks. The low back musculoskeletal structure was morphologically investigated in this dissertation. Regression models to estimate the ESMLA distance were derived from subject variables (subject characteristics and anthropometrics). Subject specific morphometric data has the potential to increase the efficiency, effectiveness, and reliability of current biomechanical models and ergonomic assessment tools.

### 1.2.4 Structure of the Dissertation

The importance of LBP in terms of prevalence, severity, and cost and biomechanical models to understand the mechanics of LBP occurrence is provided in Chapter 1. Chapter 2 is a comprehensive literature review for biomechanical models and model inputs such as the erector spinae muscle mass's (ESMM) cross-sectional area (CSA) and lever arm (ESMLA) distance. The erector spinae muscle anatomy, definition of the ESMLA, and measurement techniques regarding the ESMLA distance and CSAs are also provided in this section. After discussing the limitations of previous studies, the research objectives are hypothesized. The third chapter focuses on suggestions on measurement techniques for the ESMLA distance basing on the literature and biomechanics. Chapter 3 also provides descriptive statistics for the ESMLA distance and CSAs of the ESMMs and IVDs using a historical database provided by a hospital. Chapter 4 focuses on investigating the relationship between the ESMLA distance and subject variables. Regression models are provided to estimate the ESMLA distance. In addition to the ESMLA distance, CSAs of the ESMMs are regressed in the same chapter. A historical database of low back data was used for these purposes. Chapter 5 attempts to minimize the limitations associated with the use of the historical database. In this chapter, descriptive statistics and regression analyses were applied to a new database that includes several additional subject variables and a LBP symptom-free population. The overall findings and interpretations of the study are provided in Chapter 6.

Chapter 2

# LITERATURE REVIEW

The erector spinae is the major extensor muscle of the torso (Macintosh and Bogduk, 1991; Jorgensen, Marras, and Gupta, 2003a; Jorgensen, Marras, Gupta, and Waters, 2003b). The anatomy and architecture of the spinal musculature is very important to assess the risk associated with specific work tasks. Mathematical or biomechanical modeling requires information concerning the erector spinae muscle lever arm (ESMLA), the cross-sectional area (CSA) of erector spinae muscle mass (ESMM), direction of muscle fibers, the line-of-action of muscle force, the magnitude of intra-abdominal pressure (IAP), the dimension of the vertebral bodies and inter-vertebral disc (IVD), and the material properties of supportive structures such as the thoracolumbar fascia. Yet, the ESMLA requires special interest since it is the most critical determinant of the magnitude of the loads imposed on the spine. The accuracy of biomechanical models of the spine is dependent upon accurate anatomical representation of the lumbar back structure including the erector spinae muscle. However, the ESMLA distance is typically assumed to be a fixed value (5 cm or 2 inches) in certain biomechanical models regardless of subject anthropometry. This is a very rudimentary assumption that does not take into consideration the variation resulting from subject characteristics (e.g., age, gender) and anthropometry (e.g., height, weight, BMI).

## 2.1 Biomechanical Models

The lumbar spine is difficult to study *in-vivo* compared to other structures. It is not feasible to directly measure spinal loading in living subjects; so biomechanical torso models are used to estimate spinal loading and subsequent injury risk (Marras, Jorgensen, Granata, and Wiand, 2001) and enhance the understanding of injury mechanisms.

### 2.1.1 Biomechanical Model Types (Simple and Complex)

Biomechanical models are widely used among ergonomists, biomechanists, kinesiologists, and sport scientists to calculate forces and moments on various body parts. Ergonomists use biomechanical models to (1) assess the risk of low back pain resulting from various exposures, especially lifting tasks and (2) suggest safe work limitations. Biomechanical models are based on Newtonian mechanics that multiply forces resulting from body segment weights and lifted loads with the perpendicular distance from joint centers (moment arm) to calculate moments (Chaffin, 1997; Chaffin, 2005). There are two types of model calculation; forward and inverse calculation methods. In the forward calculation method, the inputs are muscle excitations and the outputs are body motions. Body motions are inputs and muscle forces are outputs in the inverse calculation method. Ergonomists tend to prefer the inverse calculation method to estimate and predict mechanical stresses on biological tissues or organs since external forces are known and the resulting internal forces are the outcomes that are sought.

Biomechanical models vary from very simple two-dimensional static models to complex three-dimensional dynamic models. Simple models (e.g., the revised Hand-Calculation Back Compressive Force (HCBCF) model by Merryweather *et al.*, 2009) are often preferred since they are easy to understand and apply. They provide quick results to evaluate a work task. On the other hand, precision and better representation of the actual torso structure are advantages of complex models. In general, software (e.g., ANSYS, the Michigan 3D Static Strength Prediction Program (3DSSPP), AnyBody, and ErgoIntelligence Manual Materials Handling) is utilized for complex models. Dynamic three-dimensional models better represent the actual work than static two-dimensional models since most work tasks are performed under dynamic, three-dimensional conditions.

Three-dimensional models consider awkward and asymmetric postures (e.g., twisting) when computing low back forces. Two-dimensional models are limited to sagittal plane lifts. Model selection represents trade-offs among simplicity, accuracy, and model features.

One of the very first static sagittal plane models of the lumbar spine during lifting was proposed by Morris *et al.* (1961). This model used two internal forces (muscle and intra-abdominal force) to counterbalance the resulting moment at the low back region. Schultz and Andersson (1981) introduced a ten-muscle lumbar spine loading model. Bean, Chaffin, and Schultz (1988) solved a two-objective optimization problem with two sequential linear programing models. The objective function was to minimize maximum muscle intensity for the first linear model, and to minimize spinal compression for the second linear model. They proposed a ten-muscle spinal model to calculate muscle contraction forces.

However, while models tend to become more accurate with increasing complexity, usefulness in practice may suffer (Chung, Kim, and Bloswick, 2000). The trade-off between the ability of the model to realistically assess spinal loading associated with a work task and ease of use (Marras and Radwin, 2005) has to be considered by practitioners. Merryweather *et al.* (2009) compared their revised Hand-Calculation Back Compressive Force (HCBCF) model with a sophisticated computer-based software, the University of Michigan 3D Static Strength Prediction Program (3DSSPP) and found a very high correlation ($r^2 = 0.97$) between the two models. They concluded that simple, straightforward models might be preferable over sophisticated models because of their relative simplicity, easy of use, low cost, and high level of agreement with more sophisticated models. However, it should be noted that when postures deviate significantly from sagittal plane (e.g. "2D" ) lifting, results are not as well correlated.

### 2.1.2 Assumptions in Biomechanical Models

#### Single Joint Point as the Fulcrum

The musculoskeletal system in the low back region can be simply represented by a lever system, that two types of forces (loads) can impose on a tissue or the musculoskeletal structures. External loads are the forces that are imposed on the body as a direct result of gravity acting on an object being lifted by a person. In order to maintain equilibrium, the external force must be counteracted by an internal force that is generated by the muscles (primarily) and other structural tissues such as bones, vertebral structures, ligaments, tendons, facia, and so on. External forces (load weight, body weight) create rotational moments (torques) at joints, and the skeletal muscles counteract these moments to create movement and maintain static posture. For a lifting task, the erector spinae muscles exert a force to counteract the moment about the discs. Single-joint lumbar spine musculoskeletal models are typically interested in the transverse distance across the L4/L5 or L5/S1 of the torso to estimate muscle forces and internal loads.

Simple sagittal static low back models assume that the lifting task is a lever system. McNally and Adams (1992) conducted a study with cadavers to measure the pressure inside the IVD by implementing a needle transducer in the L2/L3 and L4/L5 discs. They reported that the disc pressure is evenly distributed in healthy discs, which may imply that the centroid of the disc may be selected as the single force application point. The simplified lever system assumes that fulcrum is in the geometric center, or centroid, of the IVD; it is an estimate of joint center (Chaffin *et al.*, 1990; Santaguida and McGill, 1995). Therefore, a single counterbalance force is applied in the opposite direction. Namely, the center of inter-vertebral disc is assumed as a single joint that balances the moment at this fulcrum.

### Single Equivalent Muscle Model

A single-equivalent model involves assumptions regarding the anatomy of the trunk extensor muscles and load sharing between these muscles (van Dieen and de Looze, 1999). The first assumption in the low back biomechanical modeling is about muscle anatomy. Even though the erector spinae group is morphologically separated into individual muscles and/or fascicles, it is modeled as a single muscle unit having the same physiological characteristics and material properties throughout. It is basically a representation of two-muscle units lying on both sides of the spinous processes along the entire low back region of the torso (right and left erector spinae muscle groups). The force produced by two symmetric shaped muscle groups (symmetry is also an assumption in biomechanical modeling) is simplified as a single equivalent muscle force in low back biomechanical modeling. The single equivalent muscle force is simplified as a single force vector pulling along the spinous process of the vertebral body. Single equivalent muscle models are very common in modeling sagittally static tasks. Most force and moment predictive models do not consider asymmetric tasks. They assume that the task is performed symmetrically and the load is equally shared between the erector spinae muscles. Basically, the assumption is that all fibers of a muscle are equally loaded (Rab, Chao, and Stauffer, 1977), all extensor muscles (ESMM including ESM and multifidus) are equally active and the abdominal muscles are inactive (van Dieen and de Looze, 1999).

The prediction of tissue (including muscles and inetr-vertebral discs) loads is highly dependent upon the geometry of the load-bearing anatomical components (McGill and Norman, 1987a; McGill, Santaguida, and Stevens,1993). Even though the fascicles in the erector spinae group have different fiber orientations (morphological separation) and independent central nervous system (CNS) controls (muscle nerve innervations), which provide different responses to dynamically changing moments to protect the spine from potentially damaging forces, the ESMM is modeled as a single muscle unit throughout this dissertation. The findings of this dissertation are intended to be used in sagittally symmetric static lifting activities, rather than asymmetric and/or one-handed lifting activities. Future work, however, could address these issues and allow more sophisticated modeling that adopts asymmetric changes in torso posture.

Estimating muscle forces is a great challenge because of the complexity of the muscle and passive structures and individual variability of activation patterns. Therefore, simplifying assumptions have been made. However, simplification or assumption when defining the ESMLA has been shown to have a significant impact on modeling outcomes (Chaffin *et al.*, 1985; McGill and Norman, 1987a). Arjmand, Plamondon, Shirazi-Adl, Larivire, and Parnianpour (2011) indicated that assumptions and simplications in biomechanical models can adversely influence the accuracy of force and moment estimations, as well as their suitability for biomechanical applications. This is a trade-off that modelers encounter. Therefore, simplifications should be such that they minimize error.

## 2.2 Other Factors in Biomechanical Models

### 2.2.1 Trunk Internal Spine Loading Structures (Intra-abdominal Pressure, Ligaments, and Other Connective Tissues)

Intra-abdominal pressure (IAP) and passive loading/unloading tissues (ligaments and other connective tissues) are other topics that should be considered in biomechanical modeling (Marras and Sommerich, 1991). The effect of the IAP to support the integrity of spine has been studied in the literature (Bartelink, 1957; Morris *et al.*, 1961; Eie, 1966; McGill and Norman, 1987b; Daggfeldt and Thorstensson, 1997). The results of a gastric balloon experiment by Bartelink (1957 ) showed that the IAP increases with the magnitude of the load lifted. Ayoub and Mital (1989) also indicated that the IAP measurements can be used as a measure of the load imposed on the spinal column.

It has been reported that there is a considerable increase in the IAP during lifting (Bartelink, 1957; Morris *et al.*, 1961; Daggfeldt and Thorstensson, 1997). Bartelink (1957), Aspden (1989), and Thomson (1988) found that the IAP reduces the amount of pressure in the lumbar inter-vertebral discs. By acting in front of the spinal column, pushing the upper torso into extention, the IAP resists the flexor load moment acting on the lumbar spine (Chaffin, 1997; Chaffin, 2005). Moreover, the length of the ESMLA is shortened while the axis of rotation for sagittal movement is being shifted anteriorly into the abdomen from the inter-vertebral space, which results in less force to maintain the body in static equilibrium and therefore less spinal compression. However, the IAP has often been ignored in biomechanical calculations (de Looze *et al.*, 1996) since it has a minimal effect (Marras and Sommerich, 1991) relative to other modeling assumptions.

The thoracolumbar fascia (TLF) (or the lumbodorsal fascia) is also a lumbar support mechanism that has been considered in biomechanical models (McGill and Norman, 1988; Sullivan, 1989; Gatton, Pearcy, Pettet, and Evans, 2010; Gatton, Pearcy, and Pettet, 2011). The TLF is a structure that provides a means of attachment to the spine for the trunk muscles (Gatton *et al.*, 2010; Gatton *et al.*, 2011). Its contribution to spine extension is relatively small compared to the forces exerted by muscles; thus it is also neglected in biomechanical models (McGill and Norman, 1988). The posterior ligamentous system (the interspinous and supraspinous ligaments) is also a supportive system for sharing forces and moments in the low back (Sullivan, 1989), but they are also ignored in biomechanic models.

Muscles other than ESMM are also typically ignored in simple biomechanics models. Multiple-muscle models assume that all the muscles, if a cutting plane is passed through the lower lumbar spine, will contribute to spine support and spine loading (Schultz and Andersson, 1981; Marras and Radwin, 2005). However, the complexity of dynamic lifting tasks limits the effectiveness of results. Multiple-muscle models, on the other hand, work well for steady-state static load holding conditions (Marras and Radwin, 2005). By investigating the current literature, Marras and Sommerich (1991) concluded that loading of the lumbar spine under dynamic conditions is actually greater than under static conditions; between 22.5% and 60% higher loading due to inertial forces generated by the body segments during motion, speed of contractions, and spine loading from static gravitational forces.

### 2.2.2 Validation of Biomechanical Models

Direct measurement of tissue loads *in-vivo* is not feasible; therefore, utilization of modeling approaches is the only tenable option for predicting tissue loads. *in-vitro* modeling, on the other hand, has been used but there are some issues with validity and how well such testing mimics *in-vivo* tissue behavior. Prediction equation models, predictive linear regression models, optimization models, EMG studies, and direct *in-vivo* disc pressure measurements are common methods to evaluate spinal loadings.

Gagnon, Arjmand, Plamondon, Shirazi-Adl, and Lariviere (2011) compared a single-joint musculature model to a multiple-joint force resolution model by employing an EMG assisted optimization method. Optimization models are mathematical models, and EMG models are biological models for estimating muscle forces. EMG models can monitor the muscle activity and determine which muscles are more active in a particular work task. They can estimate muscle force loading on the spine. They can also assess co-activation of muscles and their impact on spine loading. EMG models also capture differences/variations in loading among individuals (Marras and Radwin, 2005), as well as the variations in tasks such as asymmetric or one-handed lifting. EMG-assisted optimization models are hybrid methods that combine these two approaches (Gagnon *et al.*, 2011).

The ESMLA distance is a primary input for calculation of the moments and forces loading the inter-vertebral discs. Intradiscal pressure measurement provides a direct approach to determine the effects of these moments and forces. The compression forces have been confirmed with *in-vivo* needle experiments (Nachemson and Morris, 1964; Nachemson, 1965; Nachemson and Elfstrom, 1970; Sato, Kikuchi, and Yonezawa, 1999; Wilke, Neef, Caimi, Hoogland, and Claes, 1999; Wilke, Neef, Hinz, Seidel, and Claes, 2001). Pressures at the lumbar discs can be obtained from direct experiments using transducers placed into the IVD. The complexity and health concerns about the impact of placing transducers into the discs limit *in-vivo* research. This invasive process has a relatively high risk for subject injury since the inter-vertebral disc region is very sensitive. If something goes wrong during the surgical placement of transducers, the subject might become paralyzed. The process of obtaining MRI scans and measuring the dimensions from the scans and then calculating forces and moments at the IVD level is relatively safe compared to such invasive techniques.

## 2.3 Erector Spinae Muscle Mass (ESMM)

An integral part of force and moment calculations in biomechanical models is the definition of moment arms as well as the gross and functional anatomy of muscles. Back muscles can be separated into two groups. The first group (including the multifidi) is the muscles that are directly attached to the lumbar vertebrae and provide spine segment stability, and the second group (including erector spinae) is composed of the large torque-producing muscles with no segmental attachment to the lumbar vertebrae (Bergmark, 1989; Lee, Song, Lee, Kang, Kim, and Ryu, 2011). The vertebrae and/or inter-vertebral disc level is a determining factor for the component of ESMM. Moeller and Reif (2007), in their sectional anatomy atlas used computed tomography and magnetic resonance imaging, seperated the erector spinae muscle into two tracts, lateral and medial tract. At the L3/L4 disc level and the L4 vertebral level, the lateral tracts are iliocostalis lumborum muscle and longissimus muscle and the medial tracts are multifidis muscles. At the L5 vertebral level, the iliocostalis lumborum muscle is not included in the ESMM. Due to such complexity, the careful definition of muscles and anatomical structure at the low back region is needed.

### 2.3.1 Muscles in the ESMM: Anatomy of the ESMM

Erector spinae has been used as a collective term for these three muscles (Macintosh and Bogduk, 1987). The erector spinae muscle group (ESM) in low back region consists of three posterior back extensor muscles; the spinalis thoracis, the longissimus thoracis, and the iliocostalis lumborum. However, it has been very common to also combine the multifidus in the ESM group because of functionality (Bogduk, Macintosh, and Pearcy 1992; Stokes *et al.*, 2005) and it is difficult to distinguish the multifidus from other erector spinae muscles in MRI images (Lee, Lim, Park, Kwon, Ryu, Lee, and Park, 2012). McGill *et al.* (1993) introduced the term "*erector mass*" stating that; "Erector mass includes longissimus thoracis, iliocostalis lumborum, and multifidus." Based on their jargon, the whole structure including the ESM and multifidus will be referred as the *Erector Spinae Muscle Mass (ESMM)* in this dissertation. Therefore, the ESMM is basically the muscle group that supplies internal forces to counteract to external moments in order to generate movements of the spine to perform a task such as lifting. It also provides the stability (together with other muscles such as abdominal muscles) needed to protect vital anatomical structures. The ESMM has different percentages and muscle prevalence at different vertebral levels. It could be separated into tracts to eliminate the difficulties arising from anatomical complexity. It could be concluded that the ESMM basically consists of medial (multifidus and spinalis thoracis) and lateral (longissimus thoracis and iliocostalis lumborum) tracts. Note that the muscle content of tracts is based on the vertebral level. Amonoo-Kuofi (1983) reported cross sectional areas ($mm^2$) of each muscle tract, or column, at various vertebral disc levels (Figure 2.1).

Even though the function and muscle types of the ESMM are the same across many studies, the erector spinae muscle group (ESMM) has been given many different names by different authors. For example, Chaffin *et al.* (1990) grouped the spinalis, longissimus, and iliocostalis and multifidus and called it *the erector spinae muscle*. Marras *et al.* (2001) and Marras (2008) used the term *the erector spinae group*. Anatomy texts (Ellis, Logan, and

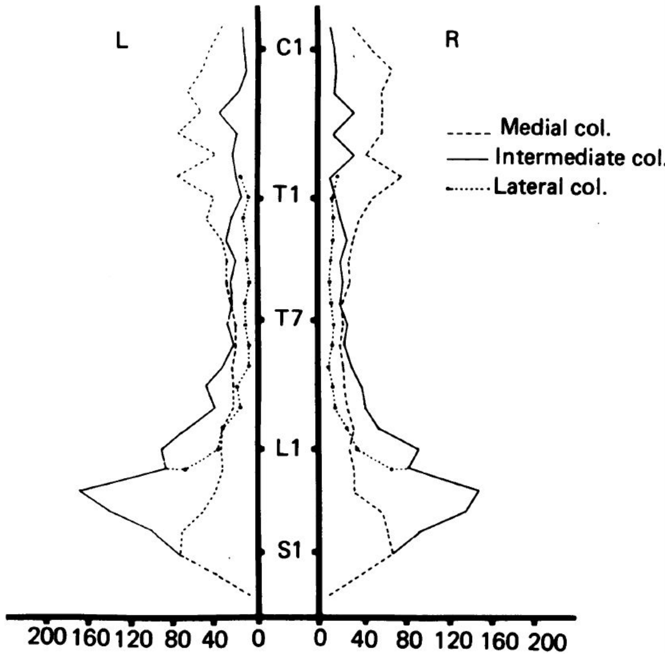



Figure 2.1: Mean areas ($mm^2$) of muscles (both sides) at several inter-vertebral levels (Retrieved from Amonoo-Kuofi, H. S. (1983). The density of muscle spindles in the medial, intermediate and lateral columns of human intrinsic postvertebral muscles. Journal of Anatomy. 136(3): 509-519.)

Dixon, 2007) and other researchers (Reid and Costigan, 1987; Reid, Costigan, and Comrie,1987; McGill, Patt, and Norman, 1988; Tracy *et al.*, 1989; Tveit *et al.*, 1994; Nussbaum and Chaffin, 1996; Jorgensen, Marras, Granata, and Wiand, 2001; Gatton *et al.*, 2010) have also considered the erector spinae as a single structure and included the multifidus in the ESMM structure. All of these muscles are innervated by the dorsal rami of the spinal nerves (Macintosh and Bogduk, 1987).

Bogduk *et al.* (1992) and Macintosh and Bogduk (1993) used the iliocostalis and longissimus as the erector spinae and mentioned the multifidus separately, but they refer to the whole structure as *the back muscles.* Jorgensen *et al.* (2003a) also combined the iliocostalis, longissimus, and multifidus using the term *the lumbar back muscle.* Dumas, Poulin, Roy, Gagnon, and Jovanovic (1988) stated that "the iliocostalis and longissimus dorsi are usually referred to as *the erectores spinae.*" Han, Ahn, Goel, Takeuchi, and McGowan (1992) pointed out that it was very difficult to differentiate the iliocostalis and longissimus muscles at the L5/S1 disc level. Delp, Suryanarayanan, Murray, Uhlir, and Triolo (2001) studied cadavers, and identified the spinalis thoracis, longissimus thoracis, and iliocostalis lumborum muscles separately using the term the erector spinae as the whole group name, but they did not mention the multifidus at all. Amonoo-Kuofi (1983) also reported the results of his cadaveric study assuming the common muscle mass of the erector spinae as one mass. He provided cross sectional areas of medial (including multifidus) and intermediate (including longissimus and iliocostalis) columns of the erector spinae mass (Figure 2.1). He also used the term "*intrinsic postvertebral muscles*" for all of the muscles lying laterally on the spine. Note that the spinalis thoracis is not included in the erector spinae muscle mass at lower vertebral levels. Han *et al.* (1992) also used the term the erector spinae muscle for the iliocostalis and longissimus muscles taken together and presented the multifidus separately.

As others, Tracy *et al.* (1989) studied the whole erector spinae mass. Being able to identify components of the erector spinae at the L2/L3 and L3/L4 IVD levels, they reported their findings for three components of the erector spinae (medial, intermediate, and lateral) and the overall erector spinae. McGill *et al.* (1993) were able to identify each individual muscle at the L1, L2, and L3 vertebral levels, but they did not differentiate individual muscles at the L4 and L5 levels, because of the difficulty in separating muscle types. Table 2.1 presents their raw cross-sectional areas ($mm^2$) measured directly from MRI scans. However, summation of the longissimus thoracis, iliocostalis lumborum, and multifidus does not equal to the value reported as the erector mass in the Table 2.1. This may be the result of reporting averages rather than each specific subject.

McGill *et al.* (1993) and Hansen *et al.* (2006) did not include the spinalis thoracis in the lumbar erector spinae. Moreover, they separated the multifidis from the erector spinae in their muscle classification. They grouped the interspinalis, intertransversai mediales, multifidi, and lumbar erector spinae (longissimus and iliocostalis) as *extensor muscles.* In the same way, Kumar (1988) separated the whole erector mass structure into two parts:

Table 2.1: Raw cross-sectional areas ($mm^2$) measured directly from MRI scans (reproduced from McGill, S. M., Santaguida, L., and Stevens, J. (1993). Measurement of the trunk musculature from T5 to L5 using MRI scans of 15 young males corrected for muscle fibre orientation. Clinical Biomechanics. 8(4): 171-178.)

| | **Vertebral Level** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | L1 | | L2 | | L3 | | L4 | | L5 | |
| Muscles | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left |
| Longissimus thoracis | 1248 | 1180 | 1175 | 1089 | 747 | 782 | - | - | - | - |
| Iliocostalis lumborum | 1181 | 1158 | 1104 | 1150 | 1368 | 1395 | - | - | - | - |
| Multifidus | 290 | 324 | 343 | 366 | 447 | 472 | - | - | - | - |
| Latissimus dorsi | 717 | 682 | 429 | 372 | 232 | 256 | - | - | - | - |
| Erector mass | 2615 | 2723 | 2854 | 2833 | 2831 | 2854 | 2151 | 2234 | 905 | 986 |

the “erectores” spinae and the transversospinalis, which is the general term for the semispinalis, multifidus, and rotatores. The transversospinal system is defined as the muscle mass filling the space between the transverse process and spinous process (Hansen *et al.*, 2006). Anderson, D’Agostino, Bruno, Manoharan, and Bouxsein (2012) measured the transversospinalis and erector spinae as two separate muscle groups. They also suggested to clearly differentiating the two muscle group in future studies since these two muscles have different functional roles. Rab *et al.* (1977) separated ESM and multifidus. They reported the erector spinae and the intrinsic rotator muscles of the spine which includes the multifidus, rotators, and interspinalis fibers.

McGill *et al.* (1988) measured the whole structure as well since they could not separate the multifidus and other erector spinae muscles referring to them as the “sacrospinalis components of the erector muscle.” The erector spinae is known as *sacrospinalis* in older texts. Morris *et al.* (1961), Nachemson (1968), and Tichauer (1971) used the term sacro-spinalis for whole muscle structure of the back, which is responsible for a lifting task. Nachemson (1968) included the multifidus, iliocostalis lumborum, and longissimus *dorsi* in the sacro-spinalis muscles. Nemeth and Ohlsen (1986) confirmed that the erector spinae was earlier called sacrospinalis. Macintosh and Bogduk (1987) indicated that the spinalis, longissimus thoracis, and iliocostalis constitute a subgroup of the erector spinae, which is referred to as *the sacrospinalis*. They also indicated that sacrospinalis has also been used synonymously and interchangeably with the erector spinae. Stokes and Gardner-Morse (1999) used the term *the dorsal muscles* for the longissimus, iliocostalis, and multidus.

Macintosh and Bogduk (1987; 1991; 1993) and Bogduk (2005) indicated that the lumbar erector spinae consists of two muscles: the longissimus thoracis and the iliocostalis lumborum; and each of these muscles has two components: a lumbar part and a thoracic part. Four divisions of the erector spinae are longissimus thoracis pars lumborum, iliocostalis lumborum pars lumborum, longissimus thoracis pars thoracis and iliocostalis lumborum pars thoracis. They did not include the spinalis thoracis and multifidus in the erector spinae muscle mass. Daggfeldt and Thorstensson (2003) also preferred using four divisions of erector spinae: the longissimus thoracis, iliocostalis lumborum, pars lumborum, and pars thoracis. By including the multifidus into these four compartments, they named the whole structure "*the back extensor muscles*." Hubley-Kozey, Butler, and Kozey (2012) also followed the same muscle description in their study.

The erector spinae muscles can also be referred to as superficial *paraspinal muscles*. Cooper, Holli, and Jayson (1992) used the term paraspinal by grouping the deep muscles (e.g., multifidus) and superficial muscles (e.g., erector spinae and longissimus) together in measurements. Danneels, Vanderstraeten, Cambier, Witvrouw, and De Cuyper (2000) and Kamaz, Kiresi, Oguz, Emlik, and Levendoglu (2007) also used the term paraspinal muscles for the multifidus, iliocostalis, longissimus, which is basically the ESMM as defined in this dissertation. To the contrary, Lee *et al.* (2011) (Figure 2.2.a), Lee *et al.* (2012) (Figure 2.2.b), and Fortin and Battie (2012) (Figure 2.2.c) separated the whole ESMM structure into two parts: the erector spinae and multifidus muscles. They named the whole structure the "paraspinal muscles." Kang, Shin, Kim, Lee, and Lee (2007) used the term paraspinal muscles for the psoas in addition to the erector spinae and multifidus. The term *deep longitudinal paravertebral muscle* is also used for the sipinalis, longissimus, and iliocostalis muscles. The prefix "para" is used to indicate it is "close to" the structure.

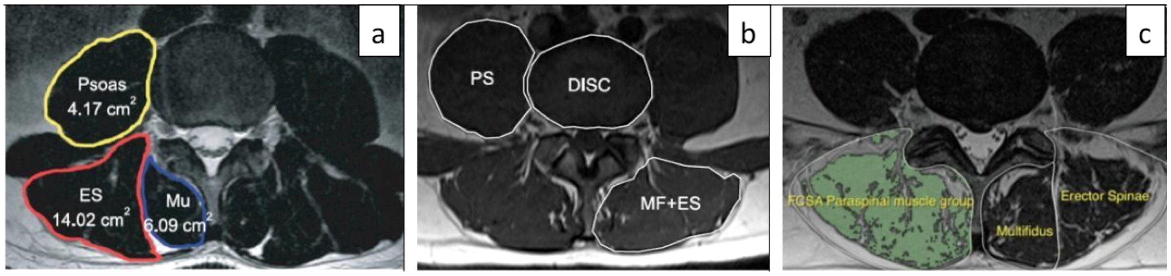



Figure 2.2: Paraspinal muscles: Erector spinae + multifidus

In the literature, unfortunately, researchers have not always followed the same conventions. For example, Wood, Pearsall, Ross, and Reid (1996) grouped the following muscles: the erector spinae, longissimus cervicis, longissimus thoracis, semispinalis thoracis, multifidus, and iliocostalis lumborum and termed "paraspinal muscles." Namely, they did not include multifidus in the erector spinae and they reported both the erector spinae and its individual muscles as different muscles. Cholewicki and VanVliet (2002) reported the iliocostalis lumborum, longissimus thoracis, multifidus, and lumbar erector spinae as if the erector spinae was another muscle name.

McGill and Norman (1987a) separated the erector spinae into four muscles: the multifidus, sacrospinalis, longissimus thoracis, and iliocostalis lumborum. After Farfan (1973), McGill and Norman (1987a) called the iliocostalis lumborum pars lumborum and longissimus thoracis pars lumborum as *sacrospinalis* to distinguish their different force vectors from the thoracis portions of iliocostalis lumborum and longissimus thoracis.

To illustrate the controversies in the literature and to emphasize the variety of erector spinae muscle definitions among authors, Macintosh and Bogduk (1987) pointed out that the definition varied even among the editions of Nomina Anatomica [Nomina Anatomica (NA) which was the international standard on human anatomic terminology from 1956 until it was replaced by Terminologia Anatomica in 1998]. According to the $2^{nd}$ edition of Nomina Anatomica, the erector spinae consists of all the muscles of the back, but the erector spinae, according to the $4^{th}$ edition of Nomina Anatomica, consists of only the iliocostalis, longissimus, and spinalis. Moreover, the multifidus was no longer considered to be a component of the erector spinae. It was grouped among the transversospinal muscles.

To summarize, it is a common practice to study all the muscles in the lumbar spine together and refer to them as the erector spinae muscle group when researchers are unable to distinguish individual muscles. Using a single description eliminates the need to explain muscle insertions and prevalence of each muscle at each vertebral level. When researchers have been able to distinguish individual muscles, they have reported both the overall erector spinae muscle group and separated them into individual muscles for each vertebrae or inter-vertebral disc level. The ESMM has been referred to in the literature as:

-The erector spinae

-The erectores spinae

-Longitudinal torso muscles

-Extensor muscles

-Erector mass

-Paraspinal muscles

-Lumbar erector spinae

-Sacrospinalis muscles

-Back extensor muscles

-Deep back muscles

Based on these names and previous definitions, the ESMM can be defined as a deep muscle group, consisting of multiple muscles in the sacral and lumbar low back regions which lays down longitudinally throughout the torso, and is assumed as a single-equivalent muscle that creates the power to extend or erect the body. Various authors have selected these names to explain this muscle group from their points of view. However, different names, even different muscle combinations, make the results of studies, including this study, difficult to compare. In reality, they typically measured the same muscles (whole structure), but used different names.

### 2.4 Erector Spinae Muscle Mass Lever Arm (ESMLA)

#### 2.4.1 Definition of the ESMLA

Kumar (1988) and Chaffin *et al.* (1990) explained how to determine the ESMLA distance in the sagittal plane (anterior-posterior perpendicular distance between the centroid of the muscle and the coronal plane) and in the coronal plane (lateral perpendicular distance between the centroid of the muscle and the sagittal plane). Mostly, the ESMLA in the sagittal plane is used in biomechanical models. As such, researchers often refer the ESMLA in the sagittal plane. The erector spinae muscle mass lever arm (ESMLA) is the "shortest" (perpendicular) distance in the sagittal plane between the geometric center of the inter-vertebral disc (the assumed joint axis of rotation or the center of rotation of skeletal structure) and the middle point (or centerline) of ESMM centroids (the line of muscle action). Rab *et al.* (1977) and Dumas *et al.* (1988) applied the Jensen's and Davy's (1975) method of representing muscles by the line of the centroids of successive cross-sections to obtain muscle force vectors. They defined the true muscle moment arm as the perpendicular distances from the disc centroid to the dominant line of action (McGill *et al.*, 1993). The action of a muscle is a vector function of the magnitude and direction of the muscle force, as well as its effective lever arm (Rab *et al.*, 1977) to create a tension to counteract the torque about the discs.

Chaffin and Moulis (1969) reported that the ESMLA is "a hypothetical construct, since neither the exact center-of-rotation nor the line-of-action of the muscles can be determined." It is a crude measurement that requires several simplifying assumptions. The ESMLA distance is used in low back models, particularly for the modeling of sagittal lifting tasks. The low back model assumes that there is a single joint as the support (the inter-vertebral disc) and a single equivalent muscle force, exerting from the ESMM. The distance between the joint and muscle force point is the effective lever arm (ESMLA) that produces a counteracting force to lift a load, control gross trunk movement, and provide general trunk stability.

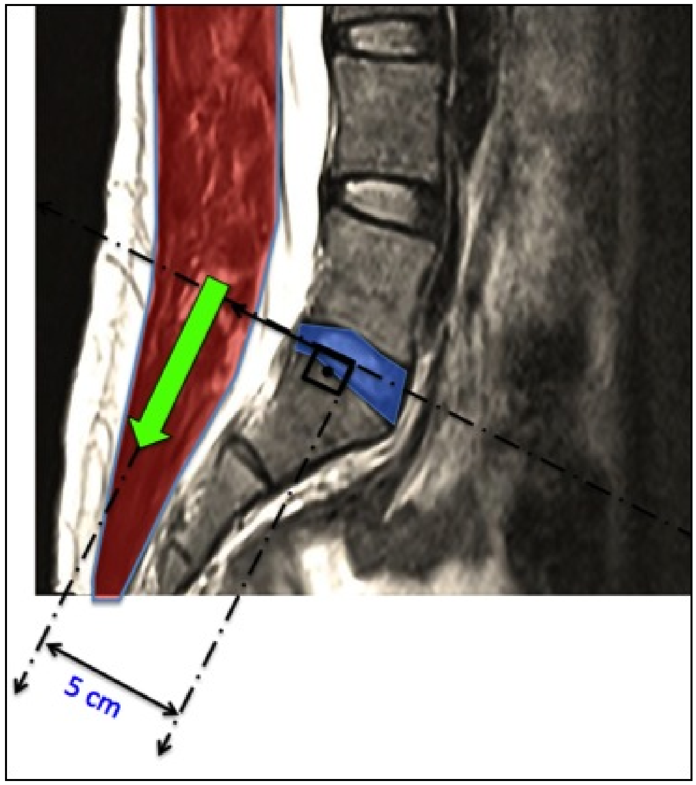



Figure 2.3: Representation of the ESMLA distance

In this dissertation, the ESMLA means the perpendicular distance from the centroid of the inter-vertebral disc to the line joining the centers of the right and left erector spinae muscle masses (Figure 2.3). The methodology of Nemeth and Ohlsen (1986), Kumar (1988), Tracy *et al.* (1989), and Chaffin *et al.* (1990) was followed to measure the length of the ESMLA.

### 2.4.2 History of Usage of the ESMLA

The ESMLA has been used in low back biomechanical models for several decades. Wilke *et al.* (2001) indicated that the first simplified biomechanical model to calculate moments and forces on the lumbosacral (L5/S1) inter-vertebral disc in lifting is from Bradford and Spurling (1945). To give some idea of the force on the L5/S1 disc, Bradford and Spurling (1945) provided an example of a man lifting a 100 lb weight with arms outstretched about 75 cm in front of him. They assumed that "the erector spinae muscles which extend approximately 7 cm behind" the center of the lumbosacral disc, and "act with a lever arm approximately 5 cm in length." In 1957, Bartelink cited them in his article investigating the role of the abdominal pressure in lifting. The only statement about the length of the ESMLA in Bartelink's article was "Bradford and Spurling (1945) calculated a muscle pull of 1500 lbs, exerted by the erector spinae muscles, and operating on a lever of two inches, ..."

Morris *et al.* (1961) later conducted a study to determine the role of trunk muscles by measuring muscle activities and the intra-abdominal and intra-thoracic pressures in different lifting positions and load weights. To validate the findings, they calculated the approximate forces on the fifth lumbar (L5/S1) disc. They used a 2 in. lever arm length for deep back muscles in their calculations without explaining why they selected this specific number.

In 1962, the International Labor Office, International Occupational Safety and Health Information Center (ILO-CIS) published an Information Sheet (No. 3) to suggest lifting weight limits for several postures along with gender and age differences (Munchinger, 1962). Munchinger (1962) used the term "the power-lever arm" for the ESMLA. He mentioned that the ESMLA is "about 5 cm long" and about 1/8 of the resistance-lever arm distance, which is the distance from the spinous process of the lower lumbar region to the spinous process of the shoulder region (Figure 2.4).

Eie (1966) studied the load capacity of the low back with 33 cadaver spines. Amount of damage on vertebras, endplates, and discs were recorded in several compression-crush tests. To evaluate the results of this study, *in-vivo* forces and moments were calculated. The distance between the nucleus pulposus of the fifth lumbar (L5/S1) disc =and the force application point of the erector spine was selected as 6.5 cm. The lever arm distance (6.5 cm) of the erector spinae was probably obtained from their planigraphic measurements.

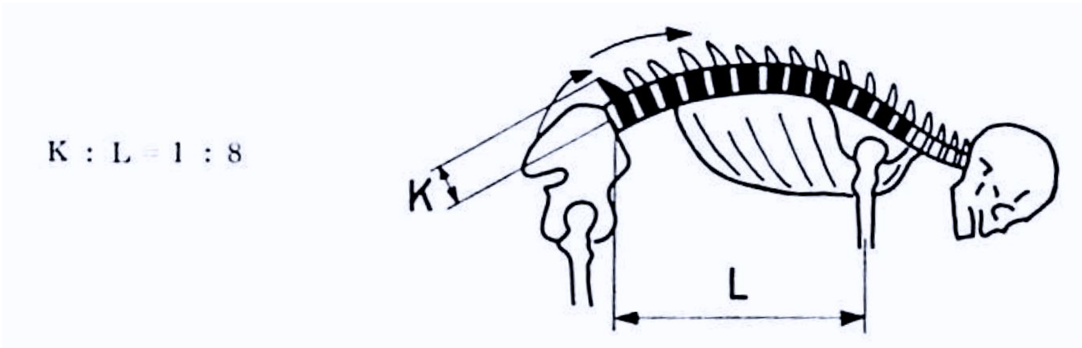



Figure 2.4: The ESMLA distance as a function of the torso length (1:8)
Retrieved from Munchinger, R. (1962). Manual Lifting and Carrying. International Labor Office, International Occupational Safety and Health Information Center (ILO-CIS), Sheet. No. 3. International Labour Organization (ILO). Geneva, Switzerland.

Nachemson (1968) investigated the stabilizing function of the psoas major muscle. In order to calculate muscle forces, Nachemson (1968) assumed that the midpoint of the sacro-spinalis muscles is 5 cm behind the center of the L3/L4 disc.

In 1969, Chaffin suggested a computerized biomechanical model to calculate shear and compression forces at the lower lumbar spinae. The computerized static sagittal plane (SSP) model used a moment arm of 5 cm by assuming the line-of-action of the lower lumbar back muscles to act parallel to the normal compressing force on the disc. Chaffin (1969) asserted that the assumed 5 cm for the moment arm of back muscles "is an average moment arm, which is based on values published by Bartelink, 1957; Perey, 1957; Munchinger, 1962; Thieme, 1950, as well as from cadaver measurements." Ayoub and El-Bassoussi (1976) added Pearson and McGinley (1961) (it should be Pearson, McGinley, and Butzel, 1961) to theses studies (Bartelin, 1957; Perey, 1957; and Thieme, 1950) and stated that "a line of action parallel to the vertebral bodies and at a distance of 5 cm posterior to the center of the discs" was assumed based on these studies. Chaffin's 5 cm muscle lever arm assumption has been cited by several other researchers. By citing Chaffin (1969), Kumar (1988) stated that "a fixed moment arm of 5 cm" has been used in most models to estimate forces. Kumar (1988) also mentioned that "based on the cadaveric measurements (Morris *et al.*, 1961 [actually, it is not a cadaveric study, 10 live subjects were used in the study]; Fartan, 1973; Rab *et al.*, 1977), the moment arm for erector spinae has been taken to be 5 cm by most modelers."

McGill and Norman (1987a) also clarified that it was an assumption by stating; "Usually the extensor muscle and ligament forces of the lumbar spine are assumed to act 5 cm posterior to a disc centre of rotation." They concluded that the compression force at the L4/L5 inter-vertebral disc is estimated to be 35% higher than a more realistic anatomical model of the erector spinae muscle group when a frequent and simplified single muscle equivalent with a 5 cm moment arm. They suggested using a 7.5 cm rather than 5 cm for the single "equivalent" extensor soft tissue moment arm since it estimated better compression forces. They included several numbers larger than 5 cm and looked at the compression forces and muscle geometry. They used Bogduk's (1980) muscle descriptions and Nemeth's and Olsen's (1986) 7.1 cm moment arm for males. But, they also used 9-10 cm moment arms. With 10 cm moment arm, they found that the calculation would yield 35% less compression forces.

Later, Chaffin (1995) used a length of "5 to 7 cm" lever arm for the erector spinae muscles in his lecture notes. On the other hand, Tveit *et al.* (1994) indicated that the ESMLA distance has ranged between "5 and 8 cm."

Chaffin (1997; 2005) indicated that the effective force of posterior erector spinae muscles, "which at that time [was] believed to exert" . . . "approximately 5 cm posterior to the centers-of-rotation of the spinal discs."

Several authors used the 5 cm ESMLA distance in their biomechanical computation examples. Schultz and Anderson (1981) assumed a 5 cm lever arm distance to analyze a sagittally symmetric wight holding task and compute the ESMM tension. Note that Schultz and Anderson (1981) used a 4.4 cm anterior-posterior lever arm (ESMLA) and 5.4 cm lateral moment arm in their non-symmetric weight holding task (they assumed that a person has a trunk width of 30 cm and trunk depth of 20 cm at the L3 level; and they calculated the anterior-posterior lever arm by multiplying the trunk depth of 20 cm with a constant of 0.22 and the lateral moment arm by multiplying the trunk width of 30 cm with a constant of 0.18). Marras and Sommerich (1991) also used Schultz's and Anderson's (1981) coefficients for anterior posterior and lateral moment arms in their three-dimensional motion model to calculate loads on the lumbar spine. Poulsen (1981) used a 5 cm back muscle lever arm in her experiment to calculate maximum load limits. McGill and Norman (1985) assumed a 5 cm effective moment arm of the combined effects of lumbar muscles and ligaments to calculate compression forces on the L4/L5 disc level for static and dynamic tasks and to compare the results with NIOSH guidelines. In the same way, Garg (1997) used 2 inches erector spinae lever arm in his lifting example, and referred to the distance as "the power arm." Hutton and Adams (1982) used a distance of 6.1 cm for the lever arm of the extensor muscles in their biomechanical model to calculate compressive strengths; 6.1 cm was assumed to be a reliable value for the lever arm of the extensor muscles. This value was based on their previous study (Adams, Hotton, and Stott, 1980). Based on a detailed investigation of this paper, it might be stated that this value could be the average value of all inter-vertebral disc levels measured on only male cadavers (female cadavers were also included in the study but they were ignored in the average). Tracy and Munro (1991) used a 5.8 cm lever arm distance to calculate spinal loading in their articulated plastic manikin. The value of 5.8 cm is the average male ESMLA distance in their previous MRI study (Tracy *et al.*, 1989). In textbook examples and reports, the distance of the action of the erector muscles from spine is frequently assumed to be 5 cm (2 inches) for simplicity (Ayoub and Mital 1989; Vincent, 1991; Chaffin *et al.*, 2006; Freivalds and Neibel, 2008). Rohlmann, Bauer, Zander, Bergmann, and Wilke (2006) used a 4.0 cm of erector spinae lever arm distance at the T12/L1 IVD level to calculate muscle forces for flexion and extension with their finite element model. Merryweather *et al.* (2009) mentioned that the ESMLA "distance is assumed to be constant at 5.0 cm (2 in) in" the previous versions of Hand-Calculation Back Compressive Force (HCBCF) models (HCBCF v1.0 and HCBCF v1.1). For the current HCBCF model (HCBCF v1.2), they used 6.6 cm for female and 6.9

cm for male subjects. These values are derived from comparison of the back compression force results from manual calculations with the results of 3D Static Strength Prediction Program (3DSSPP) calculations. They tried several ESMLA values in their manual calculations and selected 6.6 cm for females and 6.9 for males since these values were the best fit values for the results of 3DSSPP. Bean *et al.* (1988) assumed a 7.4 cm moment arm for the erector spine at the L5/S1 level in their double objective linear programming method to calculate muscle contraction forces. Chaffin was a co-author of this paper.

The 3D Static Strength Prediction Program™ (3DSSPP) Version 6.0.5 User's Manual, written by Vincent (2001), indicates that the muscle moment arm distance data were compiled from (1) McGill, Patt and Norman (1988); Reid, Costigan, and Comrie (1987a); Nemeth and Ohlsen (1986); and Chaffin *et al.* (1989, it should be 1990) for the ESMLA distance for the L5/S1 level and (2) McGill *et al.* (1988); Reid *et al.* (1987a); Nemeth and Ohlsen (1986); Chaffin *et al.* (1989, it should be 1990); Kumar (1988), Tracy *et al.* (1989); and McGill and Norman (1986) for the ESMLA distance for the L4/L5 level. The current version of 3DSSPP (6.0.6) uses the erector spine lever arm distances to calculate forces and moments at the L4/L5 IVD level for dynamic tasks by using a 5.9 cm ESMLA distance for males (for both right and left sides) and 5.4 cm and 5.2 cm ESMLA distances for females for the right and left side, respectively. These lever arm distances are for calculation of sagittal lifting tasks. Software also uses lateral ESMLA distances to calculate non-sagittal tasks. Note that 3DSSPP is not sensitive to subject anthropometrics such as height, weight, or BMI. It is only sensitive to gender.

DeSantis, DiGironimo, Pelliccia, Siciliano, and Tarallo (2010) used a 5 cm lever arm length for the extensor erector spinal muscles in their virtual manikin. They selected this number based on Bartelink (1957) and Morris *et al.* (1961).

Waters and Garg (2010) indicated that the sagittal plane moment arm for the erector spinae muscles at the L5/S1 disc are assumed to be 6.0 cm (2.4 in) for males based on Kumar (1988) and an average value of 5.6 cm (2.3 in) for females based on the studies of

Kumar (1988) and Chaffin *et al.* (1990). However, Kumar (1988) reported ESMLA distances (6 cm for males and 5.85 cm for females) at the L5 vertebral level, and did not include the transversospinalis in the erector spinae muscle group. Chaffin *et al.* (1990) also did not measure the ESMLA distance at the LS/S1 IVD level (5.4 cm for the left ESMLA distance and 5.2 cm for the right ESMLA distance at the L4/L5 IVD level).

The results of a comprehensive literature review for the ESMLA distances in anterior-posterior direction are summarized in Table 2.2 and Table 2.3. Note that Table 2.2 presents the results of researchers that measured the ESMLA distance at the vertebral level while Table 2.3 represents the findings at the inter-vertebral disc (IVD) level.

Table 2.2: Anterior-posterior ESMLA distances reported by various authors by vertebral body level

| | Subjects | Age | Height | Weight | BMI | Side | L1 | L2 | L3 | L4 | L5 | S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reid and Costigan (1987) | 20 Male | 21.2 | 176.9 | 69.7 | | | | | | | 5.64(0.4) | |
| *(MRI, Healthy)* | | | | | | | | | | | | |
| Kumar (1988) | 21 Male | 60.2 | 175.1 | 80.0 | | | | | 6.15(0.55) | | | |
| *(CT, Supine,* | 11 Female | 62.0 | 158.2 | 68.7 | | | | | 5.71(0.60) | | | |
| *Patients but not LBP)* | 8 Male | 57.7 | 178.3 | 82.6 | | | | | | | 6.00(0.37) | |
| | 5 Female | 55.2 | 162.2 | 65.5 | | | | | | | 5.85(0.49) | |
| McGill *et al.* (1993) | 15 Male | 25.3 | 176.1 | 81.5 | | Left | 6.0(0.4) | 6.2(0.5) | 6.1(0.5) | 6.1(0.5) | 6.3(0.5) | |
| *(MRI, Supine, Healthy)* | | | | | | Right | 5.9(0.5) | 6.1(0.5) | 6.1(0.5) | 6.1(0.5) | 6.4(0.6) | |
| Gilsanz *et al.* (1995) | 148 Female | 70.2 | 159.7 | 59.9 | Without vertebral fracture | | | | 5.83(0.31) | 6.06(0.42) | | |
| (CT, Osteoporosis) | (23 Female at L3, 27 Female at L4) | | | | With vertebral fracture | | | | 5.54(0.28) | 5.61(0.33) | | |
| Jorgensen *et al.* (2001) | 10 Male | 26.4 | 175.9 | 79.8 | 25.7 | Left | 5.0(0.6) | 5.4(0.6) | 5.6(0.6) | 5.7(0.5) | 6.1(0.7) | 6.3(0.8) |
| *(MRI, Supine, Healthy)* | | | | | | Right | 5.2(0.5) | 5.4(0.7) | 5.7(0.7) | 5.6(0.6) | 6.1(0.7) | 6.2(0.7) |
| | 20 Female | 25.0 | 165.5 | 57.9 | 21.2 | Left | 4.7(0.5) | 5.1(0.6) | 5.3(0.6) | 5.3(0.5) | 5.7(0.6) | 5.6(0.5) |
| | | | | | | Right | 4.8(0.4) | 4.8(0.4) | 5.0(0.5) | 4.9(0.4) | 5.4(0.5) | 5.4(0.5) |
| Anderson *et al.* (2012) | 51 Male | 59.4 | 177.6 | 81.3 | | | 5.56(0.20) | 5.89(0.36) | 6.15(0.42) | 5.61(0.47) | 5.32(0.50) | |
| *(CT, Supine, Healthy)* | 49 Female | 58.1 | 162.2 | 68.4 | | | 5.61(-) | 5.39(0.52) | 5.57(0.47) | 5.11(0.47) | 4.94(0.51) | |

Age: years; Height: cm; Weight: kg; BMI: kg/m$^2$; ESMLA distance: cm

Table 2.3: Anterior-posterior ESMLA distances reported by various authors by IVD level

| | Subjects | Age | Height | Weight | BMI | | L1/L2 | L2/L3 | L3/L4 | L4/L5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nemeth and Ohlsen (1986) | 11 Male | 70 | 176 | 75.02 | | | | | | | 7.1(0.2) |
| *(CT, Supine, Carcinomas)* | 10 Female | 63 | 166 | 60.06 | | | | | | | 6.5(0.2) |
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | | | | | 5.9(0.52) | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 5.78(0.44) | 5.76(0.46) | 6.00(0.53) | 6.17(0.59) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 5.4(0.4) | 5.3(0.2) | 5.4(0.4) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 5.4(0.4) | 5.2(0.4) | 5.2(0.3) | |
| Dumas *et al.* (1991) *(Cadavers)* | 7 Male | 55.6 | 163.6 | | (Range of avarages) | | | | | 6.0 - 6.4 | |
| Bogduk *et al.* (1992) | 9 Male | 29 | | | | (Min-Max) | 3.26-3.48 | 3.55-4.96 | 3.52-6.2 | 3.19-6.1 | 2.82-5.69 |
| *(Radiographs, Upright, Healthy)* | | | | | | | | | | | |
| Moga *et al.* (1993) | 11 Male | | | | | | 5.1 | 5.3 | 5.5 | 5.9 | |
| *(CT, Patients undertaken CT)* | 8 Female | | | | | | 4.9 | 4.7 | 5.1 | 4.9 | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 5.2 | 4.9 | 4.9 | |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 5.1 | 4.9 | 4.8 | |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis | 6.4(0.3) | 6.3(0.3) | 6.2(0.1) | 6.4(0.2) | |
| *(MRI)* | 5 Female | 31 | 173 | 64 | | | 5.6(0.5) | 5.7(0.5) | 5.9(0.3) | 6.2(0.4) | |
| | 6 Male | 37 | 185 | 82 | | Kyphosis | 5.2(0.4) | 5.3(0.4) | 5.6(0.4) | 5.5(0.1) | 5.7(0.3) |
| | 5 Female | 31 | 173 | 64 | | | 4.5(0.5) | 5.2(0.3) | 5.5(0.3) | 5.6(0.5) | 5.7(0.2) |
| Guzik *et al.* (1996) | 16 Male | 24.9 | 179.8 | 75.2 | Average | Left | 5.67(0.32) | | | | |
| *(MRI, Healthy Athlete)* | | | | | Average | Right | 6.06(0.41) | | | | |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 5.4(0.6) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | | | | | | 4.89(0.67) |
| *(MRI, Supine, Healthy Asian)* | | | | | | | | | | | |
| Jorgensen *et al.* (2003b) | 12 Male | 23.1 | 177.1 | 74.5 | | | 5.26(0.44) | 5.46(0.42) | 5.74(0.34) | 5.9(0.44) | 6.4(0.43) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 4.8(0.34) | 4.98(0.41) | 5.18(0.35) | 5.18(0.35) | 5.64(0.34) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 5.43(0.47) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 4.94(0.47) | | |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK | | | | 6.24(0.46) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control | | | | 6.86(0.40) | |

Age: years; Height: cm; Weight: kg; BMI: kg/m$^2$; ESMLA distance: cm

### 2.4.3 ESMLA Distance Measurement Techniques

Differences in measurement techniques for the ESMLA distance could be the main reason for the variation among studies. The ESMLA distance is often defined as the perpendicular distance in anterior-posterior direction from the centroid of the vertebral body [or the centroid of the inter-vertebral disc (IVD)] to the muscle centroid (Nemeth and Ohlsen 1986; Chaffin *et al.*, 1990; McGill *et al.*, 1993; Lee, Lee, and Lee, 2006). The center of the IVD which is the nucleus pulposus is also called the center of the bilateral motion (extention-flexion) axis. Since the major load carrying articulation of the lumbar spine is the nucleus pulposus (Thieme, 1950; Perey, 1957; Morris *et al.*, 1961; Chaffin and Moulis, 1969), for practical purposes, it is considered as the fulcrum of movement and the center of rotation/motion for the purpose of moment calculation (Adams *et al.*, 1980; Poulsen, 1981; McGill and Norman, 1987a; Chaffin *et al.*, 1990; Santaguida and McGill, 1995). For simplicity, the disc centroid, therefore, is assumed as the application point of the fulcrum. In this dissertation, the geometric center, or the centroid, of the IVD has been employed as an estimate of the joint center. Some researchers prefer using the vertebral level rather than the IVD level (Reid and Costigan, 1987; Kumar, 1988; McGill *et al.*, 1993; Marras *et al.*, 2001; Jorgensen *et al.*, 2001; Anderson *et al.*, 2012) for the centroid of the point of rotation. Either way, the centroid at the transverse plane is the point of interest for researchers.

Measurement techniques in the literature, however, are not well defined. Some researchers have drawn a line between the right and left ESMM centroids and measured a perpendicular distance from the disc centroid to this line (Reid and Costigan, 1987; Kumar, 1988; Bogduk *et al.*, 1992; Tveit *et al.*, 1994). They assume that the line-of-action of the ESM force is (1) in the middle of two ESMMs, (2) on the spinous process, or (3) on the absolute perpendicular plane of the transverse image. All these possible assumptions for the line that connects the disc centroid with the line-of-action will be the same line (distance) and the shortest distance in the sagittal plane if the right and left ESMMs have symmetrical shapes and the scan image is not skewed. If not, an angular adjustment could be performed to measure the ESMLA distance (Nemeth and Ohlsen, 1986; Chaffin *et al.*, 1990; Jorgensen *et al.*, 2001).

The definition given above is only for the sagittal plane moment arms, which is required for biomechanical calculation of sagittal static lifting tasks. In the literature, the coronal moment arm, which is the "medial-lateral" distance from the IVD centroid (or the vertebral centroid) to the muscle centroid in x-axis (coronal plane), is also provided by several researchers (Nemeth and Ohlsen,1986; Chaffin *et al.*, 1990; McGill *et al.*, 1993; Tsuang, Novak, Schipplein, Hafezi, Trafimow, and Anderson, 1993; Jorgensen *et al.*, 2001) (Figure 2.5).

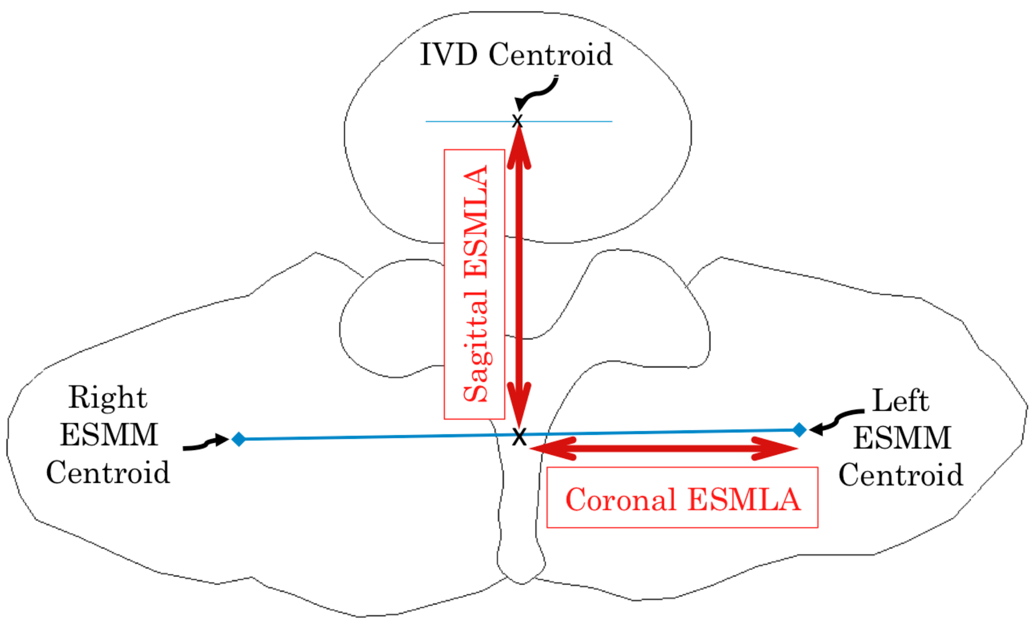



Figure 2.5: Coronal (medial-lateral) and sagittal (anterior-posterior) ESMLA distances

It is also possible to report the ESMLA distances for both ESMMs, or an arithmetic mean of two ESMLA distances. All these alternatives should yield similar ESMLA values. However, some researchers measured the ESMLA distance from the disc centroid directly to the muscle centroid (Han *et al.*, 1992; Seo, Lee, and Kusaka, 2003; Lee *et al.*, 2006 (Figure 2.6)), which yields much larger ESMLA values. If an imaginary right triangle is drawn, the direct line between the disc centroid and muscle centroid, as can be seen in

Figure 2.6, will be the hypotenuse while the perpendicular distance between the disc centroid to the line-of-action of ESMM will be the side adjacent leg, which is shorter.

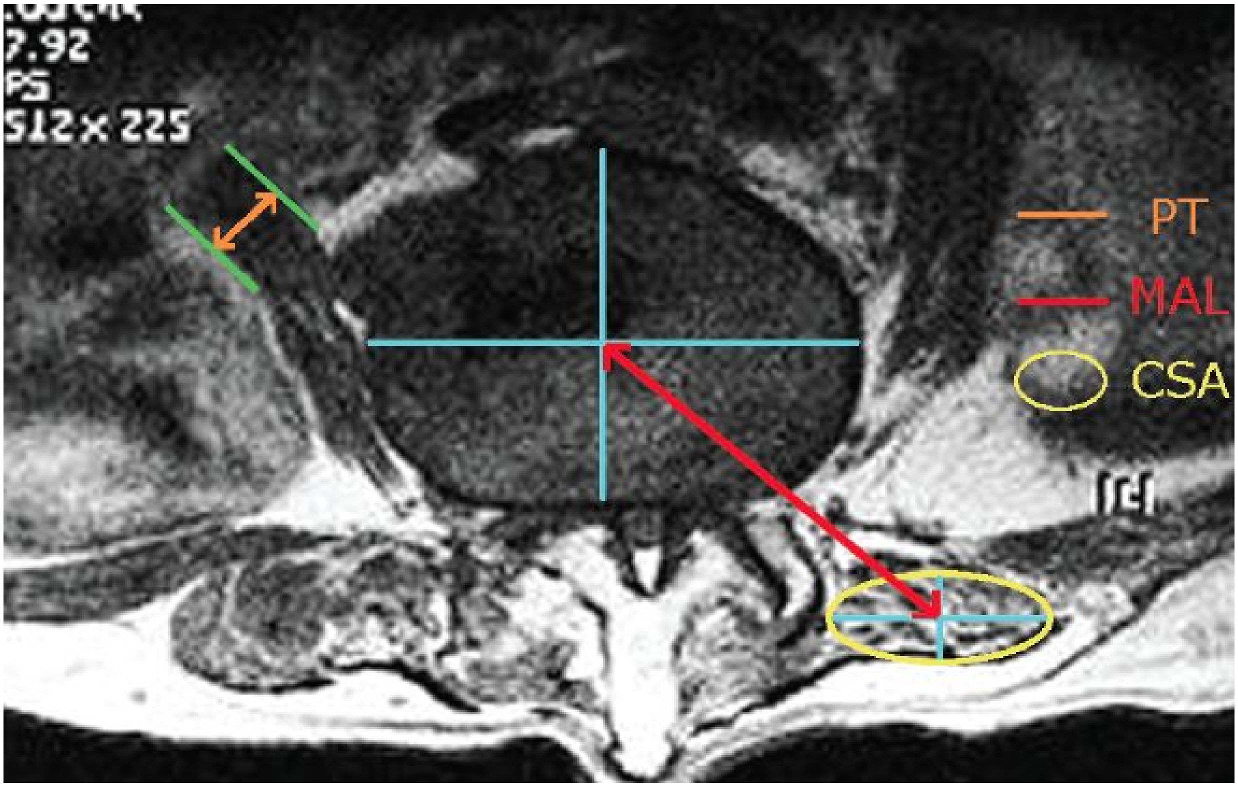



Figure 2.6: Direct measurement from the IVD centroid to the ESMM centroid
Retrieved from Lee, H., Lee, S., and Lee, S. (2006). Correlations between the cross-sectional area and moment arm length of the erector spinae muscle and the thickness of the psoas major muscle as measured by MRI and the body mass index in lumbar degenerative kyphosis patients. Journal of Korean Radiology Society. 54(3): 203-209.

The ESMLA is the perpendicular line from the disc centroid to the muscle centroids. Morris *et al.* (1961), on the other hand, defines the lever arm as "the distance from the center of the disc to the center of the spinous process," rather than the muscle centroid. Munchinger (1962) assumes the length of the spinous process is the power-lever arm or the ESMLA. He defined the lifting system of the spine as a double-armed lever arrangement and indicated that the force of the back muscles is applied to the ends of the spinous processes. As Morris *et al.* (1961), Adams *et al.* (1980) and Hutton and Adams (1982) used the distance from the center of the sagittal rotation to the middle of the interspinous ligament (supraspinous ligament). In this dissertation, the measurement technique for the ESMLA distance is proposed based on (a) previous studies: Nemeth and Ohlsen (1986), Kumar (1988), Tracy *et al.* (1989), Chaffin *et al.* (1990), McGill *et al.* (1993), and Anderson *et al.* (2012) and (b) biomechanical principles.

In common practice, the ESMLA measurement process starts with (1) manually tracing the boundaries of the IVD and ESMMs for both the right and left sides and then (2) drawing a line between right and left ESMMs, and finally (3) drawing a perpendicular line from the disc centroid to this line. This anterior-posterior axis (anterior-posterior distance) is defined as the ESMLA distance in this dissertation.

Another reason for the differences in measurements is the variation in the determination of the centers of IVD, vertebral body, and ESMMs. Moga, Erig, Chaffin, and Nussbaum (1993) indicate that the greatest differences for the ESMLA distances were perhaps "from centroid position errors based on the method used." Basically, the centroid can be determined (1) visually (Tracy *et al.*, 1989; Moga *et al.*, 1993), (2) by drawing axes at sagittal (anterior-posterior) and coronal (side-to-side) planes through widest regions for finding the intersection, which are mutually perpendicular to each others (Reid et al, 1987; Kumar, 1988; Seo *et al.*, 2003), and (3) calculation with (a) the trapezoid fitting method (Chaffin *et al.*, 1990; McGill *et al.*, 1993), (b) the formula of polygon outlines method (Reid *et al.*, 1994), and (c) software such as computed-assisted design (CAD) (Tsuang et al, 1993; Anderson *et al.*, 2012). Seo *et al.* (2003) drew two lines from anterior-posterior (long axis) and medial-lateral (short axis) directions. The centroid of the muscle (or the vertebral body and IVD) was defined as the intersection of the long and short axes (assuming that the cross-sectional shape was an ellipse).

Bogduk (1980) indicated that the actual equivalent force vector of the muscle is posterior to the centroid. On the other hand, Kumar (1988) suggested using the muscle centroid for the force application point suggesting that the muscle centroid might provide a reasonable approximation of the actual value.

### 2.4.4 Cross-sectional area (CSA) Measurement Techniques

The cross-sectional area (CSA) measurement process is very similar to the centroid determination method. In both methods, the outlines of the tissue (e.g., muscle, vertebrae, or inter-vertebral disc) are traced and the CSA of the tissue is computed (typically by software). The very first measurement technique was suggested by Davis (1961) to measure CSAs from cadavers' lower vertebral body surfaces. Outlines of vertebral bodies were traced on to paper with a pencil, and an architectural planimeter was used to measure the area (Davis, 1961). This method is applicable to measure CSAs of muscles and IVDs, as well. With the same methodology, Kumar (1988) traced the outline of the trunk, vertebral body, and muscles on paper from CT scans along with a calibration scale. Similar to Davis's methodology (1961), Seo *et al.* (2003) measured CSAs of the erector spinae and rectus abdominis muscle using a planimeter. Kang *et al.* (2007) utilized CAD software to compute CSAs of paraspinal muscles after constructing polygon points (which are outlines) around the outer margins of the muscles. Tsuang *et al.* (1993) also used CAD software to determine the locations of muscle centroids. Reid, Livingston, and Pearsall (1994) transferred MRI images of the psoas muscles to a 35 mm slide format for projection onto a digitizing tablet and later transferred the digitized images into a computer to trace the psoas muscle. They outlined the psoas muscle with a series of digitized points to derive the CSA. Reid *et al.* (1994) and Bogduk *et al.* (1992) used a digipad connected to a computer. Chaffin *et al.* (1990) traced the perimeters of muscles and discs with a graphics mouse control and then applied a trapezoid fitting method to calculate CSAs. The centroids of the muscles and discs were calculated by determining the coordinates of each trapezoidal area (Chaffin *et al.*, 1990). McGill *et al.* (1993) also used the same sequential trapezoidal fitting algorithm methodology to calculate the CSAs and centroids of muscles and IVDs. Tracy *et al.* (1989) measured distances, angles, and areas directly from the visual display monitor.

Wood *et al.* (1996) manually observed the boundaries of paraspinal muscles and discs on the computer screen and plotted them using a mouse. Later, Jorgensen *et al.* (2003a)

Table 2.4: CSAs of the ESMM reported by various authors by vertebral body level

| | **Subjects** | **Age** | **H** | **W** | **BMI** | | **Average** | **L1** | **L2** | **L3** | **L4** | **L5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reid and Costigan (1985) | 16 Male | 54.6 | 172.6 | 74.7 | | Left (M+F) | 16.2(3.93) | | | | | |
| *(CT, Healthy)* | 12 Female | 52.1 | 159.4 | 63.8 | | Right (M+F) | 15.73(4.23) | | | | | |
| Reid and Costigan (1987) | 20 Male | 21.2 | 176.9 | 69.7 | | Left + Right | | | | | | 54.38(8.37) |
| *(MRI, Healthy)* | | | | | | | | | | | | |
| Cooper *et al.* (1992) | 39 Male | 38 | | 75 | | | | | | | 25.4 | |
| *(CT, LBP)* | 53 Female | 39 | | 64 | | | | | | | 19.9 | |
| Bogduk *et al.* (1992) | 9 Male | 29 | | | | | | 18.7 | 24.5 | 28.5 | 29.9 | 11.6 |
| *(Radiographs, Upright, Healthy)* | | | | | | | | | | | | |
| McGill *et al.* (1993) | 15 Male | 25.3 | 176.1 | 81.5 | | Left | | 27.23(4.28) | 28.33(4.56) | 29.33(3.82) | 22.34(4.76) | 9.86(3.38) |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 26.15(4.05) | 28.54(5.47) | 28.31(4.58) | 21.51(5.39) | 9.05(3.31) |
| Delp *et al.* (2001) | 2M+3F | 67 | 170.6 | 76.2 | | | 11.6 | | | | | |
| *(Cadavers)* | | | | | | | | | | | | |
| Marras *et al.* (2001) | 10 Male | 26.4 | 175.9 | 79.8 | 25.7 | Left | 26.00(4.2) | 22.53(3.7) | 25.41(4.2) | 25.21(4.1) | 20.15(2.7) | 5.17(1.7) |
| *(MRI, Supine, Healthy)* | 20 Female | 25 | 165.5 | 57.9 | 21.2 | | 16.12(3.4) | 13.84(3.0) | 15.64(3.5) | 15.58(3.2) | 12.74(2.4) | 2.8(1.1) |
| | 10 Male | | | | | Right | 25.95(4.1) | 22.49(3.7) | 25.6(4.2) | 25.03(3.7) | 20.08(2.3) | 4.95(1.8) |
| | 20 Female | | | | | | 16.16(3.8) | 13.67(3.3) | 15.68(3.6) | 15.43(3.6) | 12.37(2.5) | 2.81(1.1) |
| Guzik *et al.* (1996) | 16 Male | 24.9 | 179.8 | 75.2 | | Left | 26.16(3.17) | | | | | |
| *(MRI, Healthy Athlete)* | | | | | | Right | 26.90(2.70) | | | | | |
| Lee *et al.* (2011) | 10M+3F | 29.7 | 171 | 66.4 | 22.5 | Left | | | | | (*) | 18.5 |
| *(MRI, LBP)* | 12M+13F | 28.9 | 169 | 63.8 | 22.1 | | | | | | (**) | 23.4 |
| | | | | | | Right | | | | | (*) | 18.2 |
| | | | | | | | | | | | (**) | 22.8 |
| Anderson *et al.* (2012)(') | 51Male | 59.4 | 177.6 | 81.3 | | ESM only | | 20.58(7.93) | 18.82(2.79) | 19.12(4.41) | 14.04(3.71) | 4.52(2.41) |
| *(CT, Supine, Healthy )* | 49 Female | 58.1 | 162.2 | 68.4 | | | | 13.18 (-) | 14.07(3.16) | 13.22(2.80) | 11.11(2.11) | 4.86(2.76) |
| | 51Male | | | | | ESM + Transversospinalis | | | 23.0 | 25.5 | 23.3 | 13.8 |
| | 49Femlae | | | | | | | | 16.7 | 17.8 | 18.6 | 12.6 |

(*) = LBP
(**) = Improved LBP

Age (years); H: Height (cm); W: Weight (kg); BMI (kg/m$^2$); CSA: Cross-sectional area (cm$^2$)

(') = CSAs from transverse scans. Calculated Anatomical CSAs (ACSAs) are also available.

Table 2.5: CSAs of the ESMM reported by various authors by IVD level

| | Subjects | Age | Height | Weight | BMI | | L1/L2 | L2/L3 | L3/L4 | L4/5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | L+R | | | | 45.1 | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 26.2(3.4) | 26(3.3) | 19.6(5.9) | 8.3(2.7) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 17.9(3.1) | 18.5(3.0) | 17.3(3.0) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 18.2(2.7) | 18.5(3.0) | 17.4(3.0) | |
| Han *et al.* (1992) | 6M+4F | 40.1 | 163 | 58.4 | | Left | 18.31 | 19.60 | 18.82 | 16.58 | 11.33 |
| *(CT, Supine, LBP, Japan)* | | | | | | Right | 18.23 | 19.33 | 18.47 | 16.48 | 11.44 |
| Parkkola *et al.* (1992) | 1M+11F | 23.3 | | 59.1 | | L+R | | | | 48(8) | |
| *(MRI, Healthy)* | | | | | | | | | | | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 18.1 | 19.3 | 20.0 | 8.8 |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 17.7 | 18.1 | 20.3 | 9.4 |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis(L+R) | 68(11.8) | 67(9.8) | 58.6(6.8 ) | 42.6(9.8) | 17.8(4.6) |
| *(MRI)* | | | | | | Kyphosis(L+R) | 45.1(9.2) | 55.4(9.9) | 53.1(8.3) | 49.8(6.2) | 27.2(6.7) |
| | 5 Female | 31 | 173 | 64 | | Lordosis(L+R) | 40.6(9.1) | 41.3(8.2) | 40.8(3.1) | 38.4(7.1) | 12.2(3.9) |
| | | | | | | Kyphosis(L+R) | 33.1(8.8) | 36.2(7.8) | 37.3(5.8) | 37.4(4.9) | 20.8(6.5) |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 30.6(8.4) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | Left | | | | | 21.78(6.47) |
| *(MRI, Supine, Healthy, Asian)* | | | | | | Right | | | | | 21.47(6.80) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 23.9(4.5) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 17.1(3.1) | | |
| Jorgensen *et al.* (2003a) | 12 Male | 23.1 | 177.1 | 74.5 | | Right | 20.2(3.3) | 22.1(3.1) | 22.3(3.9) | 22.7(3.4) | 17.4(4.8) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 10.7(1.3) | 12.1(1.3) | 13.7(1.8) | 14.5(2.2) | 10.6(1.9) |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK (L+R) | | | | 33.77(9.15) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control (L+R) | | | | 52.41(8.9) | |
| Kamaz *et al.* (2007) | 36 Female | 43.2 | | | 28.6 | LBP | | | 17.7(2.6) | 17.9(2.7) | |
| *(CT, Prone, Turkish)* | 34 Female | 44.4 | | | 28.5 | Control | | | 18.6(2.6) | 19.6(2.7) | |
| Kang *et al.* (2007) | 54 Female | 60 | 154 | 62 | 26.9 | LBP | | | | 39.5(5.0) | |
| *(MRI, Korean)* | 54 Female | 60 | 153 | 57 | 24.19 | LDK | | | | 29.2(4.5) | |
| Niemelainen *et al.* (2011) | 126 Male | 49.8 | 175.4 | | 25.9 | Left | | | 26.6 | 24.8 | 21.2 |
| *(MRI, Currently Healthy, Finnish)* | | | | | | Right | | | 26.9 | 24.4 | 20.5 |

Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; CSA: $cm^2$

measured CSAs based on the methods of Reid *et al.* (1994) and Wood *et al.* (1996). Rab *et al.* (1977) used Jensen's and Davy's (1975) method and outlined muscles from photographs of cadavers' cross-sectional apperences, then transferred the coordinates and perimeters of each muscle and vertebral body shape using punch cards and analyzing using a digital computer. The computer calculated the CSAs and centroid locations.

The results of a comprehensive literature review for the CSAs are summarized in Tables 2.4 and 2.5. Note that Table 2.4 presents the CSAs at the vertebrae level while Table 2.5 represents the findings at the IVD level.

### 2.4.5 Limitations of Previous Studies

The major limitation of previous studies are related to limited sample sizes, including only one gender, different age groups (e.g., "young" population, "old" population), different medical conditions (healthy, LBP patients, lumbar degenerative kyphosis patients, different physical fitness, and different occupations), and use of cadavers. Other limitations are related to variations in measurement techniques, equipment, and the region of interest in the low back region.

Relatively few subjects limits the comparison that can be made among studies. For example, Tsuang *et al.* (1993) provided the results of 5 male subjects in their report. Lin, Chen, Cheng, Chen, Lee, and Chen (2001) selected 8 male subjects. Bogduk *et al.*'s (1992) radiography study had 9 males. Han *et al.* (1992) included 6 males and 4 females in their study. Tveit *et al.* (1994) had a total of 11 subjects (6 males and 5 females) in their study. Parkkola,Kujala, and Rytokoski (1992) had 1 male and 11 females. As such, the data from small-sample-size studies may not be generalizable to wider populations.

The subject's gender also results in important differences in the morphological structures of lumbar back region. Studies with only one gender such as only male subjects (Reid and Costigan, 1987; McGill *et al.*, 1988; McGill *et al.*, 1993; Tsuang *et al.*, 1993; Wood *et al.*, 1996; Lin *et al.*, 2001) or only female subjects (Chaffin *et al.*, 1990; Lee *et al.*, 2006; Kang *et al.*, 2007; Kamaz *et al.*, 2007) might not address the effect of gender on the ESMLA distances and the CSAs of the ESMMs.

Age is also a determining factor for muscle dimensions and types. Older subjects typically have much smaller CSAs due to muscle atropy. Studying only relatively young subjects (Reid and Costigan, 1987 (male, 21.2 years old); Parkkola *et al.*, 1992 (23.3 years old); McGill *et al.*, 1993 (25.3 years old); Tsuang *et al.*, 1993 (male, 25.4 years old); Marras *et al.*, 2001 (male, 26.4 years old and female, 25.0 years old); Jorgensen *et al.*, 2001 (male, 26.4 years old and female, 25.0 years old); Jorgensen *et al.*, 2003a (male, 23.1 years old and female, 23.8 years old); Jorgensen *et al.*, 2003b (male, 23.1 years old and female, 23.8 years old)) or considerably older subjects (Nemeth and Ohlsen, 1986 (male, 70 years old and female, 63 years old); Kumar, 1988 (55.2-62 years old); Kang *et al.*, 2007 (60 years old); Lee *et al.*, 2011 (62.5-63.6 years old); Anderson *et al.*, 2012 (male, 59.4 years old and female, 58.1 years old)) may introduce bias in the measurement of low back region dimensions (muscles and IVD).

Including medical patients in muscle morphological studies may give misleading results and could bias the subsequent inferences that can be be drawn. For example, it was shown that chronic LBP patients had statistically smaller muscle CSAs than non-chronic and healthy subjects (Cooper *et al.*,1992; Lee *et al.*, 2006; Kamaz *et al.*, 2007; Lee *et al.*, 2011). However, several studies have included patients in their studies since it might be easier and less costly to access hospital databases compared to conducting a new study. Data regarding LBP patients (Tracy *et al.*, 1989; Cooper *et al.*, 1992; Han *et al.*, 1992; Kamaz *et al.*, 2007; Kang *et al.*, 2007; Lee *et al.*, 2011; Lee *et al.*, 2012), kyphosis or lumbar degenerative kyphosis (LDK) patients (Tveit *et al.*,1994; Lee *et al.*, 2006; Kang *et al.*, 2007), and lordosis patients (Tveit *et al.*,1994) had been included in studies. McGill *et al.* (1988) selected active healthy subjects but these subjects were suspected of suffering LBP (hence the need for LB imaging). Studies found that lordosis patients had consistently longer ESMLA distances than kyphosis patients (Tveit *et al.*, 1994), CT scans were obtained from hospital databases. Kumar (1988) also used patients, but selected only those not reporting LBP. Moga *et al.* (1993) included patients who had undergone CT scans. Chaffin *et al.*'s (1990) older and healthy working population sample were derived from a database collected for an osteoporosis study. Nemeth and Ohlsen (1986) studied patients who had carcinomas in their pelvic areas.

Kumar (1988) and Tracy *et al.* (1989) indicated that the literature assumes the ESMLA distance to be 5 cm and this value is derived from a limited sample of cadaveric data. The ESMLA data obtained from cadavers could be criticized as not accurately representing the *in-vivo* state because of a relatively older aged, atrophied tissues due to prolonged periods of inactivity prior to death, unknown history of the death (probably some diseases prior to death), and postmortem shape/volume distortions of soft tissues caused by the embalming process (Kumar, 1988; McGill *et al.*, 1988; McGill, 1993; Tsuang *et al.*, 1993; McGill *et al.*, 1994; Lin *et al.*, 2001). In addition to embalming process, lack of rigidity on the specimens could cause errors in the repeatability of the measurements (Dumas *et al.*, 1991). Therefore, data from cadavers may not extrapolate well to live subjects. Cadaveric data may provide poor estimates of the geometric measures of muscles including the ESMLA distance. Because of inherent limitations of cadaveric data, anatomical data from live subjects with *in-vivo* imaging should be preferred when gathering data for use in biomechanical models. Amonoo-Kuofi (1983), Macintosh and Bogduk (1987; 1991), Dumas *et al.* (1988), Dumas, Poulin, Roy, Gagnon, and Jovanovic (1991), and Delp *et al.* (2001) are examples of studies of the low back region that used cadaveric subjects. Cadaveric studies are also limited by the number of cadavers. For example, Rab *et al.* (1977) had 2 cadavers. Macintosh and Bogduk (1991) and Delp *et al.* (2001) had 5 cadavers in their studies. Amonoo-Kuofi (1983), Macintosh and Bogduk (1987), Dumas *et al.* (1991) had a little bit larger sample sizes compared to others, 8, 8, and 7 cadavers, respectively.

Subject ethnicity may also be a factor affecting the musculoskeletal structures of the low back region. In the literature, it is possible to find data for Japanese (Han *et al.*, 1992; Seo *et al.*, 2003), Korean (Lee *et al.*, 2006; Kang *et al.*, 2007), Turkish (Kamaz *et al.*, 2007), and Asian (Lin *et al.*, 2001) populations.

Measurement technology and methodology affect the outcomes. For example, the change in location and shape of muscle mass is highly probable given the typical supine posture in which X-ray, MRI, or CT scans are collected. Screening subjects when they are lying on their backs (supine) is common practice for the low back region; however, it is possible to collect scans with subjects lying on their sides (Jorgensen *et al.*, 2003a; 2003b) or lying face down (prone) (Kamaz *et al.*, 2007). Subjects could be positioned in a variety of ways such as supine with a cushion under the legs or the knees extended ("neutral" position) (Tracy *et al.*, 1989; Chaffin *et al.*, 1990; McGill *et al.*, 1993; Jorgensen *et al.*, 2001; Marras *et al.*, 2001; Anderson *et al.*, 2012), resulting in slight flexion of the hips and knees. The location of a subject's upper extremities during scan might also slightly change the back muscle geometry. Subjects have been positioned with arms extended above the head (Anderson *et al.*, 2012), on the sides, or across abdomen. Kamaz *et al.* (2007) placed a pillow under the small of the back while subjects are in the prone posture. Anderson *et al.* (2012) mentioned that their measurements might be skewed in some way toward smaller individuals since some subjects were too large to fit in the limited image field and too tall to collect data for multiple vertebral levels. Variation in the scanning posture among studies and the physical constraints of screening equipment limit comparisons across studies.

Ultrasound, radiography, computed tomography (CT), and magnetic resonance imaging (MRI) technologies have been used by researchers for *in-vivo* visualization and understanding of the geometry of the low back for a few decades. However, there are some advantages and disadvantages of each scan technology. Ultrasound, the first imaging technique for direct measurement of muscle size in living human subjects, is the least expensive technique with its low operation costs. Watanabe, Miyamoto, Masuda, and Shimizu (2004) summarized the advantages of ultrasonography as being noninvasive and the capability of measurement of soft tissues during a dynamic state in various joint angles and various postures (including upright posture). It allows portability, as well. Ultrasound provides reasonably good results for tissues and the outside boundaries of the bone, but not a distinct boundaries between soft tissues (Mehta, Rajani, and Sinha, 1997). Overall, ultrasound provides poor resolution, poor edge detection, and reduced precision for controlling image slice thickness and orientation (Engstorm, Loeb, Reid, Forrest, and Avruch, 1991). They provide good resolution for large, superficial muscle groups, but not for deep muscles for the low back region; therefore, they are not preferred in low back studies like this one. CT scans provide high-resolution images of mineralized tissue like bones while MRI scans provide superior soft tissue resolution for muscles and IVDs (Engstrom *et al.*, 1991; McGill *et al.*, 1993; Lee *et al.*, 2011). Namely, CT is sensitive to the concentration of the mineral content while MRI is sensitive to the concentration of hydrogen atoms. MRI scans provide higher image quality allowing researchers to better differentiation between muscles and connective tissues (Engstorm *et al.*, 1991; McGill *et al.*, 1993; Tsuang *et al.*, 1993; Mehta *et al.*, 1997). MRI is also a preferred technique for detailed morphometric studies of living subjects since the MRI does not produce ionizing radiation (X-ray) (Engstorm *et al.*, 1991; McGill *et al.*, 1993; Tsuang *et al.*, 1993; Lee *et al.*, 2011). Unfortunately, resolution issues still exist in the low back region because of the size and location of the pelvic and lumbar spine. The complexity of interconnecting and overlapping muscle groups also makes this process difficult.

Measuring the anthropometric dimensions with either CT or MRI is superior to manual tape measurements on cadavers since they are more repeatable and more applicable to live subjects. Engstorm *et al.* (1991) conducted pairwise comparisons for three measurement techniques MR, CT, and anatomical dissection in lower limbs (thigh muscles) with 3 cadavers. CT tended systematically overestimate anatomical CSAs (dissection); 10-20% higher than MR and/or anatomical dissection, they concluded that MR provided valid measures of (high agreement with) the anatomical dissection of most individual muscles. Clearly, MRI should be the preferred technique because of its superior resolution, accuracy, and lack of biological hazards associated with ionization. However, MRI is hindered by its expense (Lee *et al.*, 2011). In this dissertation, MRI scanning technology was used to investigate the internal anthropometric dimensions of the low back (i.e., the size, length, and CSAs of ESMMs and IVDs).

Tracy *et al.* (1989), Tveit *et al.* (1994), Jorgensen *et al.* (2001), and Marras *et al.* (2001) and *possibly* Reid and Costigan (1985), Nemeth and Ohlsen (1986), Reid and Costigan (1987), and McGill *et al.* (1988) could not take axial oblique scan images. Their images were parallel to the table, meaning they could not obtain images parallel to the IVDs. Since the true ESMLA is the perpendicular distance from the disc center to the center line of the muscles line-of-actions, they could not measure the true ESMLA distances.

One of the biggest limitations of previous studies was the simple measurement technique that was based on visual determination of the muscle and disc/vertebrae centroids (Nemeth and Ohlsen, 1986; Kumar, 1988; Tracy *et al.*, 1989; Lin *et al.*, 2001; Seo *et al.*, 2003; Lee *et al.*, 2006); as compared to mathematically computed centroids (Chaffin *et al.*, 1990; McGill *et al.*, 1993; Tsuang *et al.*, 1993). The methodologies of (1) visually determination of the centroids and/or (2) drawing axes to determine the centroid in the intersection inherently induce higher error into the measurements.

Selecting the point of interest as the vertebral body or IVD limits the studies to which these data can be compared. For example, Kumar (1988) looked at the ESMLA distance only at the L3 and L5 vertebral levels. Seo *et al.* (2003) looked at only at the L3/L4 disc level; McGill *et al.* (1988), Dumas *et al.* (1991), Wood *et al.* (1996), and Lee *et al.* (2006) looked only at the L4/L5 disc level; Reid and Costigan (1987) looked at only at the L5 vertebral level; and Nemeth and Ohlsen (1986) and Lin *et al.* (2001) looked only at the

L5/S1 disc level. These regions would be expected to differ even if researchers used identical methods.

Accurate morphometric parameters such as the ESMLA distance and CSA of the ESMM are required for musculoskeletal modeling since small variations in these parameters could cause large variations in the resultant torque (Reid and Costigan, 1985). Current biomechanical models do not often consider this variation among subjects. For example, most biomechanical models use a convenient/fixed number for the ESMLA distance, most often 5 cm (2 in). In the literature, it has been reported that the ESMLA distance is dependent on subject's gender, age, and anthropometrics (Dumas *et al.*, 1991). Therefore, valid estimation models for the geometry of the low back musculoskeletal structure could be beneficial to implement subject characteristics into the low back biomechanical models to estimate forces and moments at the spine (Jorgensen and Smith, 2006).

### 2.4.6 Contribution of This Dissertation

This study aims to provide a more accurate and realistic ESMLA measuring technique to estimate the ESMLA distances from a given subject sample. The current literature consensus assumes the ESMLA distance to be 5 cm. This value is derived from a limited sample of cadaveric data (Reid and Costigan, 1987; Tracy *et al.*, 1989). Therefore, the 5 cm ESMLA distance may not be applicable to healthy, young, and working individuals since atrophy and distortion from fluids (in the cadaveric sample set) could greatly under- or over-predict the force potential of the musculature. *In-vivo* morphological investigation of live subjects in this study provides a valuable contribution to the literature.

Current biomechanical models often use a fixed ESMLA distance for both male and female genders, all body weights and heights, for all adult populations. Both genders were be included in this study to investigate the gender effect on the geometry of the musculoskeletal structure in the low lumbar region. Since larger sample sizes were selected in this study, the results are anticipated to be more reliable to extend to the general population.

MRI scans provide superior image resolution over other imaging technologies, which increases the reliability and accuracy of this study by allowing differentiation of muscles from each and other tissues.

Contrary to some previous studies that investigated the geometry of the low back at only one level, this study focuses on three IVD levels (the L3/L4, L4/L5, and L5/S1 IVD levels) (Figure 2.7) that are most susceptible to injury. Investigation of three disc levels could provide a better understanding of low back mechanics.

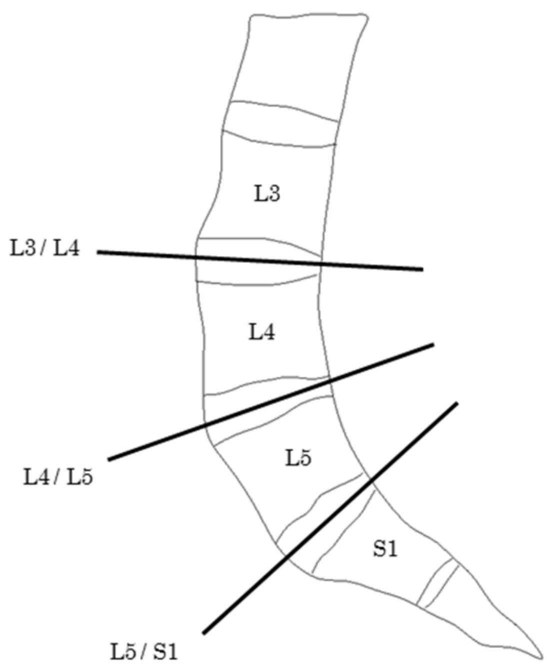



Figure 2.7: Axial oblique cuts at three lower IVD levels

The computerized centroid determination technique for the centroid points of the ESMMs and IVDs distinguishes this study from others. The common practice to determine centroids involves drawing two axes (anterior-posterior and medial-lateral) perpendicular to each other and uses the intersection of these axes as the centroid of the ESMM and IVD (or vertebral body). Since these structures have irregular shapes, this centroid determination method relies on researcher's ability to visually approximate the actual centroid point. Architectural software, Rhinoceros (version 4.0, 2011, Robert McNeel and Associates, Seattle, WA), was used in this study to determine the centroids of irregular shapes such as the ESMMs and IVDs. The computerized method should decrease the amount of error in measurements and result in more repeatable results.

The main contribution of this study is that it provides subject specific parameters to biomechanic modelers so that they might be able to better calculate forces and moments at the inter-vertebral disc joints and thereby better estimate low back forces and the subsequent risk of LBP.

### 2.4.7 Research Objectives

The primary objective of this MRI study was to perform a morphological analysis of musculoskeletal structure (including the ESMM and IVD) of the human lumbar spine and to investigate the relationship between the geometry of the ESMM and the potentially relevant and predictive subject variables (gender, height, weight, etc.). The first goal of this study was to propose a standard measuring technique for the low back musculature by considering the current literature regarding human lumbar muscle anatomy and biomechanics. The measurement technique used here should minimize the drawbacks of current measurement techniques since it is based on *in-vivo* scaning and reliable and repeatable computer aided measurement methods. This study also aimed to minimize the error in prediction of forces and moments at IVDs by producing better estimates of the individual ESMLA distances.

The following three chapters (Chapter 3, Chapter 4, and Chapter 5) focus on different objectives. The objective for Chapter 3 is two fold: (1) to build a methodology and propose a computer aided measuring technique for the morphological analysis of the musculoskeletal structures of the human lumbar spine and (2) provide descriptive statistics of the ESMLA distances and CSAs of the ESMMs and IVDs at three lower lumbar IVD levels. The research sample consists of subjects who visited a hospital and had undergone MRI scans of their low back.

In Chapter 4, the objective is to develop effective and reliable regression models to estimate the ESMLA distance at the three lower IVD levels. The ESMLA distances were obtained from a historical database by employing the computerized measurement technique proposed in Chapter 3. In addition to the ESMLA distance, regression models for CSAs of the total ESMMs at each IVD level are also provided. In Chapter 4, the dependent variables (ESMLAs and CSAs of ESMMs) are regressed with possible explanatory variables such as subject characteristics (gender, age at the time of MRI) and external anthropometric measures (height, weight).

Chapter 5 is an expansion of previous chapters. In Chapter 3 and Chapter 4, a retrospective data set derived from a hospital database was used to investigate the relationship between morphological structure of the low back and subject characteristics and anthropometrics. The historical data has symptomatic subjects from a slightly older population. Asymptomatic subjects from a young and presumed healthy population are studied in Chapter 5. Descriptive statistics and regression models to estimate the ESMLAs and CSAs of ESMMs are provided in this chapter. The objective of Chapter 5 was to investigate whether there are any significant differences between the two data sets. Note that the new study estimates the morphological structure of the low back with additional predictor variables (anthropometric measures) such as the lean body mass, limb lengths and limb circumferences.

The ultimate objective of this overall study is to provide accurate, reliable, and sensitive inputs into the current occupational injury risk assessment tools and models. By addressing the limitation of previous studies, this study provides some subject specific model inputs for biomechanical models. Injury risk assessment tools could be modified with the findings of this study, which may increase the accuracy of them.

Chapter 3

# MORPHOLOGICAL INVESTIGATION OF THE LOW BACK STRUCTURE: HISTORICAL DATA POPULATIONS

## 3.1 Introduction

Low Back Pain (LBP) is very common in the United States (AAOS, 1999; BMUS, 2011; NCHS, 2012a). Twenty-seven million adults (18 years of age and over) in the U.S. reported having back problems in 2007 (Soni, 2010). Approximately 45% of 346,400 occupational musculoskeletal disorders (MSDs) in 2010 were related to LBP (BLS, 2011). Expensive medical costs and productivity losses increase the burden of LBP to society (Maetzel and Li, 2002). The average direct expenditure for the treatment of a LBP patient was $1,589 in 2007 (Soni, 2010). In addition to direct costs such as medical care expenditures workers' compensation claim costs including indemnity and administrative costs, indirect costs such as time away from work costs, disability payments, and reduced productivity must be considered to fully understand the severity and societal burden of LBP. The total annual cost for back pain in the U.S. is estimated at between 20 billion and 50 billion dollars (Frymoyer and Durett, 1997; Deyo and Weinstein, 2001; Maetzel and Li, 2002; NINDS, 2003; Pai and Sundaram, 2004; Soni, 2010). In order to minimize the prevalence and related burden of LBP as well as to understand the mechanism of LBP, more accurate biomechanical modeling/assessment tools should be developed. The effectiveness, reliability, and accuracy of these biomechanical models depend upon accurate model inputs such as the cross-sectional areas (CSA) of muscles and inter-vertebral discs (IVD) and the effective lever arms of relevant muscles and muscle groups.

The erector spinae muscle mass lever arm (ESMLA) is one of the model inputs that determines the magnitude of moments, reaction forces produced by the erector spinae muscle mass (ESMM), and compressive forces loaded on the IVD and other structures of the low back. To calculate these forces and moments accurately, accurate ESMLAs are required for biomechanical models. The ESMLA distance is typically assumed to be a fixed value (5 cm or 2 inches) in biomechanical models regardless of subject anthropometry. This fixed ESMLA distance assumption is often applied to both genders and all subject sizes. Unfortunately, this reduces the reliability of biomechanical models. Forces and moments are overestimated for subjects having larger ESMLA values (> 5 cm) and underestimated for the subjects having smaller ESMLA values (< 5 cm). Simplifying assumptions about the ESMLA distances could cause errors as great as 40% in predictions of spinal forces (Chaffin *et al.*, 1985; McGill and Norman, 1987a; Chaffin *et al.*, 1990). The objective of this study is to provide subject specific ESMLA distances that could minimize the error associated with the calculation of forces (and moments) and therefore the subsequent risk associated with MMH tasks.

The first objective of this study is to suggest a valid, sensitive, and meaningful (in terms of biology, biomechanics, and physiology) measurement technique to measure the CSA of the ESMM and the ESMLA distance. Understanding the gross and functional anatomy of the ESMM is critical to perform morphological analyses. However, there has been a lack of agreement in the literature for defining the ESMM. The erector spinae muscle mass (ESMM) is the muscle group including the spinalis thoracis (depending on the vertebral level), longissimus thoracis, and iliocostalis lumborum, and multifidus. It is basically the entire muscle group that is positioned longitudinally on both sides of the spinous processes and supplies forces to counteract to external moments in order to generate movements of the spine to perform a manual handling task (e.g., lifting, lowering, pushing, pulling). These individual muscles are grouped as the ESMM since they have, theoretically, the same functionality (Bogduk *et al.*, 1992; Stokes *et al.*, 2005) and it is difficult to distinguish individual muscles (particularly the multifidus) from other erector spinae muscles using *in-vitro* imaging techniques, including MRI (Lee *et al.*, 2012). These muscles are basically responsible for extension of the spine when acting bilaterally and lateral flexion of the spine when acting unilaterally. Even though the function and muscle groups of the ESMM are the same, the ESMM has been given many different names by different authors. Table 3.1 summarizes studies that measured the low back musculature. For the most part, these studies analyzed the same basic muscle group. However, many different names and even different muscle combinations were identified which makes direct comparison and generalization across studies difficult.

Table 3.1: Low back muscles researched

| No | Study | Name of Muscle | Muscle Content |
|---|---|---|---|
| 01 | Morris *et al.* (1961) | Deep muscles of the back or sacrospinalis | whole muscle* |
| 02 | Hutton and Adams (1982) | Back extensor muscles | whole muscle* |
| 03 | Parkkola *et al.* (1992) | Back muscles | erector spinae + multifidus; whole muscle* |
| 04 | Stokes and Gardner-Morse (1999) | Dorsal muscles | iliocostalis + longissimus + multifidus |
| 05 | Dannels *et al.* (2000) | Back extensor muscles | paraspinal muscles [multifidus + longissimus + iliocostalis] + psoas muscle |
| 06 | Bogduk *et al.* (1992) | Lumbar back muscles | erector spinae [(Iliocostalis + longissimus) or (longissimus thoracis pars lumborum, iliocostalis lumborum pars lumborum, longissimus thoracis pars thoracis and iliocostalis lumborum pars thoracis )] + multifidus |
| 07 | Bogduk (2005) | Lumbar erector spinae | longissimus thoracis (pars lumborum and pars thoracis) + iliocostalis lumborum (pars lumborum and pars thoracis) |
| 08 | Macintosh and Bogduk (1987) | Erector spinae | iliocostalis (iliocostalis lumborum pars lumborum + iliocostalis lumborum pars thoracis) + longissimus (longissimus thoracis pars lumborum + longissimus thoracis pars thoracis) |
| 09 | Macintosh and Bogduk (1987; 1991; 1992) | Erector spinae | longissimus thoracis (longissimus thoracis pars lumborum + longissimus thoracis pars thoracis) + liocostalis lumborum (liocostalis lumborum pars lumborum + iliocostalis lumborum pars thoracis) |
| 10 | Macintosh and Bogduk (1993) | Lumbar back muscles | erector spinae [iliocostalis (iliocostalis lumborum pars lumborum + iliocostalis lumborum pars thoracis) + longissimus (longissimus thoracis pars lumborum + longissimus thoracis pars thoracis)] + multifidus |
| 11 | Daggfeldt *et al.* (2000) | Lumbar erector spinae | iliocosatalis lumborum [iliocostalis lumborum pars lumborum]+ longissimus thoracis [longissimus thoracis pars lumborum] |
| 12 | Daggfeldt and Thorstensson (2003) | Lumbar back-extensor muscle | lumbar erector spinae [longissimus thoracis pars lumborum + iliocostalis lumborum pars lumborum + longissimus thoracis pars thoracis + iliocostalis lumborum pars thoracis] + the lumbar multifidus + quadratus lumborum |
| 13 | Tveit *et al.* (1994) | Erector spinae | longissimus thoracis + iliocostalis lumborum + multifidus |
| 14 | Tracy *et al.* (1989) | Erector spinae | medial + intermediate + lateral parts; [whole muscle*] |
| 15 | McGill and Norman (1987) | Erector spinae | sacrospinalis (longissimus thoracis + iliocostalis lumborum) + multifidus |
| 16 | Delp *et al.* (2001) | Erector spinae | spinalis thoracis + longissimus thoracis + iliocostalis lumborum; [no multifidus] |
| 17 | Anderson *et al.* (2012) | Erector spinae | whole mass - transversospinalis group |
| 18 | Lee *et al.* (2006) | Erector spinae | whole muscle; [no multifidus]* |
| 19 | Reid and Costigan (1985) | Erector spinae | whole muscle* |
| 20 | Reid and Costigan (1987) | Erector spinae | whole muscle* |
| 21 | Reid *et al.* (1987) | Erector spinae | whole muscle* |
| 22 | Nemeth and Ohlsen (1986) | Erector spinae | whole muscle* |
| 23 | Chaffin *et al.* (1990) | Erector spinae | whole muscle* |
| 24 | Moga *et al.* (1993) | Erector spinae | whole muscle* |
| 25 | Tsuang *et al.* (1993) | Erector spinae | whole muscle* |

Continue on the next page ⟹

Table 3.1 (Continued): Low back muscles researched

| No | Study | Name of Muscle | Muscle Content |
|---|---|---|---|
| 26 | Nussbaum, *et al.* (1996) | Erector spinae | whole muscle* |
| 27 | Lin *et al.* (2001) | Erector spinae | whole muscle* |
| 28 | Marras *et al.* (2001) | Erector spinae | whole muscle* |
| 29 | Ellis *et al.* (2007) | Erector spinae | whole muscle* |
| 30 | Gatton *et al.*, 2010 | Erector spinae | whole muscle* |
| 31 | McGill *et al.* (1988) | Erector mass | sacrospinalis + multifidus |
| 32 | McGill *et al.* (1993) | Erector mass | iliocostalis lumborum + longissimus thoracis + multifidus |
| 33 | Han *et al.* (1992) | Erector spinae | iliocostalis + longissimus muscles; [no multifidus] |
| 34 | Nomina Anatomica (2nd edition) | Erector spinae | whole mass |
| 35 | Nomina Anatomica (4th edition) | Erector spinae | iliocostalis + longissimus + spinalis |
| 36 | Hansen *et al.* (2006) | Erector spinae or Sacrospinalis | spinalies (medial) + longissimus (intermediate) + iliocostalis (lateral); [no multifidus] |
| 37 | Dumas *et al.* (1988) | Erectores spinae | iliocostalis/iliocostalis lumborum + longissimus thoracis/dorsi |
| 38 | Dumas *et al.* (1991) | Erectores spinae | longissimus dorsi +Ilio-costalis/iliocostalis lumborum |
| 39 | van Dieen and de Looze (1999) | Extensor muscles | erector spinae (lumbar iliocostalis + lumbar longissimus + thoracis iliocostalis + thoracis longissimus) + multifidus muscle slips |
| 40 | Rab *et al.* (1977) | Low back muscles | erector spinae + the intrinsic rotator muscles of the spine (multifidus + rotators + interspinalis) |
| 41 | Jorgensen *et al.* (2001) | Erector spinae | whole muscle* |
| 42 | Jorgensen *et al.* (2003a) | Lumbar back muscles | iliocostalis + longissimus + multifidus |
| 43 | Jorgensen *et al.* (2003b) | Lumbar back muscles | iliocostalis + longissimus + multifidus |
| 44 | Fortin and Battie (2012) | Paraspinal muscle group | erector spinae + multifidus; [whole structure*] |
| 45 | Niemelainen *et al.* (2011) | Paraspinal muscles | erector spinae + multifidus |
| 46 | Wood *et al.* (1996) | Paraspinal muscles | erector spinae + longissimus cervicis + longissimus thoracis + semispinalis thoracis + multifidus + iliocostalis lumborum; whole muscle* |
| 47 | Lee *et al.* (2011) | Paraspinal muscles | erector spinae + multifidus |
| 48 | Kamaz *et al.* (2007) | Paraspinal muscles | iliocostalis + longissimus + multifidus |
| 49 | Kang *et al.* (2007) | Paraspinal muscles | psoas + erector spinae + multifidus |
| 50 | Lee *et al.* (2012) | Paraspinal muscles | back muscles (erector spinae + multifidus) + psoas muscle |
| 51 | Cooper *et al.* (1992) | Paraspinal muscles | whole muscle [the deep muscles (multifidus) + superfical muscles (erector spinae + longissimus)] |
| 52 | Nachemson (1968) | Sacro-spinalis (at L3/L4) | iliocostalis lumborum + longissimus dorsi + multidus |
| 53 | Tichauer (1971) | Sacro-spinalis | whole muscle structure of the back |
| 54 | Amonoo-Kuofi (1983) | Postvertebral muscles | whole mass (medial column but not lower than the L2 vertebral level + intermediate column + lateral column) |
| 55 | Kumar (1988) | Spinal muscles | erectores spinae + transverso spinalis + other muscles |
| 56 | Seo *et al.* (2003) | Trunk muscles | such as erector spinae (possibly whole muscle) and rectus abdominis |

***Whole muscle/mass*** means all the muscles of the back including the erector spinae muscles (ESM) (spinalis thoracis, longissimus thoracis, and iliocostalis lumborum), transversospinalis group (multifidus, semispinalis, and rotatores), and segmental muscles (interspinales and intertransversarii).
***** means that it is not stated in the study. This is an assumption based on figures provided in the study or the overall impression.

In addition to the controversies in the definition of ESMM, some limitations of previous studies make them difficult to compare to each other and to this work. Previous studies used;

**(1) limited sample size:** Rab *et al.*, 1977 (2 males); McGill *et al.*, 1988 (13 males); Dumas *et al.*, 1991 (7 males); Bogduk *et al.*, 1992 (9 males); Han *et al.*, 1992 (6 males and 4 females); Parkkola *et al.*, 1992 (11 males and 1 female); McGill *et al.*, 1993 (15 males); Moga *et al.*, 1993 (11 males and 8 females); Tsuang *et al.*, 1993 (5 males); Tveit *et al.*, 1994 (6 males and 5 females); Delp *et al.*, 2001 (2 males and 3 females); Lin *et al.*, 2001 (8 males); Guzik *et al.*, 1996 (16 males),

**(2) differing age groups:**

**(a) younger populations:** Reid and Costigan, 1987 (21.2 years old); McGill *et al.*, 1993 (25.3 years old); Parkkola *et al.*, 1992 (23.3 years old); Marras *et al.*, 2001 (26.4 years old); Jorgensen *et al.*, 2001 (26.4 years old); Jorgensen *et al.*, 2003a and 2003b (23.1-23.8 years old); Tsuang *et al.*, 1993 (25.4 years old); Lin *et al.*, 2001 (25.9 years old),

**(b) older populations:** Nemeth and Ohlsen, 1986 (63-70 years old); Kumar, 1988 (55.2-60.2 years old); Chaffin *et al.*, 1990 (49.6 years old); Dumas *et al.*, 2001 (55.6 years old); Delp *et al.*, 2001 (67 years old); Lee *et al.*, 2006 (62.5-63.6 years old); Kang *et al.*, 2007 (60 years old); Anderson *et al.*, 2012 (58.1-59.4 years old),

**(3) different medical conditions:** Nemeth and Ohlsen, 1986 (carcinomas); Kumar, 1988 (patients, but not LBP); McGill *et al.*, 1988 (LBP patients); Tracy *et al.*, 1989 (LBP patients); Han *et al.*, 1992 (LBP patients); Moga *et al.*, 1993 (patients undertaken MRI); Tveit *et al.*, 1994 (Lordotic and Kyphotic patients); Lee *et al.*, 2006 (lumbar degenerative kyphosis patients); Kamaz *et al.*, 2007 (LBP patients); Lee *et al.*, 2011 (LBP patients),

**(4) cadaveric subjects:** Rab, *et al.*, 1977; Bogduk, 1980; Dumas *et al.*, 1991; Delp *et al.*, 2001,

**(5) simple measurement techniques:** Nemeth and Ohlsen, 1986; Kumar, 1988; McGill *et al.*, 1988; Tracy *et al.*, 1989; Moga *et al.*, 1993; Lin *et al.*, 2001; Seo *et al.*, 2003; Lee *et al.*, 2006,

**(6) single gender:**

**(a) female subjects:** Chaffin *et al.*, 1990; Lee at al., 2006; Kamaz *et al.*, 2007; Kang *et al.*, 2007,

**(b) male subjects:** Rab *et al.*, 1977; Reid *et al.*, 1987; McGill *et al.*, 1988; Tracy *et al.*, 1989; Dumas *et al.*, 1991; Bogduk *et al.*, 1992; McGill *et al.*, 1993; Tsuang *et al.*, 1993; Wood *et al.*, 1996; Guzik *et al.*, 1996; Lin *et al.*, 2001,

**(7) lumbar data from different levels:**

**(a) only at the L3/L4 IVD level:** Seo *et al.*, 2003,

**(b) only at the L4 vertebral body level:** Cooper *et al.*, 1992,

**(c) only at the L4/L5 IVD level:** McGill *et al.* 1988; McGill and Norman, 1987a; Dumas *et al.*, 1991; Parkkola *et al.*, 1992; Wood *et al.*, 1996; Lee *et al.*, 2006,

**(d) only at the L5 vertebral body level:** Reid *et al.*, 1987; Lee *et al.*, 2011,

**(e) only at the L5/S1 IVD level:** Nemeth and Ohlsen, 1986; Tracy *et al.*, 1989; Lin *et al.*, 2001, and

**(f) only the average:** Reid and Costigan, 1985; Delp *et al.*, 2001.

The results of these studies may not be generalizable to the general working population. This study proposes to address the limitations of the previous studies by larger sample sizes, collecting data from live subjects using high resolution MRI scans, using computerized, and reliable measurement techniques, and analyzing data for three vertebral disc levels for both genders. The objective of this study is to provide a more accurate and reliable data set regarding musculature for low back biomechanical models.

### 3.2 Material and Methods

#### 3.2.1 Subjects

The study sample consisted of symptomatic subjects who had undertaken an MRI scan of the lumbar spine at the University of Utah Hospital in Salt Lake City, Utah. Personal identifiers (name, patient ID, birth date, etc.) of patients were purged before data was released from the University of Utah Hospital System. A total of 163 subjects (82 male and 81 female) were included in the study. Note that some analyses were performed with fewer subjects since axial oblique MRI scans were missing for some IVD levels. For example, only 51 male and 57 female subjects were included at the L5/S1 level. This is also a result of the application of subject exclusion criteria. MRI scans were reviewed by an expert with experience analyzing spinal MRI scans (the expert has a Bachelor of Science degree in Physical Therapy and a Doctor of Philosophy degree in Anatomy). Subjects who had (1) degenerative changes in the lumbar spine (e.g., crushed vertebral body, trauma, etc.) and/or in the erector spinae muscle mass (e.g., atrophy), (2) obvious spinal deformities, and (3) any known pathology relevant to and likely to alter the low back geometry (e.g., scoliosis, tumor) were excluded from the study. The research protocol for this study was approved by the Institutional Review Boards (IRBs) at both participating institutions, the University of Utah (Appendix A) and Auburn University (Appendix B). Demographic properties such as gender and age and anthropometric measurements such as body height and weight of patients at the time MRI scanning were recorded in the Picture Archiving and Communication System (PACS) embedded in the MRI scans. Body mass index (BMI) was calculated using the subject's height and weight, and then categorized into four body composition levels (underweight, less than 18.5 kg/m$^2$; normal, between 18.5 kg/m$^2$ and 24.9 kg/m$^2$; overweight, between 25.0 kg/m$^2$ and 29.9 kg/m$^2$; and obese, more than 30.0 kg/m$^2$) according to World Health Organization's BMI classification (WHO, 2012).

The average age was 30.1 (5.5) years for males and 29.6 (5.6) years for females. Note that values within parentheses are standard deviations. Male subjects were heavier ($p<0.004$) and taller ($p<0.000$) than female subjects; the average height and weight for males was 85.67 (19.76) kg and 178.77 (8.79) cm. While the average height and weight for females was 75.50 (19.96) kg and 165.37 (8.91) cm. Detailed subject descriptive statistics are provided in Table 3.2.

Table 3.2: Subject variable descriptives: Demographics and anthropometrics

| | Gender | N | Mean | St.d. | Min | Max | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|
| **Age (years)** | Female | 81 | 29.6 | 5.6 | 21.0 | 39.0 | -0.565 | 161 | 0.573 |
| | Male | 82 | 30.1 | 5.5 | 21.0 | 39.0 | | | |
| | Total | 163 | 29.8 | 5.6 | 21.0 | 39.0 | | | |
| **Height (cm)** | Female | 58 | 165.37 | 8.91 | 142.20 | 195.60 | -8.045 | 111 | *0.000** |
| | Male | 55 | 178.77 | 8.79 | 157.50 | 200.70 | | | |
| | Total | 113 | 171.89 | 11.09 | 142.20 | 200.70 | | | |
| **Weight (kg)** | Female | 81 | 76.50 | 19.96 | 45.36 | 136.08 | -2.948 | 161 | *0.004** |
| | Male | 82 | 85.67 | 19.76 | 36.29 | 178.71 | | | |
| | Total | 163 | 81.11 | 20.33 | 36.29 | 178.71 | | | |
| **BMI (kg/m$^2$)** | Female | 58 | 28.09 | 8.00 | 19.05 | 53.16 | 1.490 | 111 | 0.139 |
| | Male | 55 | 26.17 | 5.29 | 13.73 | 51.99 | | | |
| | Total | 113 | 27.16 | 6.87 | 13.73 | 53.16 | | | |

Descriptive statistics and Independent Student T-tests to compare genders for each IVD level are provided in Table 3.3. At each IVD level, male subjects were significantly taller and heavier. Age and BMI did not statistically differ between genders.

The average BMI was 26.17 (5.29) kg/m$^2$ for males and 28.09 (8.02) kg/m$^2$ for females (Table 3.3), measuring the average BMIs for both genders fell in the “overweight” category. Based on the BMI categorization, 1.8% of subjects were “underweight,” 42.5% of subjects were “normal,” 30.1% of them were “overweight,” and 25.6% of subjects were in “obese,” in category (Table 3.4).

Table 3.3: Demographics and anthropometric parameters stratified for IVD levels

| IVD Level | Variable | Gender | N | Mean | St.d. | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|
| **L3/L4** | Age | Female | 75 | 29.5 | 5.9 | -0.777 | 153 | 0.438 |
| | | Male | 80 | 30.2 | 5.5 | | | |
| | Height | Female | 54 | 165.53 | 9.24 | -7.448 | 105 | *0.000** |
| | | Male | 53 | 178.56 | 8.86 | | | |
| | Weight | Female | 75 | 77.01 | 20.28 | -2.833 | 153 | *0.005** |
| | | Male | 80 | 86.12 | 19.74 | | | |
| | BMI | Female | 54 | 28.1 | 8.2 | 1.305 | 105 | 0.195 |
| | | Male | 53 | 26.41 | 5.23 | | | |
| **L4/L5** | Age | Female | 72 | 29.5 | 5.8 | -0.272 | 134 | 0.786 |
| | | Male | 64 | 29.7 | 5.3 | | | |
| | Height | Female | 51 | 164.80 | 8.88 | -7.496 | 94 | *0.000** |
| | | Male | 45 | 178.53 | 9.04 | | | |
| | Weight | Female | 72 | 77.07 | 20.59 | -2.575 | 134 | *0.011** |
| | | Male | 64 | 85.69 | 18.16 | | | |
| | BMI | Female | 51 | 28.39 | 8.34 | 1.148 | 94 | 0.254 |
| | | Male | 45 | 26.74 | 5.17 | | | |
| **L5/S1** | Age | Female | 57 | 30.2 | 5.7 | 0.075 | 106 | 0.940 |
| | | Male | 51 | 30.1 | 5.2 | | | |
| | Height | Female | 43 | 165.87 | 9.46 | -5.785 | 78 | *0.000** |
| | | Male | 37 | 178.00 | 9.22 | | | |
| | Weight | Female | 57 | 76.21 | 20.77 | -2.473 | 106 | *0.015** |
| | | Male | 51 | 85.90 | 19.81 | | | |
| | BMI | Female | 43 | 27.45 | 8.01 | 0.430 | 78 | 0.668 |
| | | Male | 37 | 26.78 | 5.47 | | | |

Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$

### 3.2.2 Data Collection

#### Device and Recording

Magnetic Resonance Imaging (MRI) was used to study the low back architecture. MRI scans were performed on a 1.5 Tesla MRI scanner (MAGNETOM Avanto, Siemens AG, Erlangen, Germany) at the University of Utah Hospital. Subjects were placed in a head-first-supine (HFS) posture in the open-bore MRI machine. Due to its superiority in distinguishing muscles from fat tissue over T1-weighted scans, T2-weighted standard soft-tissue MRI scans were taken in both the axial and sagittal planes. Spinal curve alters

Table 3.4: BMI categorization of subjects

| BMI Category | Gender | N | % |
|---|---|---|---|
| Underweight | Female | 0 | 0.0 |
| | Male | 2 | 1.8 |
| | **Total** | **2** | **1.8** |
| Normal | Female | 25 | 22.1 |
| | Male | 23 | 20.4 |
| | **Total** | **48** | **42.5** |
| Overweight | Female | 14 | 12.4 |
| | Male | 20 | 17.7 |
| | **Total** | **34** | **30.1** |
| Obese | Female | 19 | 16.8 |
| | Male | 10 | 8.8 |
| | **Total** | **29** | **25.6** |

the direction of the muscle line-of-action as well as the action point of the force. Scans perpendicular to the scan surface will not represent the actual CSAs of the ESMM and IVD along the line-of-muscle action. To minimize projection errors associated with transverse scanning, axial oblique MRI scans through the disc center were taken (Figure 3.1) at each IVD level.

**The erector spinae muscle mass (ESMM)**

The erector spinae muscle mass (ESMM) is defined as the whole muscle structure posterior to the vertebrae, [filling the space between spinous process and transverse process and laying longitudinally throughout the torso], and share the same biomechanical functionality (e.g., extension of the spine and lateral flexion). The ESMM in the low back region consists of the erector spinae muscles (ESM) (spinalis thoracis, longissimus thoracis, and iliocostalis lumborum), the transversospinalis group (multifidus, semispinalis, and rotatores), and the segmental muscles (interspinales, intertransversarii). The prevalence and percentages of these muscles are dependent upon the vertebral level; for example, the spinalis thoracis is an erector spinae muscle but its proximal attachment only goes down to

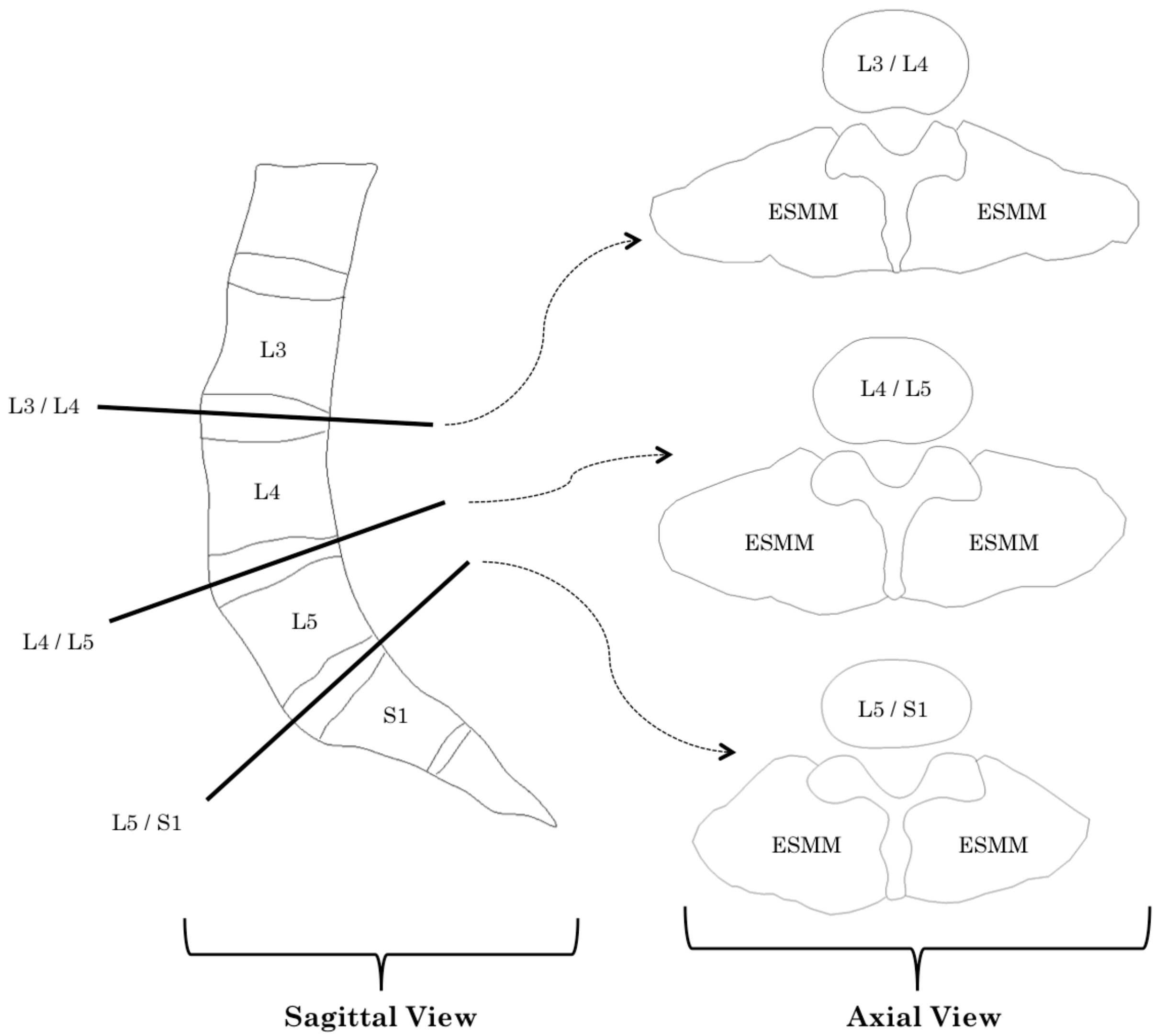



Figure 3.1: Axial oblique MRI scans at the low three IVD levels

the spinous process of the L2 vertebrae. This means that the spinalis thoracis does not exist in the lower lumbar region that is the interest of this study (L3-S1 vertebrae). The longissimus thoracis, iliocostalis lumborum, and multifidus are the major muscles in the low back region, and they constitute the main focus of this study. Figure 3.2 illustrates the muscles in the ESMM at the L3/L4 IVD level. Note that, the ESMM covers all the muscles of the back except the psoas major, quadratus lumborum, and latissumus dorsi since their functions are not directly related to sagittal plane lifting tasks (e.g., primary extension of the trunk) and/or minimal compared to the erector spinae muscles.

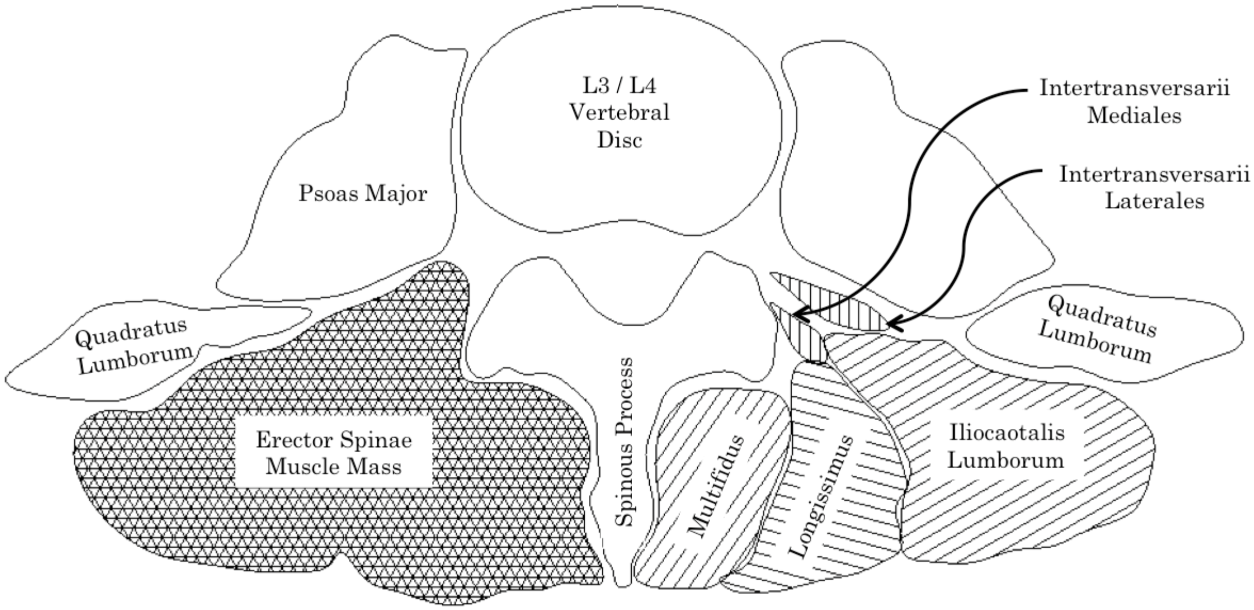



Figure 3.2: Muscles in the ESMM at the L3/L4 IVD level

**The CSA and ESMLA measurement techniques**

OsiriX® (v4.0, 2011, Antoine Rosset, Bernex, Switzerland), an open source image analysis software, was used to capture the regions of interest (low back discs and muscles). After careful evaluation of sagittal and axial plane images using OsiriX®, one oblique image was selected for each IVD. Note that the image was selected based on its representation of the whole disc. These OsiriX® images were further analyzed using Rhinoceros (known as Rhino) (v4.0, 2011) architectural design software and its plug-in software Grasshopper (v0.8.0052, 2011). Rhino is capable of estimation of the centroid of irregular shapes. The first step was to transfer the raw MRI images from OsiriX® to Rhinoceros. Since Rhinoceros works on a proportional basis, images were scaled using the scale provided with OsiriX® images taken directly from MRI scanner. Then, the contours of the ESMMs and IVDs were manually traced using a high resolution computer monitor (1280 X 1024 pixels, 60 Hz, Dell 1905FP, Dell Inc., Round Rock, TX). A Grasshopper model was created to (1) compute the centroid points of the ESMMs from these contour traces, (2) draw a line between the centroid point of the right ESMM to the centroid point of the left ESMM, which is refereed to here as “the connector line,” (3) compute the centroid point of the IVD from contour traces, and (4) draw a perpendicular line from the disc centroid to the connector line, which is the definition of the ESMLA used for this study (Figure 3.3). Note that the left appears on the right of the figure because the image is viewed from inferior to superior (bottom-to-top). The Grasshopper software outputs the CSAs of ESMMs and IVDs as well as the corresponding ESMLA distance.

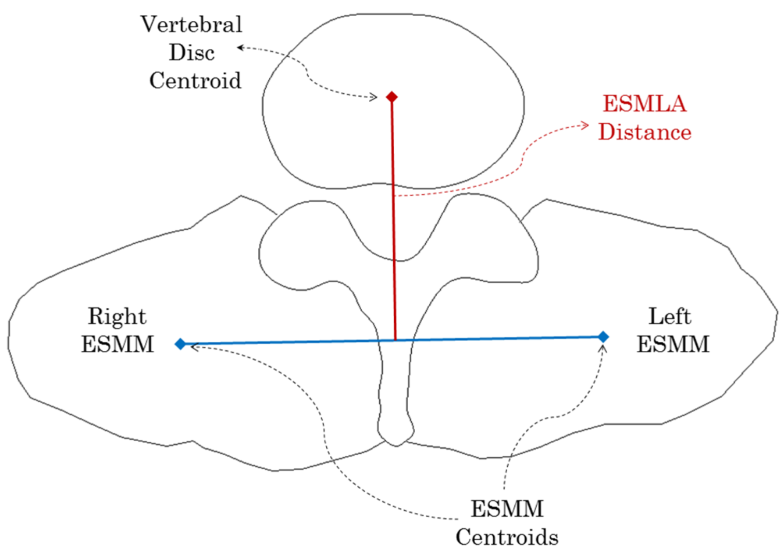



Figure 3.3: Measurement of the ESMLA distance

## 3.3 Results

### 3.3.1 Reproducibility Tests

#### Intra-rater reliability

Two researchers measured the CSA of the right and left ESMMs, CSA of the IVD, and the ESMLA distance from 40 randomly selected images (20 males and 20 females) at L5/S1 IVD level. Each researchers measured twice after at least 4 weeks intervals.

Statistical tests for intra-class correlation coefficients (ICC) performed to test how much agreement was in two measurements of both researchers. Two-way mixed model was used since the error may raise from the subject and the rater. Note that one-way models assume that the error comes from either the subject or the researcher. Mixed model was preferred since raters were fixed. Note that subjects may be random in mixed models. Absolute agreement type was selected as the analysis type since it provides how consistence the raters are to each other. Results of intra-rater reliability tests (Table 3.6) indicated that there was a highly significant correlation (excellent ICC, ranging from 0.968 to 0.998) between the first and second measurements of both researchers. Interpretations of ICC results are based on Portney's and Watkins's (2000) descriptions (Table 3.5).

Table 3.5: Interpretation of ICC reliability

| | ICC |
|---|---|
| Excellent | 0.900 and over |
| Good | 0.800 - 0.899 |
| Fair | 0.700 - 0.799 |
| Poor | 0.699 and less |

Table 3.6: Results of intra- and inter-reliability tests

| Measurement | Intra-rater reliability | | Inter-rater reliability | | | |
|---|---|---|---|---|---|---|
| | R1M1-R1M2 | R2M1-R2M2 | R1M1-R2M1 | R1M1-R2M2 | R1M2-R1M1 | R1M2-R1M2 |
| Right ESMM | 0.982 | 0.988 | 0.870 | 0.875 | 0.891 | 0.885 |
| Left ESMM | 0.968 | 0.990 | 0.820 | 0.811 | 0.870 | 0.857 |
| IVD | 0.997 | 0.998 | 0.995 | 0.993 | 0.997 | 0.994 |
| ESMLA | 0.990 | 0.995 | 0.990 | 0.986 | 0.995 | 0.990 |

R1: first researcher; R2: second researcher; M1: first measurement; M2: second measurement

### Inter-rater reliability

Two-way mixed models were also used to test how much two researchers were agree to each other. The CSA of the right and left ESMMs, CSA of the IVD, and the ESMLA distance from 40 randomly selected images (20 males and 20 females) at L5/S1 IVD level were measured. Statistical tests for inter-class correlation coefficients performed to test how much agreement was in two researchers. Results of the first and second measurements of the first researcher were compared with results of the first and second measurements of the second researcher. Results of inter-rater reliability tests (Table 3.6) indicated that there was a highly significant correlation (ranging from 0.811 to 0.997) between two researchers. Note that these inter-class correlation coefficients were single measure, and the correlation coefficients of the average measure were much higher than these values.

### 3.3.2 Descriptive Statistics

**Cross sectional areas (CSAs) of the erector spinae muscle masses (ESMMs)**

The mean cross sectional areas (CSA) of the right and left erector spinae muscle masses (ESMM) as well as standard deviation and minimum and maximum values of CSAs are presented in Table 3.7. Because not all levels were available in all subjects, the number of subjects measured ranged from 108 to 155 for inter-vertebral levels. Table 3.7 provides descriptive statistics for each gender and average for both genders. CSAs of ESMMs are the largest at the L3/L4 level; the average CSA for the ESMM at the L3/L4 level was 26.85 $cm^2$ for the right side and 26.75 $cm^2$ for the left side. The average CSA for the ESMM at the L4/L5 level was approximately 2-3% smaller than the L3/L4 level, 26.08 $cm^2$ for the right side and 26.32 $cm^2$ for the left side. The size of ESMM at the lowest lumbar disc level dramatically reduced; the average CSA for the ESMM at the L5/S1 level was approximately 5-7% smaller than the L4/L5 level and 6-9% smaller than the L3/L4 level. The average CSA for the ESMM at the L5/S1 level was 24.46 $cm^2$ for the right side and 25.06 $cm^2$ for the left side. These percentages represent the decline for the entire sample; however, males had greater reduction in muscle sizes with lower disc levels. The CSA of the right ESMM of male subjects at the L5/S1 level, for instance, was approximately 13% smaller than the L4/L5 level and 18% smaller than the L3/L4 disc level. On the contrary, the CSAs of the ESMMs in female subjects increased with lower disc levels. This means that female subjects had the smallest muscle size in L3/L4 level and the largest muscle size at the L5/S1 level. Figure 3.4.a and 3.4.b show comparisons between genders for each IVD level. Note that bars represent the 95% confidence internals (CI).

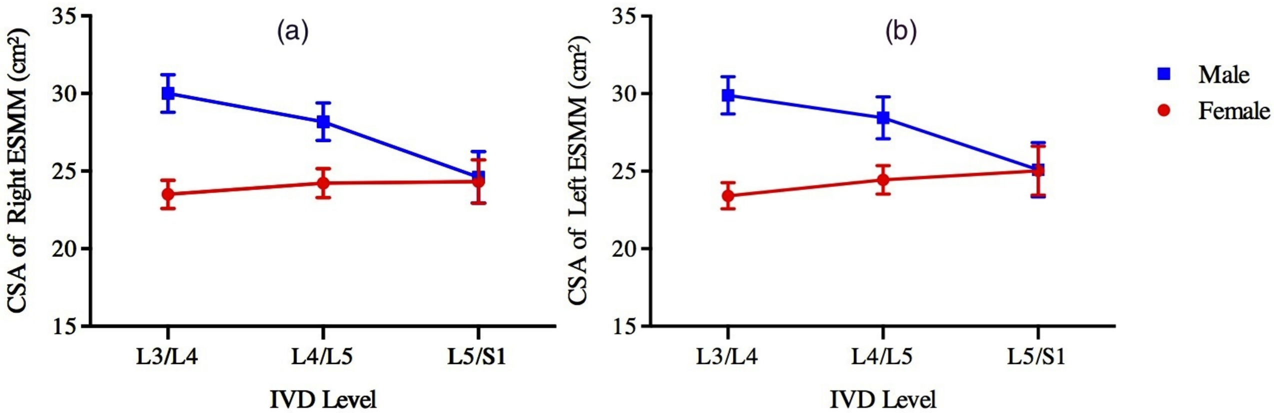



Figure 3.4: Gender comparison on the ESMM size

Table 3.7: CSAs of the right and left ESMMs

| | | | **CSA of Right ESMM ($cm^2$)** | | | | **CSA of Left ESMM ($cm^2$)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **N** | **Mean** | **St.d.** | **Min** | **Max** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 75 | 23.50 | 3.94 | 15.07 | 35.56 | 23.41 | 3.66 | 14.78 | 32.70 |
| | Male | 80 | 30.00 | 5.44 | 13.56 | 42.84 | 29.89 | 5.41 | 11.89 | 49.29 |
| | Total | 155 | 26.85 | 5.76 | 13.56 | 42.84 | 26.75 | 5.66 | 11.89 | 49.29 |
| **L4/L5** | Female | 72 | 24.22 | 3.98 | 14.43 | 33.92 | 24.44 | 3.92 | 14.71 | 36.52 |
| | Male | 64 | 28.18 | 4.85 | 17.95 | 44.38 | 28.44 | 5.41 | 18.57 | 50.06 |
| | Total | 136 | 26.08 | 4.82 | 14.43 | 44.38 | 26.32 | 5.08 | 14.71 | 50.06 |
| **L5/S1** | Female | 57 | 24.33 | 5.23 | 12.40 | 42.37 | 25.03 | 5.92 | 13.73 | 44.61 |
| | Male | 51 | 24.60 | 5.90 | 15.72 | 45.69 | 25.09 | 6.21 | 15.29 | 42.01 |
| | Total | 108 | 24.46 | 5.53 | 12.40 | 45.69 | 25.06 | 6.03 | 13.73 | 44.61 |
| **All** | Female | 204 | 23.99 | 4.35 | 12.40 | 42.37 | 24.22 | 4.52 | 13.73 | 44.61 |
| | Male | 195 | 27.99 | 5.77 | 13.56 | 45.69 | 28.16 | 5.93 | 11.89 | 50.06 |
| | Total | 399 | 25.94 | 5.47 | 12.40 | 45.69 | 26.15 | 5.60 | 11.89 | 50.06 |

A 2 X 3 split-plot factorial design (SPF) analysis was performed to test the effect of gender and IVD level on the CSA of the right and left ESMMs. Note that the number of subjects used in SPF analyses was 99 (51 females and 48 males). It means that only 51 females and 48 males had MRI scans for all three levels. Subjects with any missing MRI scan at any IVD level were removed from analyses. Results of the SPF analysis are given in Table 3.8 (for the right ESMM's CSA) and Table 3.9 (for the left ESMM's CSA). The statistical analyses found main effects of gender and IVD levels for both ESMMs. The interaction between the IVD level and gender was also significant for both ESMMs. Figure 3.4.a for the right ESMM size and Figure 3.4.b for the left ESMM size are presented to demonstrate these relationships graphically.

Table 3.8: ANOVA summary table for main and interaction effects of gender and IVD level on the CSAs of the right ESMM

| Source | SS | df | MS | F-stat | Sig. |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 707.67 | 1 | 707.67 | 13.31 | *0.000** |
| Subject(Gender) | 5156.48 | 97 | 53.16 | 6.98 | |
| **Within Subjects** | | | | | |
| IVD Level | 288.93 | 2 | 154.50 | 20.29 | *0.000** |
| Gender*IVD Level | 392.47 | 2 | 196.23 | 25.76 | *0.000** |
| IVD Level * Subject(Gender) | 1477.62 | 194 | 7.62 | | |
| Total | 8023.18 | 296 | | | |

Table 3.9: ANOVA summary table for main and interaction effects of gender and IVD level on the CSAs of the left ESMM

| Source | SS | df | MS | F-stat | Sig. |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 710.16 | 1 | 710.16 | 12.44 | *0.001** |
| Subject(Gender) | 5538.92 | 97 | 57.10 | 7.28 | |
| **Within Subjects** | | | | | |
| IVD Level | 140.29 | 2 | 76.82 | 9.80 | *0.000** |
| Gender*IVD Level | 403.20 | 2 | 201.60 | 25.71 | *0.000** |
| IVD Level * Subject(Gender) | 1521.31 | 194 | 7.84 | | |
| Total | 8313.88 | 296 | | | |

The right and left ESMMs are compared with pairwise t-test to determine whether there is any significant difference between the CSA of the right ESMM and left ESMM. The results suggested that the CSAs of the right and left ESMMs were highly correlated (correlation coefficients ranging from 0.883 to 0.938) and there was not any significant differences between both ESMMs for both genders and at all IVD levels (Table 3.10). Therefore, the side where measurements were taken did not have any significant effect on the ESMM size and both sides are statistically equal.

Table 3.10: Comparisons of the right and left ESMM CSAs

| | | | Right ($cm^2$) | | Left ($cm^2$) | | Correlations | | Paired Samples T-tests | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Mean | St.d. | Coeff. | Sig. | t | df | Sig. |
| L3/L4 | Female | 75 | 23.50 | 3.94 | 23.41 | 3.66 | 0.909 | *0.000** | 0.509 | 74 | 0.612 |
| | Male | 80 | 30.00 | 5.44 | 29.90 | 5.41 | 0.908 | *0.000** | 0.407 | 79 | 0.685 |
| L4/L5 | Female | 72 | 24.22 | 3.98 | 24.44 | 3.92 | 0.938 | *0.000** | -1.309 | 71 | 0.195 |
| | Male | 64 | 28.18 | 4.85 | 28.44 | 5.41 | 0.912 | *0.000** | -0.944 | 63 | 0.349 |
| L5/S1 | Female | 57 | 24.33 | 5.23 | 25.03 | 5.92 | 0.883 | *0.000** | -1.909 | 56 | 0.061 |
| | Male | 51 | 24.60 | 5.90 | 25.09 | 6.21 | 0.889 | *0.000** | -1.213 | 50 | 0.231 |

**Cross sectional areas (CSAs) of the inter-vertebral discs (IVDs)**

Descriptive statistics for CSAs of inter-vertebral discs of the L3/L4, L4/L5, and L5/S1 levels are presented for each gender and average for both genders (Table 3.11). The average CSAs of IVD were larger for male subjects than female subjects at all levels; approximately 24% larger at the L3/L4 and L4/L5 levels and 27% larger at the L5/S1 level. To test the effect of gender and IVD level on the CSA of the total ESMM, a 2X3 SPF analysis was performed. Results of the SPF ANOVA are given in Table 3.12. The ANOVA found a main effect of gender ($p = 0.000$) and main effect of IVD level ($p = 0.000$). This means that males had different IVD sizes than females and at least two IVD levels were significantly different.The interaction between gender and IVD level was not significant (0.973).

Independent samples T-tests statistical analyses (Table 3.13) suggested that males had larger IVD sizes at all levels (L3/L4 level ($p<0.000$), L4/L5 level ($p<0.000$), and L5/S1

Table 3.11: CSAs of IVDs

| | | | CSA of IVD ($cm^2$) | | | |
|---|---|---|---|---|---|---|
| | | **N** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 75 | 14.78 | 1.71 | 11.09 | 18.33 |
| | Male | 80 | 18.26 | 2.54 | 13.39 | 27.96 |
| | Total | 155 | 16.58 | 2.79 | 11.09 | 27.96 |
| **L4/L5** | Female | 72 | 14.64 | 1.74 | 11.15 | 18.78 |
| | Male | 64 | 18.19 | 2.12 | 13.60 | 24.55 |
| | Total | 136 | 16.31 | 2.62 | 11.15 | 24.55 |
| **L5/S1** | Female | 57 | 13.34 | 1.94 | 9.99 | 17.79 |
| | Male | 51 | 16.90 | 2.69 | 13.42 | 27.12 |
| | Total | 108 | 15.02 | 2.92 | 9.99 | 27.12 |
| **Total** | Female | 204 | 14.33 | 1.88 | 9.99 | 18.78 |
| | Male | 195 | 17.88 | 2.51 | 13.39 | 27.96 |
| | Total | 399 | 16.06 | 2.84 | 9.99 | 27.96 |

Table 3.12: ANOVA summary table for main and interaction effects of gender and IVD level on the IVD size

| **Source** | **SS** | **df** | **MS** | **F-stat** | **Sig.** |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 948.82 | 1 | 948.82 | 89.43 | *0.000** |
| Subject(Gender) | 1029.16 | 97 | 10.61 | 8.74 | |
| **Within Subjects** | | | | | |
| IVD Level | 122.39 | 2 | 61.17 | 50.41 | *0.000** |
| Gender*IVD Level | 40.07 | 2 | 0.03 | 0.03 | 0.973 |
| IVD Level * Subject(Gender) | 235.39 | 194 | 1.21 | | |
| Total | 2335.82 | 296 | | | |

level ($p<0.000$)) than female subjects. Multiple comparison procedures (post-hocs) were also performed to determine which IVD levels differ. Tukey's HSD (honestly significant difference) Post-hoc test was used for three IVD size comparisons. HSD values were calculated with the formula:

HSD = q * $\sqrt{MS_{Within}/n}$ ; where q is the studentized range statistic (q = 3.31 for 3 treatments and 99 subjects at $\alpha$=0.05), $MS_{Within}$ is mean square term within subjects, and n is the number of subjects (99 subjects).

When the absolute difference between two IVD sizes are larger than the HSD value, it is concluded that the difference is significant. Table 3.14 presents absolute differences, HSD values, and significancy of differences. Post-hocs tests suggested that the IVD sizes at the L5/S1 level were significantly smaller than the other two IVD levels (the L3/L4 and L4/L5). The CSA of the IVD was larger at the L3/L4 level than the L4/L5 level; however, this difference was not statistically significant.

Table 3.13: Gender effect on CSA of IVD for each disc level

| **CSA ($cm^2$)** | **Gender** | **N** | **Mean** | **St.d.** | **t** | **df** | **Sig.** |
|---|---|---|---|---|---|---|---|
| **L3/L4** | Female<br>Male | 51<br>48 | 14.72<br>18.34 | 1.61<br>2.44 | -8.750 | 97 | *0.000** |
| **L4/L5** | Female<br>Male | 51<br>48 | 14.63<br>18.18 | 1.66<br>2.18 | -9.142 | 97 | *0.000** |
| **L5/S1** | Female<br>Male | 51<br>48 | 13.33<br>16.89 | 1.97<br>2.53 | -7.859 | 97 | *0.000** |

Table 3.14: Post-hocs tests: Pairwise comparisons of the IVD sizes at IVD levels

| (I) Level | (J) Level | Mean Difference (I-J) | HSD | |
|---|---|---|---|---|
| L3/L4 | L4/L5<br>L5/S1 | 0.27<br>1.56 | 0.37<br>0.37 | Not Sig.<br>*Significant* |
| L4/L5 | L3/L4<br>L5/S1 | -0.27<br>1.29 | 0.37<br>0.37 | Not Sig.<br>*Significant* |
| L5/S1 | L3/L4<br>L4/L5 | -1.56<br>-1.29 | 0.37<br>0.37 | *Significant*<br>*Significant* |

**The erector spinae muscle mass lever arm (ESMLA) distance**

Descriptive statistics such as mean, standard deviation, and minimum and maximum values about the erector spinae muscle mass lever arm (ESMLA) distances are presented in Table 3.15 for each gender as well as the average for both genders. The average ESMLA distance for both genders was 5.35 cm at the L3/L4 vertebral disc level. The lever arm distance decreased at the L4/L5 disc level; 5.24 cm which is the smallest lever arm distance among the three vertebral disc levels. Subsequently, the ESMLA distance became the largest at the L5/S1 disc level (Figure 3.5).

Table 3.15: Erector spinae muscle mass lever arm (ESMLA) distances

| | | | **ESMLA distance (cm)** | | | |
|---|---|---|---|---|---|---|
| | | **N** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 75 | 5.09 | 0.42 | 4.08 | 5.93 |
| | Male | 80 | 5.60 | 0.44 | 4.22 | 6.65 |
| | Total | 155 | 5.35 | 0.50 | 4.08 | 6.65 |
| **L4/L5** | Female | 72 | 5.00 | 0.40 | 3.97 | 5.89 |
| | Male | 64 | 5.52 | 0.40 | 4.66 | 6.42 |
| | Total | 136 | 5.24 | 0.47 | 3.97 | 6.42 |
| **L5/S1** | Female | 57 | 5.10 | 0.44 | 4.03 | 6.14 |
| | Male | 51 | 5.71 | 0.53 | 4.81 | 7.68 |
| | Total | 108 | 5.39 | 0.57 | 4.03 | 7.68 |
| **Total** | Female | 204 | 5.06 | 0.42 | 3.97 | 6.14 |
| | Male | 195 | 5.60 | 0.46 | 4.22 | 7.68 |
| | Total | 399 | 5.33 | 0.51 | 3.97 | 7.68 |

A split plot ANOVA test was performed to determine the effects of gender, IVD level, and gender*IVD interaction. The results of split plot factorial design ANOVA tests (Table 3.16) suggested that there was a main effect of gender ($p<0.000$), main effect of IVD level ($p<0.000$), and an interaction effect of gender and IVD level ($p<0.000$) on the ESMLAs. Figure 3.5 graphically represents how gender and IVD level affect the size of ESMLA.

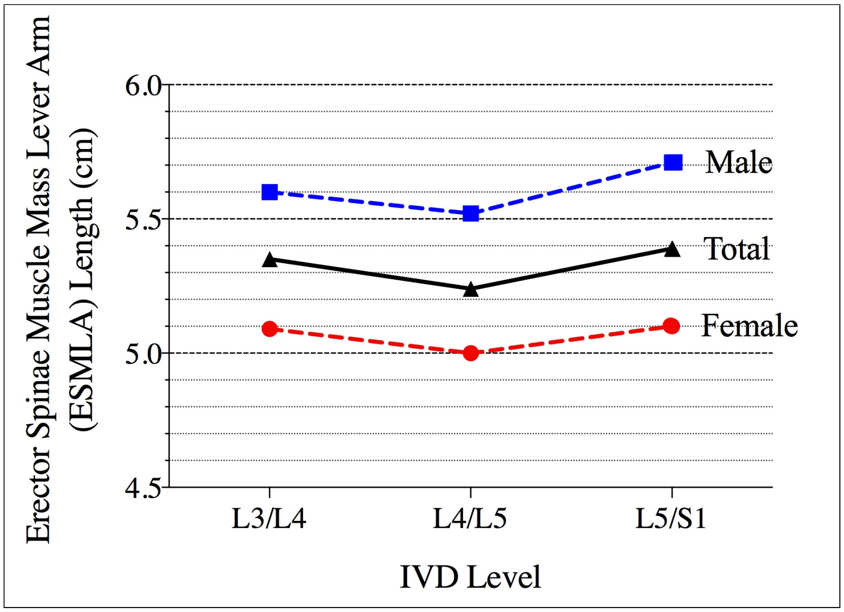



Figure 3.5: ESMLA distances for each gender at each IVD level

Table 3.16: ANOVA summary table for main and interaction effects of gender and IVD level on the ESMLA distance

| **Source** | **SS** | **df** | **MS** | **F-stat** | **Sig.** |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 17.20 | 1 | 17.20 | 33.31 | *0.000** |
| Subject(Gender) | 50.08 | 97 | 0.52 | 14.49 | |
| **Within Subjects** | | | | | |
| IVD Level | 0.63 | 2 | 0.33 | 9.31 | *0.000** |
| Gender*IVD Level | 0.69 | 2 | 0.34 | 9.63 | *0.000** |
| IVD Level * Subject(Gender) | 6.91 | 194 | 0.04 | | |
| Total | 75.51 | 296 | | | |

## 3.4 Discussion

The purpose of this MRI study was to provide accurate morphological measurements regarding the musculoskeletal structure for use in biomechanical models. Cross sectional areas (CSA) of erector spinae muscle mass (ESMM) and inter-vertebral discs (IVD), and the erector spinae muscle mass lever arm (ESMLA) distances were measured using a computer-aided methodology. Most measurement values have agreed with previous studies. However, some differences in these values were observed, and they were possibly due to differences in sampling, measurement techniques, and muscle definitions.

### Cross-sectional Area of Erector Spinae Muscle Mass

Some researchers have calculated CSAs of ESMM at the vertebral body level (rather than disc level), so it is not possible to directly compare the results of this study with those studies (Reid and Costigan, 1985 and 1987; Cooper *et al.*, 1992; Bogduk *et al.*, 1992; McGill *et al.*, 1993; Delp *et al.*, 2001; Marras *et al.*, 2001; Lee *et al.*, 2011; Anderson *et al.*, 2012) since measurement locations are "offset." However, it may be beneficial to compare them with the results of this study since values may correlate because the measurement locations are similar. Table 3.17 is provided to compare those studies with the present study.

Delp *et al.* (2001) reported an average of 11.6 $cm^2$ CSA of ESMM for all lumbar vertebral levels. Their value was relatively small compared to CSAs found in the current study. It might be because of subject sampling. They had 5 cadavers, while the present study had 163 live subjects. They also did not include the multifidus in their measurements. The multifidus was considered as part of the muscle tract of ESMM in this study.

Males subjects had 29.9 $cm^2$ and 30.0 $cm^2$ ESMM CSAs at the left and right side, respectively at the L3/L4 IVD level in the present study. Bogduk *et al.* (1992) reported 28.5 $cm^2$ CSA for 9 male subjects. McGill *et al.* (1993) reported 29.3 and 28.3 $cm^2$ for the left and right CSAs of ESMM at the same vertebral level. These values were very close

Table 3.17: Comparison of CSAs of ESMM reported by various authors by vertebral body level

| | Subjects | Age | Height | Weight | BMI | | Average | L1 | L2 | L3 | L4 | L5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reid and Costigan (1985) | 16 Male | 54.6 | 172.6 | 74.7 | | Left (M+F) | 16.02(3.93) | | | | | |
| *(CT, Healthy)* | 12 Female | 52.1 | 159.4 | 63.8 | | Right (M+F) | 15.73(4.23) | | | | | |
| Reid and Costigan (1987) | 20 Male | 21.2 | 176.9 | 69.7 | | Left + Right | | | | | | 54.38(8.37) |
| *(MRI, Healthy)* | | | | | | | | | | | | |
| Cooper *et al.* (1992) | 39 Male | 38 | | 75 | | | | | | | 25.4 | |
| *(CT, LBP)* | 53 Female | 39 | | 64 | | | | | | | 19.9 | |
| Bogduk *et al.* (1992) | 9 Male | 29 | | | | | | 18.7 | 24.5 | 28.5 | 29.9 | 11.6 |
| *(Xray, Upright, Healthy)* | | | | | | | | | | | | |
| McGill *et al.* (1993) | 15 Male | 25.3 | 176.1 | 81.5 | | Left | | 27.23(4.28) | 28.33(4.56) | 29.33(3.82) | 22.34(4.76) | 9.86(3.38) |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 26.15(4.05) | 28.54(5.47) | 28.31(4.58) | 21.51(5.39) | 9.05(3.31) |
| Delp *et al.* (2001) | 2M+3F | 67 | 170.6 | 76.2 | | | 11.6 | | | | | |
| *(Cadavers)* | | | | | | | | | | | | |
| Marras *et al.* (2001) | 10 Male | 26.4 | 175.9 | 79.8 | 25.7 | Left | 26.00(4.2) | 22.53(3.7) | 25.41(4.2) | 25.21(4.1) | 20.15(2.7) | 5.17(1.7) |
| *(MRI, Supine, Healthy)* | 20 Female | 25 | 165.5 | 57.9 | 21.2 | | 16.12(3.4) | 13.84(3.0) | 15.64(3.5) | 15.58(3.2) | 12.74(2.4) | 2.8(1.1) |
| | 10 Male | | | | | Right | 25.95(4.1) | 22.49(3.7) | 25.6(4.2) | 25.03(3.7) | 20.08(2.3) | 4.95(1.8) |
| | 20 Female | | | | | | 16.16(3.8) | 13.67(3.3) | 15.68(3.6) | 15.43(3.6) | 12.37(2.5) | 2.81(1.1) |
| Guzik *et al.* (1996) | 16 Male | 24.9 | 179.8 | 75.2 | | Left | 26.16(3.17) | | | | | |
| *(MRI, Healthy Athlete)* | | | | | | Right | 26.90(2.70) | | | | | |
| Lee *et al.* (2011) | LBP: 10M+3F | 29.7 | 171 | 66.4 | 22.5 | Left | | | | | | 18.5 |
| *(MRI, LBP)* | I.LBP: 12M+13F | 28.9 | 169 | 63.8 | 22.1 | | | | | | | 23.4 |
| | | | | | | Right | | | | | | 18.2 |
| | | | | | | | | | | | | 22.8 |
| Anderson *et al.* (2012) | 51Male | 59.4 | 177.6 | 81.3 | | ESM only | | 20.58(7.93) | 18.82(2.79) | 19.12(4.41) | 14.04(3.71) | 4.52(2.41) |
| *(CT, Supine, Healthy )* | 49 Female | 58.1 | 162.2 | 68.4 | | | | 13.18 (-) | 14.07(3.16) | 13.22(2.80) | 11.11(2.11) | 4.86(2.76) |
| | 51Male | | | | | ESM + Transversospinalis | | | 23.0 | 25.5 | 23.3 | 13.8 |
| | 49Femlae | | | | | | | | 16.7 | 17.8 | 18.6 | 12.6 |

| | Subjects | Age | Height | Weight | BMI | | | L1/L2 | L2/L3 | L3/L4 | L4/L5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gungor (2013)* | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | Left | | | | 29.9(5.4) | 28.4(5.4) | 25.1(6.2) |
| *(MRI, Supine, LBP)* | | | | | | Right | | | | 30.0(5.4) | 28.2(4.9) | 24.6(5.9) |
| | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | Left | | | | 23.4(3.7) | 24.4(3.9) | 25.0(5.9) |
| | | | | | | Right | | | | 23.5(3.9) | 24.2(4.0) | 24.3(5.2) |

Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; CSA: $cm^2$

to the findings of this study at the L3/L4 IVD level. Marras *et al.* (2001) measured a smaller CSA for both left and right sides, 25.2 and 25.0 $cm^2$. They had a smaller sample size (10 males) compared to the present study and did not include the multifidus muscle in the ESMM. Anderson *et al.* (2012) reported approximately 36% smaller muscle CSAs at the L3 vertebral level (19.1 $cm^2$). These relatively large differences might be due to the definition of muscles and measurement technique. The whole muscle structure was measured in the present study while Anderson *et al.* (2012) measured erector spinae group and transversospinalis group separately. If the CSAs of the erector spinae group (19.1 $cm^2$) and transversospinalis group (6.4 $cm^2$) are summed, the result will be much closer to the results of the present study (a total of 25.5 $cm^2$), but still approximately 15% smaller than the finding of the present study. For female subjects, Marras *et al.* (2001) reported 15.6 and 15.4 $cm^2$ CSAs for the left and right sides, respectively. It was 67% smaller than the findings of the present study; the female CSA at the L3/L4 level was 23.4 and 23.5 $cm^2$ for the left and right sides, respectively. The results were also larger than Anderson *et al.*'s (2012) results even though they treated the erector spinae and transversospinalis groups as a one single muscle mass.

The results of the present study for the CSA of ESMM at the L4/L5 IVD level were compared with the previous studies at the L4 vertebral level. Bogduk *et al.* (1992) reported results very close to the present study; 29.9 $cm^2$ CSA for male subjects. The CSAs of the ESMM at the L4/L5 level were measured as 28.4 $cm^2$ (left side) and 28.2 $cm^2$ (right side) for male subjects and 24.4 $cm^2$ (left side) and 24.2 $cm^2$ (right side). These results were in the range of Cooper *et al.*'s (1992) study. However, they were larger than McGill *et al.*'s (1993) study with 15 male subjects with a reported a 22.3 $cm^2$ for the left side and 21.5 $cm^2$ for the right side. Difference between their study and the present study might be due to the sample population. Their male population was younger (25.3 years old) and lighter (81.5 kg) than the present study (30.1 years old and 85.7 kg). Marras *et al.* (2001) also had younger and lighter subjects. They measured 10 males and did not include the multifidus muscle in the ESMM structure. The difference between CSAs was very large within female subjects for both studies. For example, Marras *et al.* (2001) measured 12.7 $cm^2$ for the left CSA of ESMM at the L4 vertebral levels while the present study measured 24.4 $cm^2$. It might be also due to the differences between subject anthropometrics of two studies. Marras *et al.* (2001) had 20 female subjects that weighed an average of 57.9 kg while the average weight of the subjects in the present study was 76.5 kg. Anderson *et al.* (2012) also reported smaller CSA for females (18.6 $cm^2$) and males (23.3 $cm^2$) for the total of ESM and transversospinalis group, most likely due to having lighter subjects.

There are great variations in the CSAs of the ESMM at the lowest lumbar spine observed across previous studies. Marras *et al.* (2001) reported a 2.8 $cm^2$ right CSA for female subjects at L5 vertebral level while Reid and Costigan (1987) reported a 54.38 $cm^2$ for the total CSA (left and right sides) for male subjects at the same vertebral body level. These differences may be due to the definition of ESMM at the lowest vertebral level. Lee *et al.* (2011) reported 22.8 $cm^2$ CSA in their study that had a total of 25 male and female subjects. The results of the present study are 25.1 and 24.6 $cm^2$ for male subjects and 25.0 and 24.3 $cm^2$ for female subjects on the left and right sides, respectively, which are close to Reid's and Costigan's (1987) and Lee and his colleagues' (2011) results.

Direct comparisons were possible with the studies that measured the CSA at an inter-vertebral disc level. The CSA from the present study are mostly smaller than previous studies. The differences may be due to the subject characteristics and muscle group definition. In the present study, the ESMM was assumed as a single, wholistic muscle structure on the back including the erector spine muscles (longissimus and iliocostalis) and transversopinalis muscles (semispinalis, multifidus, and rotators). The muscle mass was not separated from fat tissue, as well. The present study proposed a measurement technique that can be easily understood and consistently applied by other researchers, therefore, the entire (paraspinal) muscle mass that is responsible for spinal extension was defined as the main muscle mass.

Table 3.18: Comparison of CSAs of ESMM reported by various authors by IVD level

| | Subjects | Age | Height | Weight | BMI | | L1/L2 | L2/L3 | L3/L4 | L4/5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | L+R | | | | 45.1 | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 26.2(3.4) | 26(3.3) | 19.6(5.9) | 8.3(2.7) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 17.9(3.1) | 18.5(3.0) | 17.3(3.0) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 18.2(2.7) | 18.5(3.0) | 17.4(3.0) | |
| Han *et al.* (1992) | 6M+4F | 40.1 | 163 | 58.4 | | Left | 18.31 | 19.60 | 18.82 | 16.58 | 11.33 |
| *(CT, Supine, LBP, Japan)* | | | | | | Right | 18.23 | 19.33 | 18.47 | 16.48 | 11.44 |
| Parkkola *et al.* (1992) | 1M+11F | 23.3 | | 59.1 | | L+R | | | | 48(8) | |
| *(MRI, Healthy)* | | | | | | | | | | | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 18.1 | 19.3 | 20.0 | 8.8 |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 17.7 | 18.1 | 20.3 | 9.4 |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis(L+R) | 68(11.8) | 67(9.8) | 58.6(6.8 ) | 42.6(9.8) | 17.8(4.6) |
| *(MRI)* | | | | | | Kyphosis(L+R) | 45.1(9.2) | 55.4(9.9) | 53.1(8.3) | 49.8(6.2) | 27.2(6.7) |
| | 5 Female | 31 | 173 | 64 | | Lordosis(L+R) | 40.6(9.1) | 41.3(8.2) | 40.8(3.1) | 38.4(7.1) | 12.2(3.9) |
| | | | | | | Kyphosis(L+R) | 33.1(8.8) | 36.2(7.8) | 37.3(5.8) | 37.4(4.9) | 20.8(6.5) |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 30.6(8.4) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | Left | | | | | 21.78(6.47) |
| *(MRI, Supine, Healthy Asian)* | | | | | | Right | | | | | 21.47(6.80) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 23.9(4.5) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 17.1(3.1) | | |
| Jorgensen *et al.* (2003a) | 12 Male | 23.1 | 177.1 | 74.5 | | Right | 20.2(3.3) | 22.1(3.1) | 22.3(3.9) | 22.7(3.4) | 17.4(4.8) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 10.7(1.3) | 12.1(1.3) | 13.7(1.8) | 14.5(2.2) | 10.6(1.9) |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK (L+R) | | | | 33.77(9.15) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control (L+R) | | | | 52.41(8.9) | |
| Kamaz *et al.* (2007) | 36 Female | 43.2 | | | 28.6 | LBP | | | 17.7(2.6) | 17.9(2.7) | |
| *(CT, Prone, Turkish)* | 34 Female | 44.4 | | | 28.5 | Control | | | 18.6(2.6) | 19.6(2.7) | |
| Kang *et al.* (2007) | 54 Female | 60 | 154 | 62 | 26.9 | LBP | | | | 39.5(5.0) | |
| *(MRI, Korean)* | 54 Female | 60 | 153 | 57 | 24.19 | LDK | | | | 29.2(4.5) | |
| Niemelainen *et al.* (2011) | 126 Male | 49.8 | 175.4 | | 25.9 | Left | | | 26.6 | 24.8 | 21.2 |
| *(MRI, Healthy, Finnish)* | | | | | | Right | | | 26.9 | 24.4 | 20.5 |
| Gungor (2013)* | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | Left | | | 29.9(5.4) | 28.4(5.4) | 25.1(6.2) |
| *(MRI, Supine, LBP)* | | | | | | Right | | | 30.0(5.4) | 28.2(4.9) | 24.6(5.9) |
| | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | Left | | | 23.4(3.7) | 24.4(3.9) | 25.0(5.9) |
| | | | | | | Right | | | 23.5(3.9) | 24.2(4.0) | 24.3(5.2) |

Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; CSA: $cm^2$

Tracy *et al.* (1989) reported 26.0 $cm^2$ CSA for 26 male subjects at the L3/L4 IVD level and 19.6 $cm^2$ and 8.3 $cm^2$ for the L4/L5 and L5/S1 levels. Note that they reported the right ESMMs only. These values were smaller than the findings of the present study which were 30.0 $cm^2$ for the L3/L4, 28.2 $cm^2$ for the L4/L5, and 24.6 $cm^2$ for the L5/S1 IVD levels for the right ESMMs of male subjects. Tracy *et al.* (1989) did not report subject anthropometrics so the comparison is difficult to make.

Chaffin *et al.* (1990) had older female subjects in their study. They measured the whole muscle mass as was done in the present study. They reported 18.5 $cm^2$ for both left and right erector spinae at the L3/L4 IVD level and 17.3 $cm^2$ for the left and 17.4 $cm^2$ for the right erector spine muscles at the L4/L5 level. They had older subjects in their study and age related muscle atrophy (a decrease in the mass of the muscle associated with aging) has been reported by several studies (Lexell, Taylor, and Sjostrom, 1988; Brooks and Faulkner, 1994; and Faulkner, Larkin, Clain, and Brooks, 2007). The average weight was 67.6 kg in their study while the average female weight was 76.5 kg in the present study.

A total of 10 subjects (6 males and 4 females) was included in Han *et al.*'s (1992) study. The average of height and weight of these Japanese subjects were 163.1 cm and 58.4 kg. They also did not include the multifidus muscle in the erector spinae group. However, subjects in the present study were taller and heavier. Moreover, the multifidus was measured and included in the present study. These differences might explain why the CSAs of ESMM in the present study were larger than in these previous studies.

Parkkola *et al.* (1992) studied CSAs of the ESMM with 1 male and 11 female subjects. They measured the CSA at the L4/L5 IVD level as 48 $cm^2$ for the total of both sides. It might be meaningful to compare their results with the results of female subjects of the present study. For the same disc level, the present study measured 24.4 and 24.2 $cm^2$ for the left and right side in female subjects, respectively. The summation of CSAs of both sides yields a total of 48.6 $cm^2$ CSAs, which is virtually identical to their 48 $cm^2$ CSA.

Another small sample size study (5 male subjects) was conducted by Tsuang *et al.* (1993). Their male subjects were quite a bit smaller with an average weight of 64.6 kg as compared with 85.7 kg for the present study. The difference in subject mass (approximately 33% greater) could explain the difference in the CSA measurements.

Tveit *et al.* (1994) had 11 subjects with lumbar lordosis and kyphosis. The average weight of their male subjects (82 kg) was close to the average weight of male subjects in the present study (85.7 kg), but they had very small female subjects. The results of lordotic male subjects could be comparable with the results of male subjects of the present study. They measured 58.3 $cm^2$ CSA for the total ESMM at the L3/L4 disc level, which was very close to the total CSA for the present study (59.9 $cm^2$). However, there are large differences at the other IVD levels. These differences could be a result of their lordotic subjects. Lumbar lordosis curvature increases with lower vertebrae levels. Also, if their CSAs are not oblique projections they will over estimate ESMLA which would explain greater errors in the L5/S1 level where the angle is most different.

Guzik, Keller, Szpalski, Park, and Spengler (1996) reported average male CSAs for the ESMM (Table 3.17) for measurements taken from T12/L1 IVD level to L5/S1 IVD level. They reported 26.16 and 26.90 $cm^2$ CSAs for the left and right ESMMs, respectively. Both values are in the range of the present study, 25.1-29.9 $cm^2$ for the left ESMM and 24.6-30.0 $cm^2$ for the right ESMM.

Wood *et al.* (1996) tried to explain the variation in the trunk muscles with the obesity level. They took transverse images of 26 male subjects. They reported 30.6 $cm^2$ CSA at the L4/L5 IVD level.

A study with 8 Asian males by Lin *et al.* (2001) reported 21.8 $cm^2$ for the CSA of left ESMM and 21.5 $cm^2$ for the right side at L5/S1 level, which is approximately 13% smaller than the present study. Note that their subject average weight was 64 kg while the average weight for male subjects is the present study was 85.7 kg. The difference in weight might help to explain the difference in CSA measurements.

Seo *et al.* (2003) also included smaller subjects than the present study. The average height and weight were 168.5 cm and 65.5 kg for males and 155.5 cm and 54.4 kg for females. The CSAs of ESMM were 23.9 $cm^2$ for males and 17.1 $cm^2$ for females, which are approximately 25% smaller than the finding of the present study.

Jorgensen *et al.* (2003a) investigated the effect of torso flexion on the magnitude of CSA of the lumbar back muscles. They performed MRI scans with the subject lying on their left sides in several torso flexion postures. Their results for the measurements taken while subjects were lying on their sides with neutral torso flexion ($0^o$) could be compared with the present study. They reported the CSAs of the ESMM for the right side for several IVD levels; males had 22.3 $cm^2$, 22.7 $cm^2$, and 17.4 $cm^2$ and females had 13.7 $cm^2$, 14.5 $cm^2$, and 10.6 $cm^2$ for the L3/L4, L4/L5, and L5/S1 IVD levels, respectively. These values were much smaller than the values measured in the present study. It could be a result of different lying posture since the subjects were lying supine in the present study. Differences in subject anthropometry or age might also explain the variation between studies. They had younger subjects (males were 23.1 years old and females were 23.8 years old in average) and smaller subjects (males were 74.5 kg and females were 56.5 kg in average).

A study with Korean female subjects was conducted by Lee *et al.* (2006) to investigate the relationship between the size of ESMM and low back pain (LBP). They reported the results of both lumbar degenerative kyphosis (LDK) patients and a control group. The results of CSAs for the control group could be compared to the results of the present study for female subjects; however, it should be noted that they had much older (63.6 years old), shorter (156 cm), and smaller (59.7 kg) subjects than the present study. They also did not include the multifidus muscle in the ESMM definition. Since they had smaller subjects with potentially atrophied muscles and did not include the multifidus in the measurements, they should be expected to report smaller CSAs than the present study and other studies. **However, they reported a 52.4 $cm^2$ CSAs for the total of the left and right**

**ESMMs at the L4/L5 disc level, which is the largest reported value in the literature.**

Kang *et al.* (2007) conducted a very similar study to Lee *et al.* (2006); older female Korean subjects with similar anthropometric characteristics. They also did not include the multifidus muscle in the ESMM and studied only the L4/L5 level. The difference was that they compared LDK patients with LBP patients. They reported 26.4 $cm^2$ erector spine CSA and 8.4 $cm^2$ multifidus CSA, yielding 39.5 $cm^2$ CSA for the entire ESMM for LBP paints. For LDK patients, the entire ESMM was calculated as 29.2 $cm^2$. Unfortunately, they did not mention whether these values were the average of both ESMM sides or the summation of both ESMM sides. By considering their older and smaller samples and their subjects' health conditions (LDK and LBP), it is likely a total value for the both sides.

Kamaz *et al.* (2007) also investigated the effect of muscle size on LBP in the upper and lower endplates of L4 vertebral level, which could be considered as similar to the L3/L4 and L4/L5 levels. They reported 18.6 and 19.6 $cm^2$ CSAs for their control group which were free from LBP. Their female control group was older (44.4 years old) than the present study (29.6 years old), but their reported BMI values (28.5 $kg/m^2$) were similar to the present study (28.1 $kg/m^2$). However, it is not possible to directly compare their study with ours since they did not report height and weight measurements. Their subjects were places in a prone position while the subjects in the present study were placed in a supine posture.

Niemelainen, Briand, and Battie (2011) studied asymmetry in the CSA of paraspinal muscle among 126 Finnish male twins. They reported CSAs of the erector spinae and multifidus separately. However, the data presented in Table 3.18 is the summation of the erector spinae and multifidus muscles, which they called paraspinal muscles while it is called ESMM in the present study. Their results were approximately 10-20% smaller than the present study. It can be a result of sampling differences. Their subjects were older (49.8 years old) and smaller (175.4 cm) than the present study. Of 126 subjects, 78 subjects had previous LBP (but not in the last 12 months), as well.

The estimated ESMM CSAs in the present study were mostly larger than other studies attempting to measure low back musculature. The differences in subject anthropometrics and age might be the major reasons for these differences. The definition of ESMM is also an important factor for the results. In the present study, the ESMM is considered as a single muscle structure that includes the longissimus, iliocostalis, and multifidus; however, some researchers (Han *et al.*, 1992; Lee *et al.*, 2006; Kang *et al.*, 2007) did not include the multifidus in the ESMM structure. Differences in measurement techniques may also explain the differences among the CSAs of ESMMs.

**Erector spinae muscle mass lever arm (ESMLA) distance**

In the present study, the ESMLA distances were measured at inter-vertebral disc levels. There have been studies in the literature that measured the ESMLAs at vertebral body levels (Reid and Costigan, 1987; Kumar, 1988; McGill *et al.*, 1993; Gilsanz *et al.*, 1995; Jorgensen *et al.*, 2001; Anderson *et al.*, 2012). Table 3.19 is given below to compare previous studies with this current study.

Reid and Costigan (1987) reported a 5.64 cm ESMLA distance at the L5 vertebral level for 20 male subjects, which is in the range of the results in the present study; 5.52 cm for the L4/L5 and 5.71 cm for the L5/S1 disc level.

Kumar (1988) reported muscle lever arm distances separately for both the erector spinae and the transverse spinalis muscles, which were considered as a whole muscle mass in the present study. He had older male and female subjects. The reported lever arm distances for the L3 and L5 vertebraes were approximately 15% larger than the results of the present study.

McGill *et al.* (1993) also reported larger ESMLA distances than the present study. The difference between McGill *et al.* (1993) and the present study is that they positioned subjects in a supine posture with knees extended while subjects in the present study were positioned in a supine posture with knees flexed by a cushion under legs.

Table 3.19: Comparison of anterior-posterior ESMLA distances reported by various authors by vertebral body level

| | Subjects | Age | Height | Weight | BMI | Side | L1 | L2 | L3 | L4 | L5 | S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reid and Costigan (1987) | 20 Male | 21.2 | 176.9 | 69.7 | | | | | | | 5.64(0.4) | |
| *(MRI, Healthy)* | | | | | | | | | | | | |
| Kumar (1988) | 21 Male | 60.2 | 175.1 | 80.0 | | | | | 6.15(0.55) | | | |
| *(CT, Supine,* | 11 Female | 62.0 | 158.2 | 68.7 | | | | | 5.71(0.60) | | | |
| *Patients but not LBP)* | 8 Male | 57.7 | 178.3 | 82.6 | | | | | | | 6.00(0.37) | |
| | 5 Female | 55.2 | 162.2 | 65.5 | | | | | | | 5.85(0.49) | |
| McGill *et al.* (1993) | 15 Male | 25.3 | 176.1 | 81.5 | | Left | 6.0(0.4) | 6.2(0.5) | 6.1(0.5) | 6.1(0.5) | 6.3(0.5) | |
| *(MRI, Supine, Healthy)* | | | | | | Right | 5.9(0.5) | 6.1(0.5) | 6.1(0.5) | 6.1(0.5) | 6.4(0.6) | |
| Gilsanz *et al.* (1995) | 148 Female | 70.2 | 159.7 | 59.9 | Without vertebral fracture | | | | 5.83(0.31) | 6.06(0.42) | | |
| (CT, Osteoporosis) | (23 Female at L3, 27 Female at L4) | | | | With vertebral fracture | | | | 5.54(0.28) | 5.61(0.33) | | |
| Jorgensen *et al.* (2001) | 10 Male | 26.4 | 175.9 | 79.8 | 25.7 | Left | 5.0(0.6) | 5.4(0.6) | 5.6(0.6) | 5.7(0.5) | 6.1(0.7) | 6.3(0.8) |
| *(MRI, Supine, Healthy)* | | | | | | Right | 5.2(0.5) | 5.4(0.7) | 5.7(0.7) | 5.6(0.6) | 6.1(0.7) | 6.2(0.7) |
| | 20 Female | 25.0 | 165.5 | 57.9 | 21.2 | Left | 4.7(0.5) | 5.1(0.6) | 5.3(0.6) | 5.3(0.5) | 5.7(0.6) | 5.6(0.5) |
| | | | | | | Right | 4.8(0.4) | 4.8(0.4) | 5.0(0.5) | 4.9(0.4) | 5.4(0.5) | 5.4(0.5) |
| Anderson *et al.* (2012) | 51 Male | 59.4 | 177.6 | 81.3 | | | 5.56(0.20) | 5.89(0.36) | 6.15(0.42) | 5.61(0.47) | 5.32(0.50) | |
| *(CT, Supine, Healthy)* | 49 Female | 58.1 | 162.2 | 68.4 | | | 5.61(-) | 5.39(0.52) | 5.57(0.47) | 5.11(0.47) | 4.94(0.51) | |
| | **Subjects** | **Age** | **Height** | **Weight** | **BMI** | | **L1/L2** | **L2/L3** | **L3/L4** | **L4/L5** | **L5/S1** | |
| Gungor (2013)* | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | | | | 5.60(0.44) | 5.52(0.40) | 5.71(0.53) | |
| *(MRI, Supine, LBP)* | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | | | | 5.09(0.42) | 5.00(0.40) | 5.06(0.42) | |

Age: years; Height: cm; Weight: kg; BMI: kg/m$^2$; ESMLA distance: cm

***** These are the results of this report. Note that the number of subjects vary depend on the vertebral disc level.
The anthropometric properties given in the table are for the overall study population.
It is not known for sure that subjects had LBP, but they were suspected for LBP.

Gilsanz, Loro, Roe, Sayre, Gilsanz, and Schulz (1995) studied with 232 elderly women with osteoporosis to determine the factors contributing vertebral fractures. They measured the bone density, CSA of vertebral body, and ESMLA distances with 32 paired subjects who were with and without vertebral fractures. The average subject age was 70.2 years. Their ESMLA measurement results for subjects without vertebral fracture was 5.83 cm at the L3 level and 6.06 cm at the L5 level, which is assumed that they are approximately 14-20% larger than the present study. They also found that subjects who had vertebral fractures had smaller ESMLAs compared to subjects who did not have vertebral fractures.

The results of the present study agreed with Jorgensen *et al.* (2001). They reported lever arm distances for last three vertebral levels ranging from 5.6 to 6.1 cm for males and 4.9 to 5.7 cm for females . The results of the present study were in these ranges (5.52 to 5.71 cm and 5.00 to 5.09 cm, respectively).

Anderson *et al.* (2012) had elderly subjects in their study. They reported very close ESMLA distance values to the present study for the L4 vertebral level and slightly smaller values for the L5 vertebral level.

The results of the present study can be compared to the studies that measured the ESMLAs at the lower IVD levels (Table 3.20). The findings of the present study tended towards the lower end of the spectrum of previous studies. Nemeth and Ohlsen (1986) reported the largest ESMLA distances in the literature (Figure 3.10 and 3.11). They included older patients in their study; the averages were 70 years old for 11 males and 63 years old for 10 females. These subjects had carcinomas in their pelvic areas, which may result in inactive life-style and muscle atrophy. They reported 7.1 cm and 6.5 cm ESMLA distances, at the L5/S1 disc level, for males and females, respectively. They possibly had transverse CT scans rather than axial oblique scans, which results in larger distances since the lumbar curvature is not taken into the consideration in such scans. The ESMLA distances at the same level were 5.71 cm for males and 5.06 cm for females in the present study.

Table 3.20: Comparison of anterior-posterior ESMLA distances reported by various authors by IVD level

| | Subjects | Age | Height | Weight | BMI | | L1/L2 | L2/L3 | L3/L4 | L4/L5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nemeth and Ohlsen (1986) | 11 Male | 70 | 176 | 75.02 | | | | | | | 7.1(0.2) |
| *(CT, Supine, Carcinomas)* | 10 Female | 63 | 166 | 60.06 | | | | | | | 6.5(0.2) |
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | | | | | 5.9(0.52) | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 5.78(0.44) | 5.76(0.46) | 6.00(0.53) | 6.17(0.59) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 5.4(0.4) | 5.3(0.2) | 5.4(0.4) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 5.4(0.4) | 5.2(0.4) | 5.2(0.3) | |
| Dumas *et al.* (1991) *(Cadavers)* | 7 Male | 55.6 | 163.6 | | (Range of avarages) | | | | | 6.0 - 6.4 | |
| Bogduk *et al.* (1992) | 9 Male | 29 | | | | (Min-Max) | 3.26-3.48 | 3.55-4.96 | 3.52-6.2 | 3.19-6.1 | 2.82-5.69 |
| *(Radiographs, Upright, Healthy)* | | | | | | | | | | | |
| Moga *et al.* (1993) | 11 Male | | | | | | 5.1 | 5.3 | 5.5 | 5.9 | |
| *(CT, Patients undertaken CT)* | 8 Female | | | | | | 4.9 | 4.7 | 5.1 | 4.9 | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 5.2 | 4.9 | 4.9 | |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 5.1 | 4.9 | 4.8 | |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis | 6.4(0.3) | 6.3(0.3) | 6.2(0.1) | 6.4(0.2) | |
| *(MRI)* | 5 Female | 31 | 173 | 64 | | | 5.6(0.5) | 5.7(0.5) | 5.9(0.3) | 6.2(0.4) | |
| | 6 Male | 37 | 185 | 82 | | Kyphosis | 5.2(0.4) | 5.3(0.4) | 5.6(0.4) | 5.5(0.1) | 5.7(0.3) |
| | 5 Female | 31 | 173 | 64 | | | 4.5(0.5) | 5.2(0.3) | 5.5(0.3) | 5.6(0.5) | 5.7(0.2) |
| Guzik *et al.* (1996) | 16 Male | 24.9 | 179.8 | 75.2 | Average | Left | 5.67(0.32) | | | | |
| *(MRI, Healthy Athlete)* | | | | | Average | Right | 6.06(0.41) | | | | |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 5.4(0.6) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | | | | | | 4.89(0.67) |
| *(MRI, Supine, Healthy Asian)* | | | | | | | | | | | |
| Jorgensen *et al.* (2003b) | 12 Male | 23.1 | 177.1 | 74.5 | | | 5.26(0.44) | 5.46(0.42) | 5.74(0.34) | 5.9(0.44) | 6.4(0.43) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 4.8(0.34) | 4.98(0.41) | 5.18(0.35) | 5.18(0.35) | 5.64(0.34) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 5.43(0.47) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 4.94(0.47) | | |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK | | | | 6.24(0.46) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control | | | | 6.86(0.40) | |
| Gungor (2013)* | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | | | | 5.60(0.44) | 5.52(0.40) | 5.71(0.53) |
| *(MRI, Supine, LBP)* | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | | | | 5.09(0.42) | 5.00(0.40) | 5.06(0.42) |

Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; ESMLA distance: cm

***** These are the results of this research. Note that the number of subjects varies depending on the vertebral disc level. The anthropometric properties given in the table are for the overall study population.

McGill *et al.* (1988) studied 13 male subjects who were active but symptomatic of LBP. They reported a 5.9 cm ESMLA distance at the L4/L5 disc level. For the same level, the present study measured an ESMLA of 5.5 cm. The 95% confidence intervals of the present study and McGill *et al.*'s (1988) overlap. Figure 3.8 compares studies in terms of confidence intervals.

Tracy *et al.* (1989) included 26 male subjects (22 of them had disc degeneration or protrusion) in their MRI study. They had transverse scans rather than oblique views, which results in larger measurements. Their subjects were positioned in a supine with knees extended. They measured anterior-posterior lever arm distances by "visual determination of the centroids of muscles and vertebral discs." Their results for ESMLA distances were larger than the present study at all disc levels. It is difficult to completely explain the differences between their study and the present study since they did not provide any anthropometric data in their report.

Chaffin *et al.* (1990) included 96 older female subjects (49.6 years old) in their study. They reported 5.2 cm ESMLA distance for both the L3/L4 and L4/L5 disc levels, which are good agreement with the findings of the present study; just slightly larger (2% and 4% for the L3/L4 and L4/L5 disc levels, respectively).

Dumas *et al.* (1991) used 7 male cadavers in their study. The average age was 55.6 years old at the time of death. Cadaveric specimens might not represent the geometrical properties of live subjects. Dumas *et al.* (1991) provided a range for the flexion-extension moment arm lengths, 6.0 cm to 6.4 cm with respect to the L4/L5 disc, which is approximately 9-16% larger ESMLA distances compared to the present study. The difference might be due to use of cadaveric subject. Moreover, they did not include the multifidus muscle in the ESMM. The multifidus is anatomically close to the spinous process, which results in alternation of the centroids of the ESMMs.

Bogduk *et al.* (1992) studied 9 male subjects using their universal model of the lumbar back muscles. They provided minimum and maximum ESMLA values rather than averages. The results of the present study were in their ranges, except at the L5/S1 level. Their maximum measured value for the L5/S1 muscle lever arm was 5.69 cm while the average of the present study was 5.71 cm. The difference might be due to their small sample size. In addition, they took radiograph images with subjects in a standing posture. The activation of and placement of the muscles alters as a function of the posture. Therefore, direct comparison of their study with the present study might not be appropriate. It should be noted that the standing "loaded" posture and aspect of their study adds some occupational fidelity to their results.

The results of the present study were similar to Moga *et al.*'s (1993) study. They estimated 5.1 cm and 4.9 cm lever arm distances for females with respect to the L3/L4 and L4/L5 discs, which nearly identical to the 5.09 cm and 5.00 cm in the present study. They also found the ESMLA to be larger at the L3/L4 level than the L4/L5 level. However, this pattern did not hold for male subjects in the present study where the results were 5.5 cm at the L3/L4 level and 5.9 cm at the L4/L5 level. Moga *et al.* (1993) had a small sample size (11 males and 8 females) to generalize their findings to the entire population. They also did not provide subject anthropometrics to compare with other studies. It is possible that their female subjects more closely resembled an average height and weight than their male subjects.

Tsuang *et al.* (1993) studied 5 male subjects. The ESMLA distances were reported as 4.9 cm for both the L3/L4 and L4/L5 levels, which is 12-14% smaller than the present study. Note that their subjects were approximately 33% lighter (21.1 kg less) than subjects in the present study. In the same way, Lin *et al.* (2001) had smaller Asian subjects (34% less body mass) and reported 14% smaller ESMLA distance at the L5/S1 level.

The results of the present study agree with Guzik *et al.* (1996). They included 16 healthy male athletes and measured the geometric parameters of the whole muscle mass (ESMM). They provided average ESMLA distance values derived from T12/L1 IVD level to L5/S1 IVD level. The average ESMLA was 5.67 cm for the left side and 6.06 cm for the right side. The range for ESMLA distances in the present study was 5.52-5.71 cm for three IVD levels.

Wood *et al.*'s (1996) subjects had very similar anthropometrics as subjects in the present study. The average ESMLA distance for 26 males was 5.4 cm at the L4/L5 level. The present study reported 5.52 cm lever arm distance for the same gender and IVD level.

Tveit *et al.* (1994) compared lumbar lordotic and kyphotic patients. Kyphotic male subjects were compared to male subjects in the present study; however, their results were approximately 15% larger for lordotic subjects for both genders, and larger for kyphotic female subjects. Differences might be due to lumbar lordosis curvature. The larger the curvature is, the larger the ESMLA distance is. Moreover, data collection methods that do not use oblique cross-sections will be further exaggerated by such curvature.

The results of Jorgensen *et al.* (2003b) were larger than the present study for all IVD levels and for both genders. However, their MRI images were taken while subjects were lying on their left sides, which makes direct comparisons difficult. Deformation of ESMM in a supine position can be possible, as well.

Seo *et al.* (2003) reported a slightly smaller ESMLA distance at the L3/L4 level for both male and female subjects. Their Japanese subjects were smaller and shorter than the present study's subjects, which could explain the differences in ESMLA measurements.

Lee *et al.* (2006) conducted a study with Korean female subjects who had lumbar degenerative kyphosis (LDK) and non-LDK controls. Even though they had older, shorter and lighter subjects than the present study and did not include the multifidus in the measurements, they reported larger ESMM CSAs than the present study. As with the CSAs, they reported the largest ESMLA distance for the L4/L5 level; approximately 37% larger than the present study. It should be noted that Lee *et al.* (2006) measured the ESMLA distance from the ESMM centroid directly to the IVD centroid rather than the perpendicular distance. This would explain why they measured such a large ESMLA distance.

Comparisons of ESMLA distances across studies including the present study are given in Figures 3.6, 3.7, 3.8, 3.9, 3.10, and 3.11. Note that Figures 3.6 and 3.7 compare studies that measured ESMLA distances at the L3/L4 level for males and females, respectively. Figures 3.8 and 3.9 are for the L4/5 and Figures 3.10 and 3.11 for the L5/S1 levels. Dots in the figures are the average values reported in the studies and lines represent the 95% confidence intervals (CI) for associated mean value. Dots without any CI-lines are from studies that did not report any standard deviation in the report and therefore CIs could not be generated. The blue dotted vertical lines represent the mean value for the present study and the red dotted lines represent the lower and upper CI bands of for the present study.

**Advantages of using average ESMLA distances rather than the fixed 5 cm ESMLA distance**

In early biomechanical models, the ESMLA distance was generally assumed to be 5 cm. Bradford and Spurling (1945), Morris *et al.* (1961), Munchinger (1962), Nachemson (1968) (for the L3/L4 disc), Ayoub and El-Bassoussi (1976), Poulsen (1981), and McGill and Norman (1985) assumed a 5 cm or 2 inch lever arm distance in their biomechanical models to estimate the compression forces exerted on the spine. Some biomechanical models (Garg, 1997; DeSantis *et al.*, 2010) also use a 5 cm ESMLA distance in their calculations or "virtual manikins." In text books, the ESMLA distance is typically given as 5 cm to explain the mechanics of lifting task (Ayoub and Mital, 1989; Chaffin, Andersson, and Martin, 2006). Kumar (1988), McGill and Norman (1987a), and Merryweather *et al.* (2009) stated that the lever arm distance had been selected as 5 cm by other researchers for simplicity. The results of the present study indicated that the ESMLA distance was 5.10 cm for females and 5.71 cm for males at the L5/S1 vertebral disc level. This implies that these previous studies may overestimate the compression forces (and therefore the risk of LBP) at the vertebral disc (approximately 12% for males). By assuming a fixed lever arm distance for both genders, these studies failed to differentiate gender specific spine

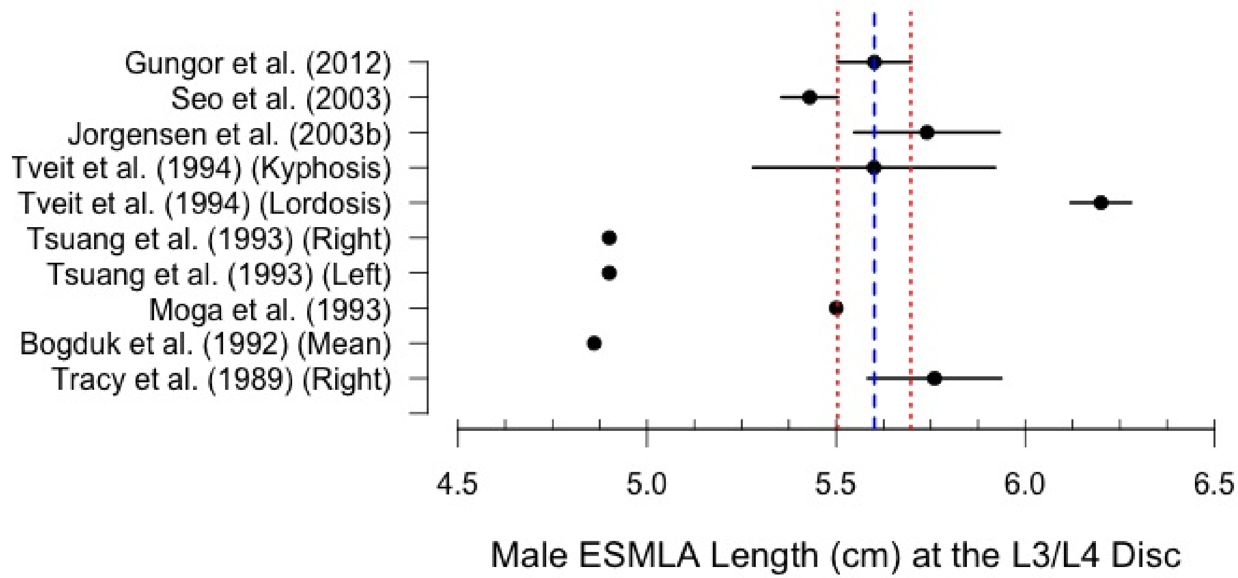



Figure 3.6: Comparison of male ESMLA distances at the L3/L4 IVD level

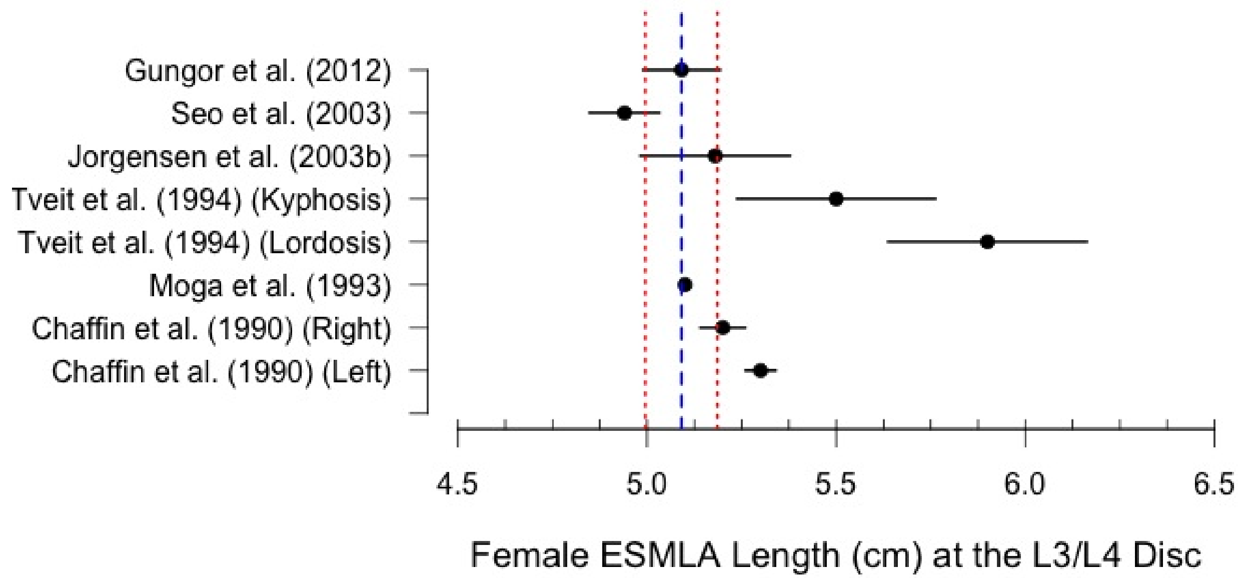



Figure 3.7: Comparison of female ESMLA distances at the L3/L4 IVD level

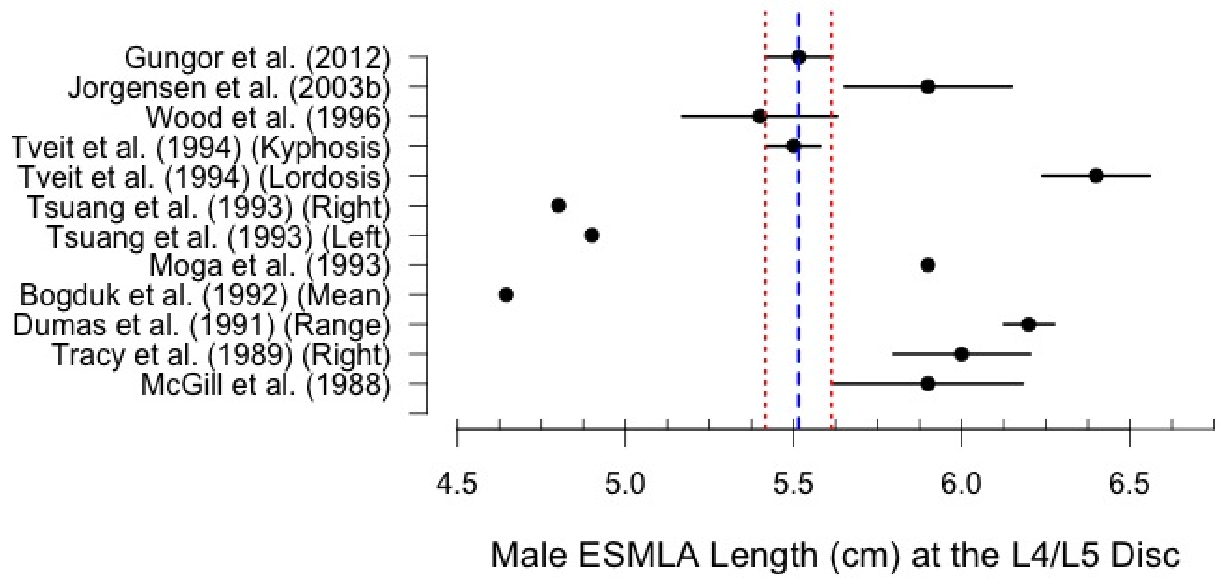



Figure 3.8: Comparison of male ESMLA distances at the L4/L5 IVD level

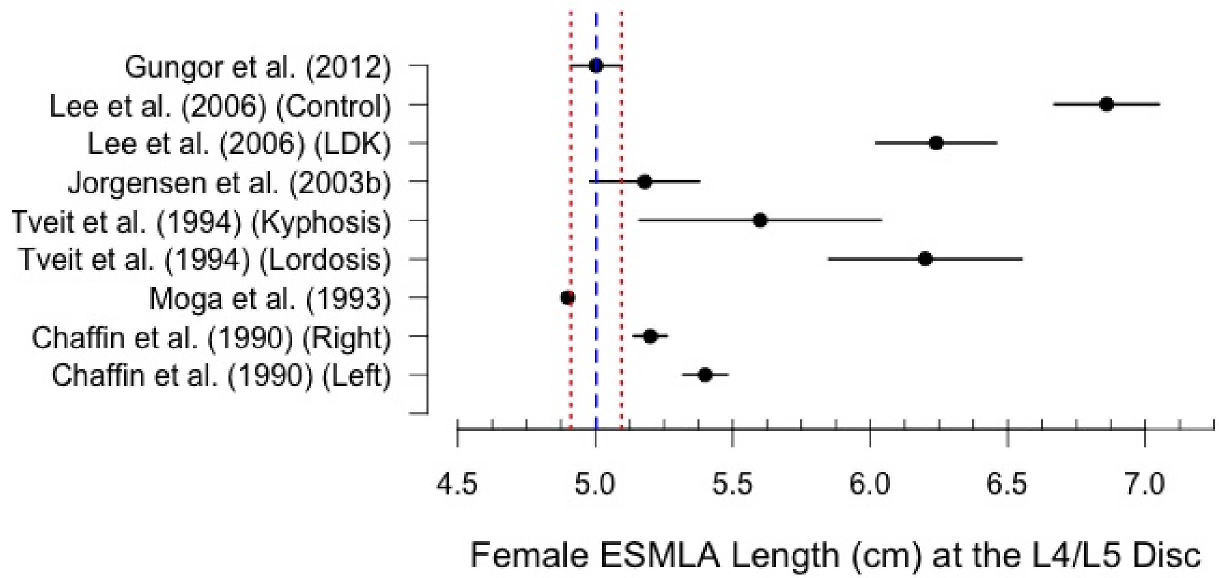



Figure 3.9: Comparison of female ESMLA distances at the L4/L5 IVD level

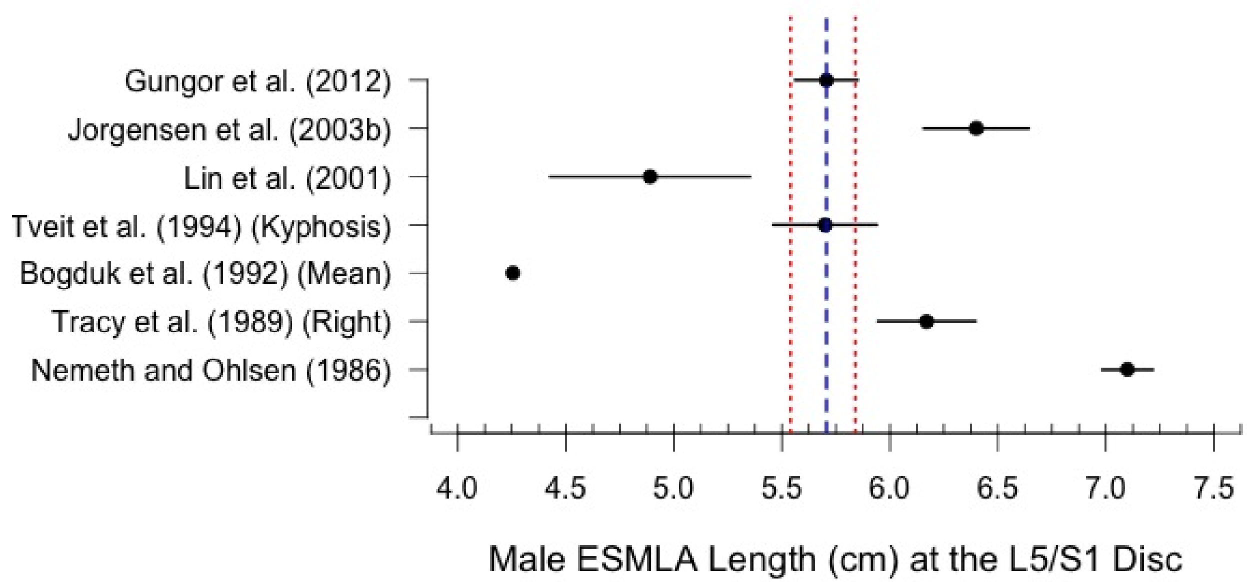



Figure 3.10: Comparison of male ESMLA distances at the L5/S1 IVD level

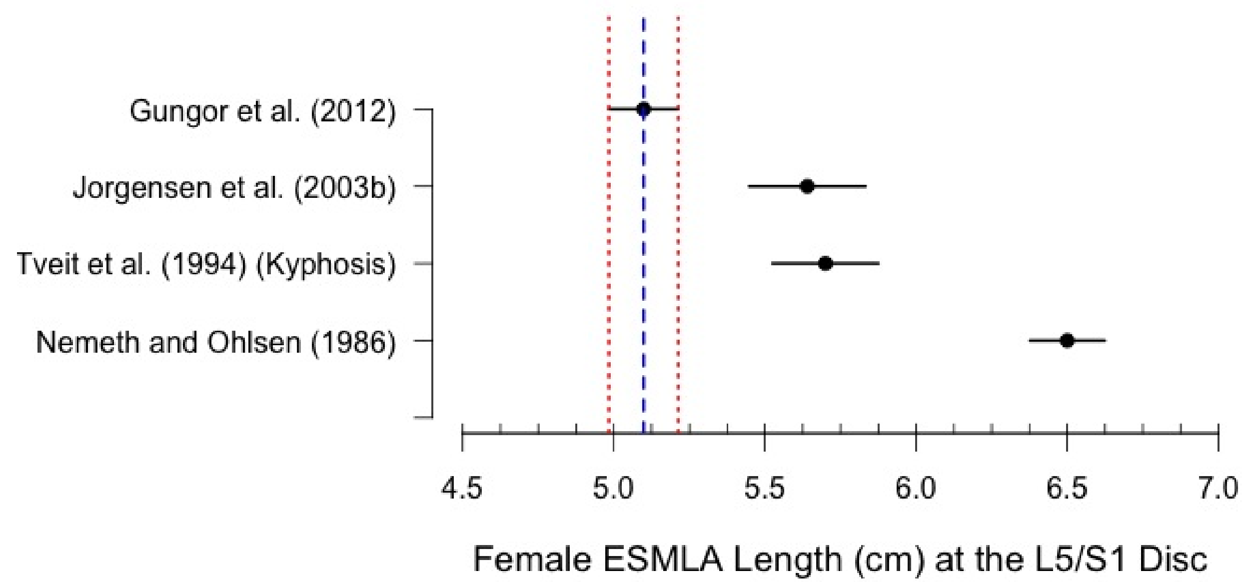



Figure 3.11: Comparison of female ESMLA distances at the L5/S1 IVD level

loadings. Models using these genderless estimates will tend to calculate less risk regarding LBP to male subjects than female subjects.

Rather than a 5 cm ESMLA distance, Hutton and Adams (1982) used a distance of 6.1 cm, McGill and Norman (1987a) suggested using a 7.5 cm, Bean *et al.* (1988) used a 7.4 cm, Tveit *et al.* (1994) proposed using a range of 5 to 8 cm, Chaffin (1995) suggested using a range of 5 to 7 cm, Merryweather *et al.* (2009) used 6.6 cm for females and 6.9 cm for males, and Waters and Garg (2010) used 6.0 cm for males and 5.6 cm for females. The current version of 3DSSPP (6.0.6) uses 5.9 cm for males and 5.3 cm (note that this is an average of right and left ESMM) ESMLA distances for females. Models using these larger ESMLAs will tend to underestimate the injury risk. Merryweather *et al.* (2009), for instance, underestimated the compression forces and therefore the risk for LBP approximately 17% for males and 23% for females. This may put subjects at higher risk.

Figure 3.11 shows the deviations of actual measurements for the present study from averages. The dotted black line depicts the assumed ESMLA distance of 5 cm, and the dotted green line is for actual ESMLA measurements measured from the study sample. As can be seen in the figure, the deviations (the distance between the dotted green and black lines) are larger with extremes. The objective of the present study was to suggest several ESMLA distances that will accommodate most of the population. The present study suggests using a separate ESMLA distance for each disc level and each gender. The red lines are actual ESMLA measurements for females, and the blue lines are actual ESMLA measurements for males. They are presented for each disc level. The horizontal solid black lines are the average values for each gender and each disc level. Using these average values rather than a fixed ESMLA distance can be justified with absolute error terms. Table 3.21 presents absolute errors associated with using 1) a 5 cm ESMLA distance ($\Delta 1$) and 2) the average value calculated from the present study ($\Delta 2$). Absolute errors are used to eliminate the direction of error; namely, the difference might be positive or negative, and direct arithmetic average will fail to represent the amount of actual error. The results show that using the average value for a specific gender and IVD level will decrease the error. If the average value is preferred over the fixed number, the absolute error reduced from 0.63 cm to 0.34 cm (46.0%) for males at the L3/L4 disc level. The error reductions for male subjects were 38.9% for the L4/L5 and 43.6% for the L5/S1 IVD level. Note that the error reduction was smaller for female subjects since their average ESMLA distances were closer to the assumed 5 cm ESMLA distance at all three IVD levels. Moreover, note that these error reductions are the averages and they are actually much more dramatic with extreme ESMLAs. For example, a male subject with a 6 cm ESMLA distance at the L5/S1 level will have 16.7% error ((6 cm - 5 cm) / 6 cm = 0.167); if he is assumed to have a 5 cm ESMLA distance. However, if the average value (5.71 cm) for the L5/S1 disc is used rather than 5 cm, the error will reduce to 4.8% ((6 cm - 5.71 cm) / 6 cm = 0.048%).

Table 3.21 also provides the percent reduction in error terms. For female subjects, the error associated with using a fixed number for all IVD levels was the same as using mean values provided in the present study. It is because the average ESMLA values were closer to the fixed ESMLA distance of 5 cm. However, the percent errors dramatically reduced for male subjects; 11.3% to 6.1% at the L3/L4 level, 9.8% to 6.0% at the L4/L5 level, and 12.4% to 7.0% at the L5/S1 level. It can be concluded that the error increases when an individual's ESMLA distance is departing from the fixed 5 cm value.

**Morphometric changes with the scanning posture**

The posture in which MRI scans are taken is very important for the geometry of musculoskeletal structure at the low back (McGill *et al.*, 1996; Seo *et al.*, 2003). MRI scans were taken with subjects lying in a supine position due limitation in the physical design of MRI equipment. However, most MMH activities involve a standing posture and flexion and/or extension of torso. The geometry and locations of soft tissues (i.e., muscle, fat, facia, etc.) may shift from the supine posture to the standing posture (Kumar, 1988; McGill *et al.*, 1993). In the literature, it is indicated that the ESMLA at the L3 vertebral level can increases 3% in males and 12% in females when in a standing posture compared to the supine posture (McGill *et al.*, 1996). This may be the result of changing lumbar curvature and/or gravity acting upon the internal visceral structures (Jorgensen and Smith, 2006). Jorgensen and Smith (2006) indicated that the mean L1/S1 lumbar curvature increased significantly when transiting from a supine posture to standing. It should be noted that muscles in the supine posture are relaxed or inactive compared to standing or bending postures.

Note that subjects could be positioned in a supine posture with a cushion under the legs (knee extended) or in an (anatomically) neutral position which is defined as supine lying with the knees extended. Arms could be extended above the head or on sides. Subjects could be positioned in prone posture, as well. All these postures may result in different ESMM size and ESMLA distance measurements.

Torso angle also affects the muscle geometry of the lumbar back (Tveit *et al.*, 1994; Jorgensen *et al.*, 2003a; Jorgensen *et al.*, 2003b; Anderson *et al.*, 2012). Tveit *et al.* (1994) indicated that lordotic subjects had approximately 10-24% longer ESMLAs than kyphotic subjects.

Table 3.21: Absolute differences and error percentages in the ESMLA distances

| | | | | **Differences (cm)** | | **% Error** | |
|---|---|---|---|---|---|---|---|
| | | **N** | **Mean** | **Δ1 (5 cm)** | **Δ2 (Av.)** | **Δ1 (5 cm)** | **Δ2 (Av.)** |
| **L3/L4** | Female | 75 | 5.09 | 0.34 | 0.34 | 6.7 | 6.7 |
| | Male | 80 | 5.60 | 0.63 | 0.34 | 11.3 | 6.1 |
| | Total | 155 | 5.35 | 0.49 | 0.34 | 9.2 | 6.4 |
| **L4/L5** | Female | 72 | 5.00 | 0.32 | 0.32 | 6.4 | 6.4 |
| | Male | 64 | 5.52 | 0.54 | 0.33 | 9.8 | 6.0 |
| | Total | 136 | 5.24 | 0.42 | 0.32 | 8.0 | 6.1 |
| **L5/S1** | Female | 57 | 5.10 | 0.36 | 0.36 | 7.1 | 7.1 |
| | Male | 51 | 5.71 | 0.71 | 0.40 | 12.4 | 7.0 |
| | Total | 108 | 5.39 | 0.53 | 0.38 | 9.8 | 7.1 |
| **Total** | Female | 204 | 5.06 | 0.34 | 0.34 | 6.7 | 6.7 |
| | Male | 195 | 5.60 | 0.62 | 0.35 | 11.1 | 11.1 |
| | Total | 399 | 5.33 | 0.48 | 0.35 | 9.0 | 6.6 |

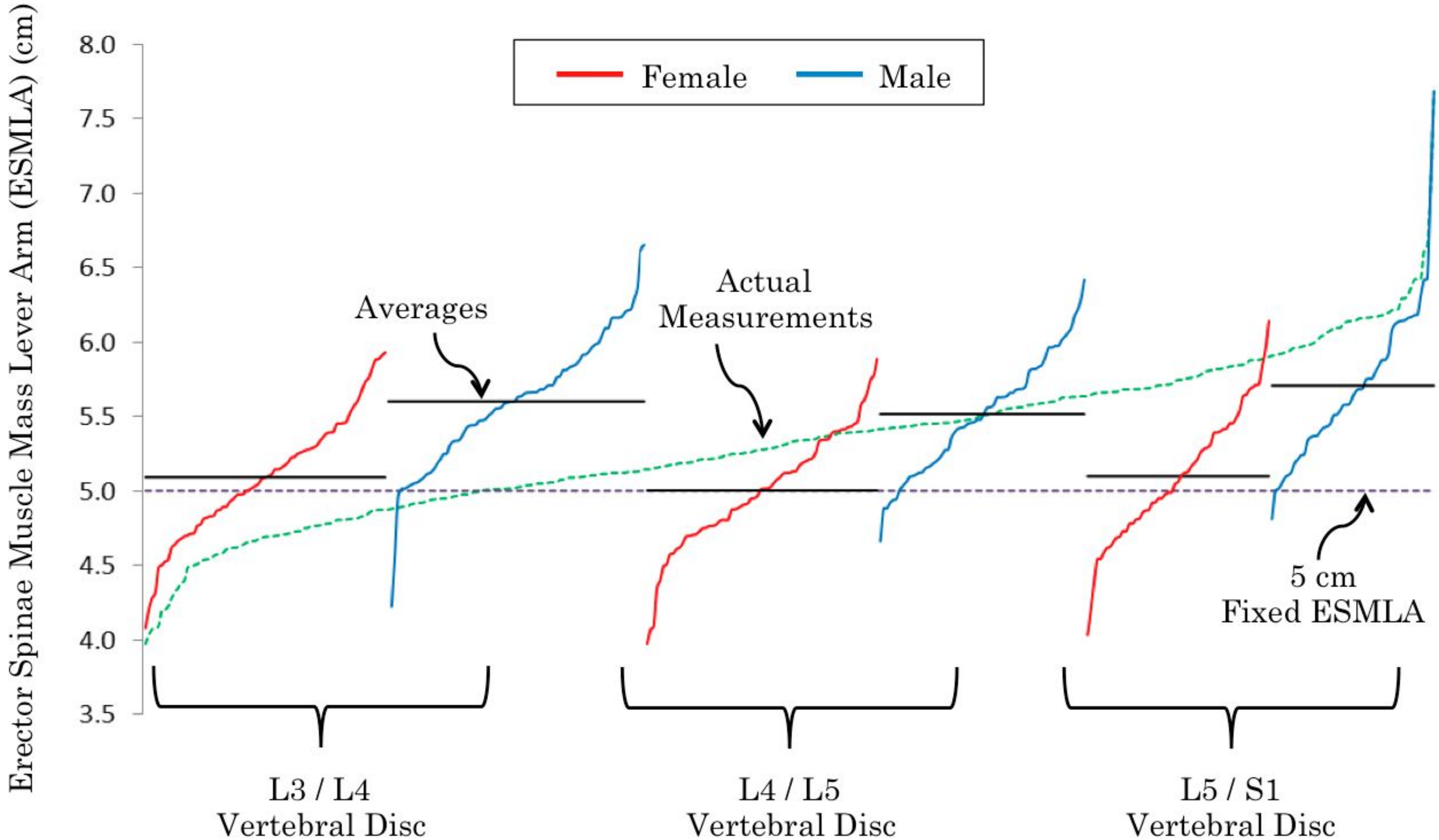



Figure 3.12: Comparisons of using a fixed ESMLA distance (5 cm) with average ESMLA distances for each gender and each IVD level

The CSA of the ESMM increases with extension and decreases with flexion (Jorgensen *et al.*, 2003a; Jorgensen *et al.*, 2003b; Watanabe *et al.*, 2004; Masuda, Miyamoto, Oguri, Matsuoka, and Shimizu, 2005). The angles of the muscle fibers also change with posture (McGill, Hughson, and Parks, 2000). Therefore, muscle geometry obtained from supine MRI scans may need to be adjusted for application to upright postures (McGill *et al.*, 1993; McGill *et al.*, 1996; Anderson *et al.*, 2012). The results of the present study are limited to the supine posture. The results of the present study may be corrected by implementing the correction factors provided by previous studies to transform from supine posture to standing posture (McGill *et al.*, 1996; Jorgensen *et al.*, 2006).

### 3.5 Conclusion

The objective of the present study was to perform a morphological analysis of low back musculoskeletal structure to provide reliable and generalizable inputs for biomechanical models so that they may better estimate forces and moments on the lumbar spine. Better force and moment estimations are very critical to understanding low back forces and underlying injury mechanisms which may help prevent or minimize low back pain (LBP) injuries. The cross-sectional areas (CSA) of the erector spinae muscle mass (ESMM) and inter-vertebral disc (IVD) and the length of the erector spinae muscle mass lever arm (ESMLA) were measured using magnetic resonance imaging (MRI) scans. MRI scans provide higher soft tissue resolution compared to computed tomography (CT) and ultrasonography (US), and MRI technology is safer since it does not produce biological hazards such as ionizing radiation. MRI scans are more reliable than manual tape measurements on cadavers, as well. T2-weighted standard soft-tissue MRI scans were taken using a 1.5 Tesla MRI scanner in the present study.

An architectural design software, Rhinoceros, was used to measure CSAs and ESMLAs. The software was programmed to compute the areas and centroid points of the irregular shapes of IVDs and ESMMs. Therefore, compared to simple measurement techniques such as the visual determination of centroids, more reliable and repeatable measurements were gathered in the present study.

Reproducibility tests indicated that the agreement between two researchers who measured morphological structure from 40 randomly selected subjects was high. Inter-rater reliability correlation coefficients were ranging from 0.811 to 0.997. This indicates that the suggested methodology is highly reliable and repeatable by different researchers. Intra-reliable correlation coefficient were excellent (ranging from 0.968 to 0.998) (for interpretation basis, see Table 3.5), which means that the same researcher can get the same (or very close) number while measuring the same subject again. It also suggest that the reliability of the measurement technique is high.

A total of 163 subjects (82 male and 81 female) were included in the present study. Since the present study includes a larger sample size compared to other studies in the literature, the results will likely provide more sensitive data with smaller confidence intervals. The average age was 30.1 (5.5) years for males and 29.6 (5.6) years for females. The average height was 178.78 (8.8) for males and 165.4 (8.9) for females. The average weight was 85.7 (19.8) kg for males and 76.5 (20.0) kg for females. Males were significantly taller and heavier than females. Anthropometric statistics from the U.S. general adult population are very similar to the subjects of the present study. The average height and weight in the U.S. adults were 176.02 cm and 88.68 kg for males and 162.05 cm and 73.57 kg for females (NCHS, 2012b).

Male CSAs of the ESMM and IVD were larger than female subjects at all disc levels. Male CSAs of the ESMM decreased with disc level. The largest male muscle CSAs were at the L3/L4 level and the smallest at the L5/S1 level. On the other hand, the largest female muscle CSAs were at the L5/S1 level and the smallest at the L3/L4 level. The difference between genders could be explained by the physiological differences between males and females. The lumbar curvature and pelvic angle are larger in female subjects than male subjects. CSAs of IVD were the largest at the L3/L4 level and the smallest at the L5/S1 level for both genders. Figure 3.13 (for females) and 3.14 (males) summarize the findings of the present study.

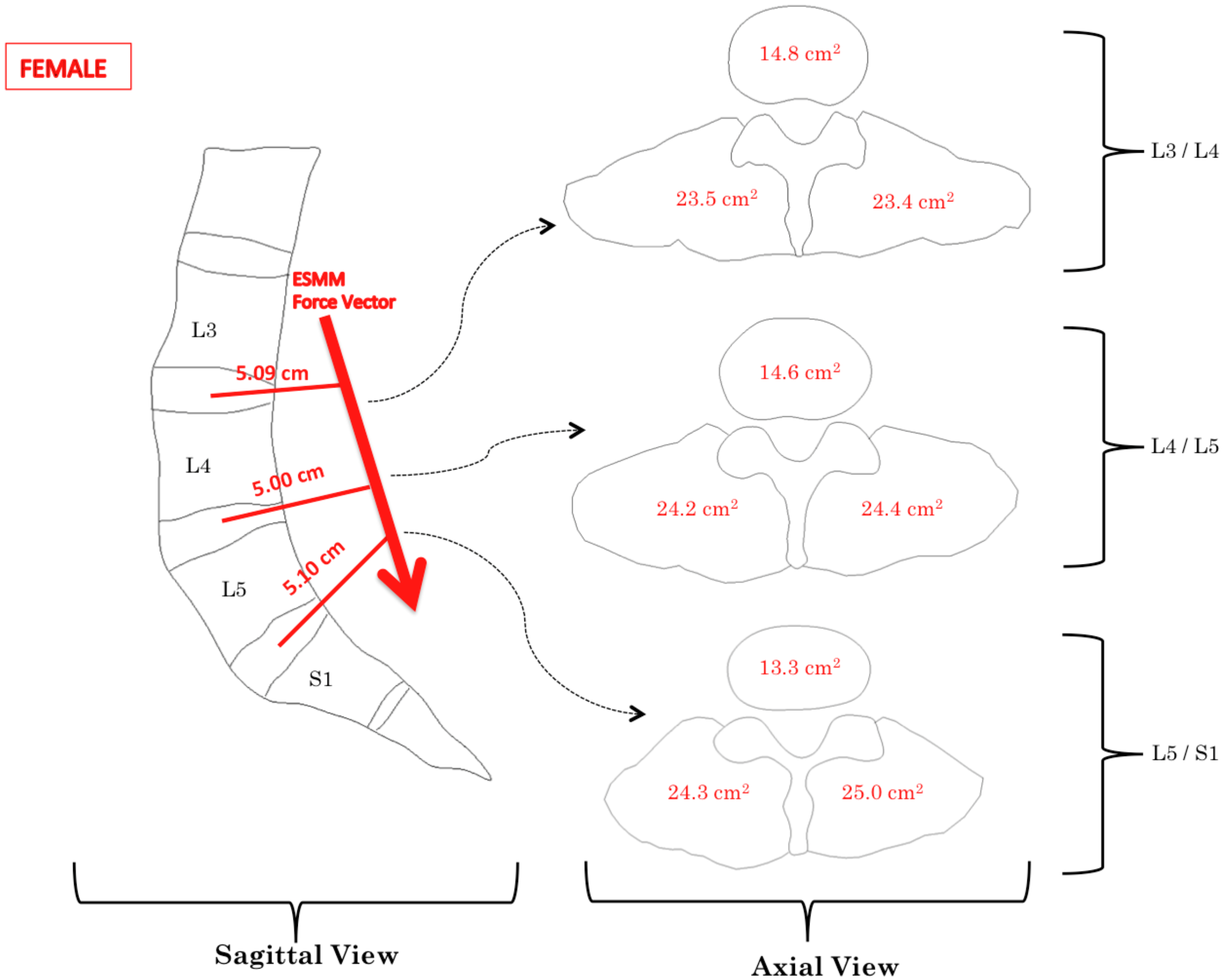



Figure 3.13: Figure representation of the female results of the present study

The ESMLA distance is typically assumed to be a fixed value (5 cm or 2 in) in biomechanical models regardless of subject variables. The ESMLA distances were measured as 5.09, 5.00, and 5.10 cm for females, 5.60, 5.52, and 5.71 cm for males at the L3/L4, L4/L5, and L5/S1 levels, respectively. The results of the present study found that gender affects the length of ESMLA distances. The present study suggests using a separate ESMLA distance for each disc level and each gender rather than a fixed length (5 cm).

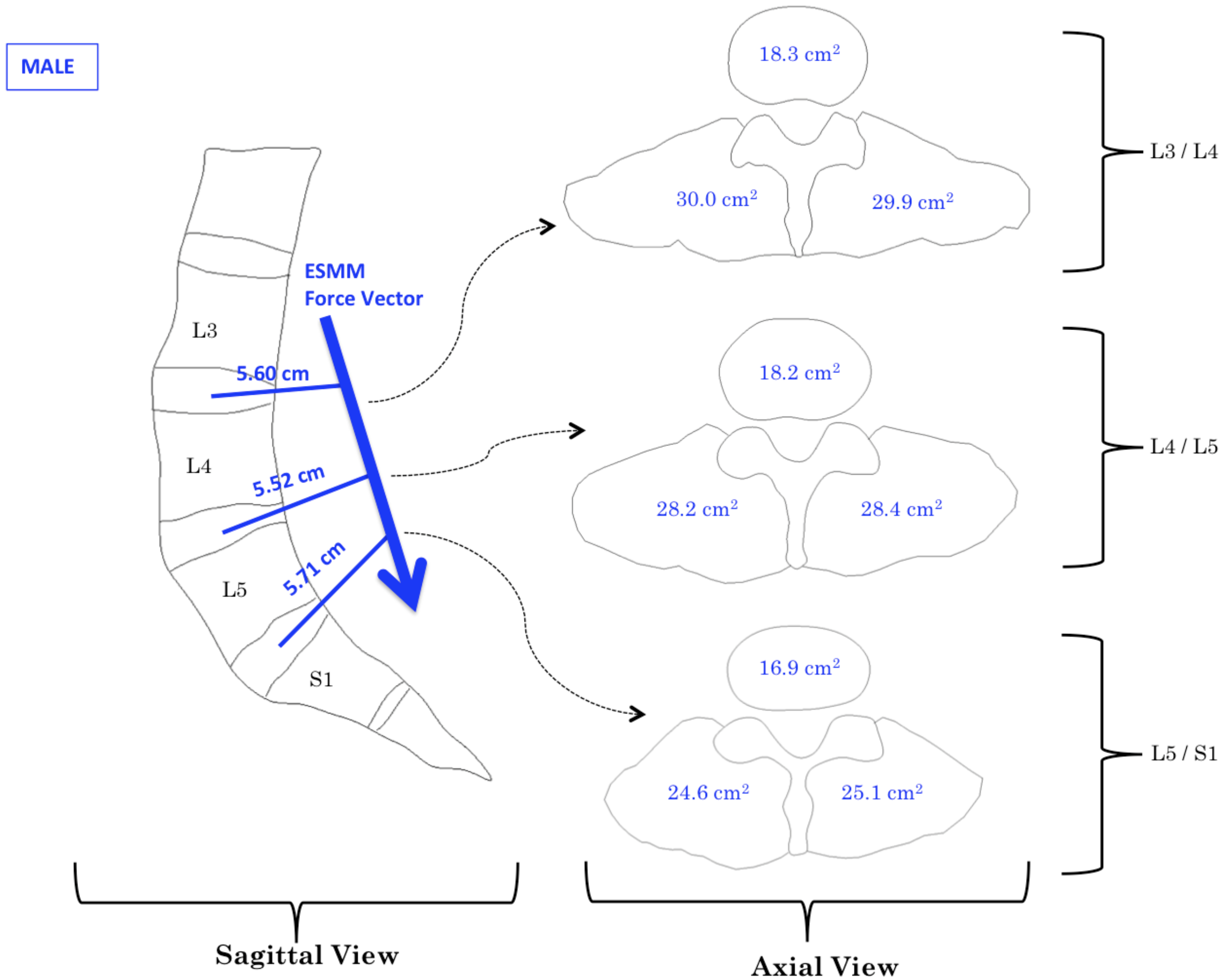



Figure 3.14: Figure representation of the male results of the present study

Using the average value for a specific gender and IVD level decreases the average absolute error. If the average value is used rather than the historical fixed number (5 cm), the absolute error is reduced from 11.3% to 6.1% at the L3/L4 level, 9.8% to 6.0% at the L4/L5 level, and 12.4% to 7.0% at the L5/S1 level for males. These values are for the averages, however, the error term is very high when considering subjects on an individual basis. For example, the error term for a male subject having a 7.0 cm ESMLA distance is 28.6%. The error increases significantly when an individual's actual ESMLA distance is further from the average. Forces and moments for this subject therefore might be overestimated approximately 28.6%. On the other hand, forces and moments for a subject with a smaller ESMLA distance will be underestimated.

The present study proposed to address the limitations of previous studies and provide data for CSAs of ESMMs and IVDs and ESMLA distances which could be generalizable to wider populations. However, it should be noted that the data provided in this chapter is gender and IVD level specific, not subject specific! It only provides a mean value for a gender at a specific IVD level. To be able to estimate an individual's low back morphometry, regression models could be used. In Chapter 4, the present study addresses this problem by providing subject specific regression models. Subject specific regression models may provide better estimates for the actual low back geometry. The closer the back geometry is estimated, the more reliable the ergonomic task assessment tools (relying on these geometries) will be.

Future studies might investigate the relationship between the lumbar curvature and subject variables such as gender, height, and weight to better understand the gender effect on the low back structure. Future studies might also investigate dominate and non-dominant hand sides as the difference between right and left CSAs as this phenomenon is likely due to asymmetric loading of the body. Since most subjects are right hand dominant the left side low back musculature would likely be more developed particularly for subjects who wield tools primarily in one hand.

Chapter 4

# PREDICTION OF THE ERECTOR SPINAE MUSCLE MASS LEVER ARM (ESMLA) DISTANCE: REGRESSION MODELS FOR HISTORICAL DATA POPULATIONS

## 4.1 Introduction

Low back pain (LBP) is associated with forces and moments loading the spine (Chaffin *et al.*, 2006; Marras, 2008). To accurately calculate forces and moments and assess a manual material handling (MMH) task (i.e., lifting) in terms of the LBP risk, morphological data of the musculoskeletal structure at the low back region is required. The accuracy and reliability of morphological data such as the cross-sectional area (CSA) of the erector spinae muscle mass (ESMM) and the erector spinae muscle mass lever arm (ESMLA) distance is required. Morphological data of an individual can be used to calculate forces and moments and assess LBP risk for this specific individual. Using a fixed number or an average number for an entire population results in probably higher error in calculations, particularly for those who are further from the fixed or average value (tolerance of the spine is also necessary). For example, the ESMLA distance is typically assumed to be a fixed value (5 cm or 2 in) in some biomechanical models regardless of subject characteristics (Chaffin, 1969; Poulsen, 1981; McGill and Norman, 1985; Kumar, 1988; Ayoub and Mital 1989; Garg, 1997; Merryweather *et al.*, 2009), which results in "overestimation" of forces and moments and LBP risk for subjects with larger ESMLA distances and "underestimation" of forces and moments and LBP risk for subjects with smaller ESMLA distances. To minimize over and under estimation of forces and moments, individualized model parameters could be included in biomechanical models.

The relationship between the muscular morphology at the low back region [**the CSA of ESMM** (Reid *et al.*, 1987; McGill *et al.*, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990;

Cooper *et al.*, 1992; Wood *et al.*, 1996; Marras *et al.*, 2001; Jorgensen *et al.*, 2003a; Seo *et al.*, 2003; Lee *et al.*, 2006; Anderson *et al.*, 2012) and **the ESMLA distance** (Reid and Costigan, 1985; Reid *et al.*, 1987; Kumar, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990; Moga *et al.*, 1993; Wood *et al.*, 1996; Jorgensen *et al.*, 2001 and 2003b; Seo *et al.*, 2003; Lee *et al.*, 2006; Anderson *et al.*, 2012)] and subject variables such as subject's gender, age, height, and weight have been studied for several decades to understand the variation among the measurements and develop subject specific estimation models.

**Prediction models for the cross-sectional area (CSA) of the erector spinae muscle mass (ESMM)**

The force producing capacity of a muscle is associated with its size (Farfan, 1973; Reid and Costigan, 1987; McGill *et al.*, 1988; Marras and Sommerich, 1991; Bogduk *et al.*, 1992; Parkkola *et al.*, 1992; Davis, Marras, and Waters, 1996; van Dieen, 1997; Gatton *et al.*, 1997; Delp *et al.*, 2001; Daggfeldt and Thorstensson, 2003; Hansen *et al.*, 2006). The range of values for the ESMM contraction force per unit CSA is 10 to 100 N/cm$^2$ (McGill *et al.*, 1988; Marras and Granata, 1997; Daggfeldt and Thorstensson, 2003, Hansen *et al.*, 2006), but approximate mean values have been used in biomechanical calculations (for example, 34 N/cm$^2$ by Farfan (1973), 46 N/cm$^2$ by Bogduk *et al.* (1992) and van Dieen (1997), 48 N/cm$^2$ by Reid and Costigan (1987), 50 N/cm$^2$ by McGill *et al.* (1988)).

In biomechanical modeling, the CSA of a muscle must be known to estimate the force capacity of the muscle. Schultz, Andersson, Haderspeck, Ortengren, Nordin, and Bjork (1982) calculated the CSA of the ESMM at the L3 vertebral level by multiplying the product of the trunk cross-section depth and width with a constant value of 0.0389 (this means the CSA of the ESMM is 3.89% of the trunk area). They assumed that an individual's trunk muscles are proportional to their trunk. Marras and Sommerich (1991) designed 3D motion model of the trunk. They also multiplied the trunk area (trunk area = trunk breadth*trunk depth) with the constant of 0.0389 to calculate the CSA of ESMM.

Marras and Sommerich (1991) cited Schultz *et al.* (1982) for the constant. Note that Marras's and Sommerich's (1991) model was designed for the L5 vertebral level while Shultz *et al.*'s (1982) model was designed for the L3 vertebral level.

Reid and colleagues (1987) conducted an MRI study with 20 young ($\bar{x}$ = 21.2 years) healthy males to determine the anthropometric parameters that are correlated with and capable of predicting the CSA of the ESMM. They took 27 anthropometric measurements including height, weight, and seated height. Information about subject anthropometrics, muscle sizes, and lever arm distances for the same study sample (the same 20 male subjects) can be found in their later study (Reid and Costigan, 1987). They found a significant correlation between the CSA of the ESMM and subject weight (r = 0.64), but not for height (r = 0.12). It should be noted that they selected the significance probability (p-value) for the correlation coefficient as 0.15 rather than the conventional value of 0.05. They also performed regression analyses and provided a regression equation for the CSA of ESMM at the L5 vertebral level (Table 4.1). The subject's weight and some other measurements (e.g., circumference of upper arm, trunk circumference at the ilium, etc.) were included in this regression model, but height was not included. Their small age range (17-25 years old) did not permit them to address the effect of subject age on ESMM size. They also could not address potential gender effects on the ESMM size since they studied only male subjects.

With a CT study, McGill *et al.* (1988) provided descriptive statistics for the CSA of the ESMM at the L4/L5 IVD level for 13 male subjects who were healthy, but suspected of LBP. They sought to determine the relationship between the ESMM size and individual variables (height, weight, and height*weight) with a multiple regression model; however, they could not find any significant regression model for the entire ESMM and its individual muscles (multifidus and sacrospinalis). They did not include age in the model. They mentioned that they had a small sample size to determine the variation in measurements and suggested using a larger sample size for future studies.

Tracy *et al.* (1989) had 26 male subjects with LBP. They measured the CSA of the right ESMM on transverse MRI scans, which means that scans were not necessarily parallel to the IVDs. They used trunk depth, trunk width, the product of trunk depth and width, height, weight, and an "index of fat" in their regression models. They did not develop multiple regression models, but preferred using simple regression models that have only one independent variable in model, in addition to a constant. The results of this simple regression analyses did not find any significant variable that can explain the variation in CSA measurements. They suggested using skinfold measurements in future studies.

Among subjects included in an osteoporosis study, Chaffin *et al.* (1990) selected 96 LBP-free subjects for their low back morphometry study. Their subjects were middle aged ($\bar{x}$ = 49.6 years). Lexell *et al.*,1988, Brooks and Faulkner, 1994, and Faulkner *et al.*, 2007 reported an association between a decrease in the muscle mass and aging. Age related muscle atrophy might be suspect in Chaffin *et al.*'s (1990) study, as well. Chaffin *et al.* (1990) performed correlation analyses between the CSA of ESMM and independent variables (height, weight, trunk area as a function of trunk depth and width, and all combinations of these variables including second order models with interactions). The outcomes with the highest correlations were chosen for their regression analyses. Chaffin *et al.* (1990) provided two alternative regression models for predicting the CSA of ESMM (Table 4.1). The first model has height and weight independent variables and the second model is a simple model with only torso area as the independent variable. Note that both models had very small coefficient of determination values ($R^2$); 0.26 and 0.12, respectively even though they were statistically significant.

The effect of gender on the ESMM dimensions at the L4 vertebral level was investigated by Cooper *et al.* (1992). They took CT scans from 92 LBP patients (39 females and 53 males) in a neutral posture with no cushioning under their knees. They had statistically heavier male subjects in their study. They found significant correlations between subject's weight and the CSA of the ESMM (correlation coefficients were 0.68 for females and 0.61 for males). They indicated that the CSA of ESMM increases 0.18 $cm^2$ per kg for both genders. Instead of providing a regression model, they provided a figure demonstrating the effect of subject weight on the ESMM size (Figure 4.1) at the L4 vertebral level. By looking at the figure, it can be estimated that female subjects had approximately 16 $cm^2$ ESMM if they were 40 kg, and their ESMM size increased by 0.18 $cm^2$ per additional kg. Male subjects had the same constant (slope) value (0.18 $cm^2$ increase per kg) but they had larger CSAs (approximately 2 $cm^2$) for a given weight. They did not include subject height in the study, and did not investigate the effect of the subject's age on the ESMM size. Emphasizing that female subjects had wider pelvises and more exaggerated lumbar lordosis, they concluded that gender should be taken into consideration to determine the ESMM size.

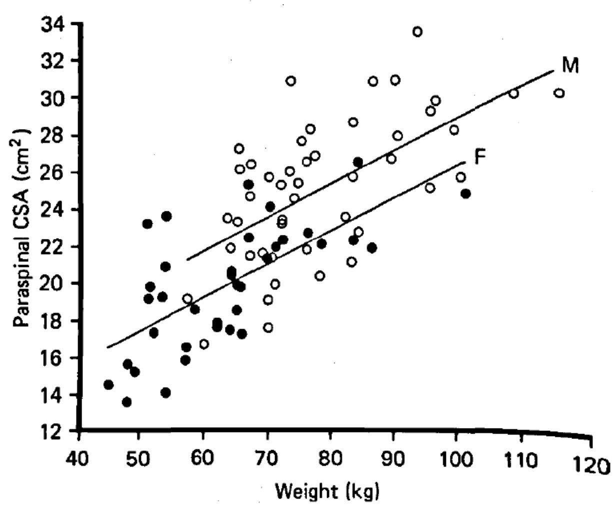



Figure 4.1: The correlation between the CSA of the ESMM and subject weight
Retrieved from Cooper, R. G., Holli, S., and Jayson, M. I. V. (1992). Gender variation of human spinal and paraspinal structures. Clinical Biomechanics. 7(2): 120-124.

Wood *et al.* (1996) studied 26 male subjects to compare lean and obese groups in terms of ESMM sizes. They computed the CSAs of ESMM at L4/L5 IVD level from transverse MRI scans. Statistical analyses did not find any significant difference between BMI categories. After normalizing of muscle CSAs by dividing the CSA by the trunk CSA, they compared BMI categories and found that the CSA of ESMM was significantly smaller among the obese subjects compared to the lean subjects. However, they could not derive any regression model from the anthropometric variables to estimate the ESMM size. Their anthropometric measurements included height, weight, skinfold thicknesses at triceps, biceps, chest, subscapular, iliac crest, rib, thigh, and calf and circumference measurements at arm, chest, hip, thigh, calf, and waist at the umbilicus level, and several ratios derived from these measurements. Further descriptives about their anthropometric measurements can be found in an earlier study (Ross, Leger, Morris, de Guise, and Guardo, 1992).

An MRI study with 10 males and 20 females was conducted by Marras *et al.* (2001) to develop a gender specific database of trunk musculature and develop prediction equations for muscle sizes as a function of gender and anthropometry. They measured the CSA of ESMM from transverse scans that were taken from subjects in a supine posture with extended knees. They converted CSAs (obtained from transverse images) to physical-CSAs (PCSA) by using the same correction angles for both genders. They performed regression analyses to estimate CSAs of the ESMM by using subject's weight, ratios of height to weight and weight to height. Even though they found that male subjects had significantly larger CSAs than female subjects, they did not include gender in the regression model. Instead, they provided three alternative regression equations for each gender and each muscle side (the left and right ESMM) (Table 4.1). All of their regression equations were statistically significant.

Jorgensen *et al.* (2003a) conducted an MRI study with 12 male and 12 female subjects. The objective of the study was to determine the effect of torso flexion on lumbar muscle CSAs. They took transverse MRI scans with subjects lying on their left sides with different torso angles. Raw CSA measurements were corrected. Note that the lumbar erector spinae fascicle orientation data utilized to convert the CSA to the PCSA (these researchers referred to it as anatomical cross-sectional area, ACSA) were based on male data available in the literature. They were not sure if significant gender differences exist with regard to fascicle orientations and fascicle orientation. Since their subjects were lying on their left sides, they measured the CSAs on the subject's right sides (therefore, they minimized the changes in muscle shapes resulted from body weight loading). They performed regression analyses to determine the relationship between the ESMM size and independent variables including subjects anthropometrics such as weight, product of height and weight, trunk circumference, trunk depth and width at xyphoid process and iliac crest. In addition to external anthropometric variables, they included internal variables such as the segmental lordosis, L1/L5 lordosis, and L1/S1 lordosis. They found that male subjects had significantly larger ESMM CSAs than female subjects. Regression equations for the lower lumbar IVD levels are provided in Table 4.1.

An MRI study by Seo *et al.* (2003) investigated the relationship between independent subject variables such as subject's age, height, weight, and interaction terms of these variables up to third-order and the size of ESMM at the L3/L4 IVD level. They had a large sample size (152 males and 98 females) of Japanese healthy subjects. They first checked the correlations between the CSA of ESMM and subject variables including age, height, and weight. The results showed that the CSA of ESMM was significantly correlated with subject weight for both genders (0.576 for males and 0.465 for females). Height was significantly correlated with male CSAs (0.285), but not with female CSAs. They also performed forward method multiple regression analyses. Each high-order polynomial equation was limited to one intercept and a maximum of two independent variables. They provided one significant regression model for each gender. Subject weight was the only estimator parameter explaining the variation among the ESMM CSA for both models (Table 4.1).

Lee *et al.* (2006) conducted an MRI study with Korean female patients. Seventeen of them were lumbar degenerative kyphosis (LDK) patients and 17 of them were control group with spinal stenosis and/or herniated disc. They used transverse scans of patients at the L4/L5 level. They did not include the multifidus muscle in the ESMM, resulting in a smaller ESMM CSA as compared with other studies. The objective of their study was to investigate the relationship between the CSA of the erector spinae muscle and subject's BMI. LDK patients had significantly smaller erector spinae CSAs than the control group. Spearman's rho correlation analyses showed a significant correlation between the BMI and CSA in the LDK group (0.49, $p = 0.046$), but not for the control group (0.449, $p = 0.071$). They did not provide any regression model to estimate the CSA of the erector spinae muscle.

A recent CT study by Anderson *et al.* (2012) was conducted to estimate muscle parameters including the CSA of muscles. Authors measured transverse scans from T6 to L5 vertebral level. They converted the results of raw CSAs obtained from transverse scans into anatomical (also called physiological) CSAs by multiplying the raw CSA of a specific muscle with the cosine of the line-of-action retrieved from the literature. They did not include the transversospinalis muscles (including multifidus) into the ESMM, which results in smaller CSAs than other researchers who included the entire muscle mass in the ESMM. Note that the ESMM can be calculated if the CSAs of the erector spinae group muscles and transversospinalis group muscles are summed. They had to exclude larger subjects from the study due to the limited CT image field. They had relatively older subjects (51 males, mean age 59.4 years old and 49 females, mean age 58.1 years old). They included subject gender, age, height, and weight in regression equations even though some of these variables were not significant. Their results suggested that the subject gender had significant effect on the erector spinae muscle size at the L2 and L3 levels. There was also significant association between the size of the erector spinae and the subject's weight at L2, L3, and L4 vertebral levels. The results of the raw CSA of the erector spinae muscle are given in Table 4.1. The regression models at L3 and L4 levels were significant, which means the variation in the measurements could be explained by predictor variables (gender, age, height, and weight). However, the regression model to estimate the CSA of the erector spinae muscle at L5 was not significant.

Table 4.1: Prediction equations for the CSA of ESMM reported by various authors

| Study | Subjects | Age | Height | Weight | Level | Regression equations for the CSA of the ESMM | $R^2$ | S.E. | p-value |
|---|---|---|---|---|---|---|---|---|---|
| Schultz *et al.* (1982) | - | - | - | - | L3 | = 0.0389*(TD*TW) | - | - | - |
| Reid *et al.* (1987) *(MRI, Healthy)* | 20 Male | 21.2 | 176.9 | 69.7 | L5 | = 54.38 + 1.00*(W - 69.79) + 1.91*(IC - 79.07) + 2.90*(ARM - 30.01) - 3.14*(CHW - 29.12) + 5.95*(ABLW - 27.33) - 2.39*(XIPSPL - 37.45) | 0.77 | - | - |
| McGill *et al.* (1988) *(CT, Supine, LBP)* | 13 Male | 40.5 | 173.8 | 89.1 | L4/L5 | Could not find any regression model for H, W, and H*W | - | - | - |
| Tracy *et al.* (1989) *(MRI, Supine, LBP)* | 26 Male | - | - | - | L2-S1 | Could not find any regression model for H, W, TD, TW, TD*TW, and IF | - | - | - |
| Chaffin *et al.* (1990) *(CT, Supine, Healthy)* | 96 Female | 49.6 | 163.1 | 67.6 | - | = 6.7 + 0.1166*W + 0.017*H | 0.26 | 14% | 0.001 |
| | | | | | | = 14.7 + 0.0065*TA | 0.12 | 16% | 0.001 |
| Marras and Sommerich (1991) | - | - | - | - | L5 | = 0.0389*(TD*TW) | - | - | - |
| Cooper *et al.* (1992) *(CT, LBP)* | 39 Male | 38 | - | 75 | L4 | [Approximate equation] = 16 + 2*G + 0.18*W | - | - | - |
| | 53 Female | 39 | - | 64 | | | | | |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | L4/L5 | Could not find any regression model for anthropometric measurements | - | - | - |
| Marras *et al.* (2001) *(MRI, Supine, Healthy)* | 10 Male | 26.4 | 175.9 | 79.8 | Left | = 6.86 + 0.24*W | 0.58 | 2.87 | 0.0103 |
| | | | | | | = 53.65 - 12.34*(H/W) | 0.62 | 2.72 | 0.0065 |
| | | | | | | = 0.106 + 57.28*(W/H) | 0.59 | 2.85 | 0.0098 |
| | | | | | Right | = 9.27 + 0.209*W | 0.47 | 3.12 | 0.0283 |
| | | | | | | = 50.7 - 11.04*(H/W) | 0.53 | 2.94 | 0.0166 |
| | | | | | | = 2.83 + 51.16*(W/H) | 0.50 | 3.04 | 0.0225 |
| | 20 Female | 25.0 | 165.5 | 57.9 | Left | = -7.51 + 0.408*W | 0.61 | 2.15 | 0.0001 |
| | | | | | | = 38.21 - 7.65*(H/W) | 0.54 | 2.34 | 0.0002 |
| | | | | | | = -8.12 + 69.25*(W/H) | 0.61 | 2.15 | 0.0001 |
| | | | | | Right | = -12.34 + 0.492*W | 0.69 | 2.19 | 0.0001 |
| | | | | | | = 43.72 - 9.54*(H/W) | 0.65 | 2.32 | 0.0001 |
| | | | | | | = -13.78 + 85.55*(W/H) | 0.72 | 2.07 | 0.0001 |
| Jorgensen *et al.* (2003a) *(MRI, Lying on side)* | 12 Male | 23.1 | 177.1 | 74.5 | L3/L4 | = -8.63 +3.7*G +0.001*H*W -0.02*(TD*TWI) +0.74*TWX +0.07*L1/L5 | 0.86 | 1.9 | 0.0001 |
| | 12 Female | 23.8 | 162.3 | 56.5 | L4/L5 | = -6.48 + 3.15*G + 0.29*W - 0.03*(TD*TWI) + 0.52*TWX + 0.08*L1/S1 | 0.85 | 1.8 | 0.0001 |
| | | | | | L5/S1 | = 14.29 + 0.002*(H*W) - 0.58*IC + 0.69*TWX + 0.13* L1/S1 | 0.73 | 2.3 | 0.0001 |
| Seo *et al.* (2003) *(MRI, Supine, Healthy, Japan)* | 152 Male | 36.2 | 168.5 | 65.5 | L3/L4 | = 5.32 + 0.284*W | 0.576 | 3.70 | 0.0001 |
| | 98 Female | 39.7 | 155.5 | 54.4 | L3/L4 | = 11.36 + 0.001912*$W^2$ | 0.469 | 2.73 | 0.0001 |
| Anderson *et al.* (2012) *(CT, Supine, Healthy)* | 51 Male | 59.4 | 177.6 | 81.3 | L3 | = 2.52 - 3.02*G - 0.0439*A + 0.048*H + 0.124*W | 0.55 | 3.19 | - |
| | 49 Female | 58.1 | 162.2 | 68.4 | L4 | = 4.97 - 1.19*G - 0.0234*A + 0.0198*H + 0.0808*W | 0.30 | 2.82 | - |
| | | | | | L5 | [Not sig.] = 8.54 + 0.37*G + 0.00953*A - 0.0437*H + 0.366*W | 0.04 | 2.55 | - |

G: Gender (0 for female, 1 for male); A: Age (year); H: Height (cm); W: Weight (kg); TD: Trunk depth (cm); TW: Trunk width (cm); TWI: Trunk width at iliac crest; TWX: Trunk width at xyphoid process; IC: Trunk circumference at ilium; ARM: Circumference of upper arm (straight); CHW: Width at chest; ABLW: Abdominal's least width; XIPSPL: Vertical length the xyphoid process to the symphysis pubis; IF: Index of fat; TA: Torso area ($cm^2$);

All these studies discussed above indicate that the ESMM size can be estimated by some subject variables (i.e., gender, age, height, weight). However, their methodologies, muscle definitions, and study populations should be carefully evaluated before using their prediction models. For example, studying with small sample sizes may mislead the results and conclusions of a study, which results in some suspects with the generalizability to all populations.

**Prediction models for the erector spinae muscle mass lever arm (ESMLA) distances**

Schultz *et al.* (1981; 1982) designed a three-dimensional model to estimate loads on the lumbar spine (particularly, on the L3 vertebral level) in tasks involving bending and twisting. They assumed that the ESMLA in the sagittal plane is a proportion (22%) of the trunk depth. For example, they provided an example of a non-symmetric weight holding task and assumed a person had a trunk depth of 20 cm, which yields a 4.4 cm sagittal plane ESMLA distance. Marras and Sommerich (1991) also, based on Schultz *et al.* (1981; 1982), used the same multiplier (22%) for their three-dimensional motion model. However, their model estimated the loads at the L5 vertebral level while Schultz *et al.* (1981; 1982) estimated the loads at the L3 vertebral level.

A CT study with 28 older subjects (16 males and 12 females) was conducted by Reid and Costigan (1985). They concluded that there was no difference in terms of the ratio of ESMLA distance to the anterior-posterior trunk depth. However, they provided two different ratios for both genders (29.3% for males and 28.0% for females). They took transverse CT scans from the xyphoid process to the symphysis pubis and measured the trunk depth at the L5 vertebral level. Note that they had 28 subjects but they included fewer subjects (10 males and 5 females) in their ratio calculations. They concluded that the length of ESMLA was 29% of the trunk depth for "adults."

Reid *et al.* (1987) studied 20 young ($\bar{x} = 21.2$ years) healthy males in their MRI study to investigate the relationship between the anthropometric parameters and the ESMLA distance using 27 anthropometric measurements. It should be noted that they measured the ESMLA distance only at the L5 vertebral level. They determined the centroid of ESMM by drawing axes from the furthest points of each muscle CSAs. They found significant correlations between the ESMLA distance and subject height ($R^2 = 0.16$) and weight ($R^2 = 0.29$) using a p-value of 0.15 or smaller. However, neither height nor weight was in their prediction model (Table 4.2). Even though they mentioned that they performed a stepwise linear regression analysis by backward elimination, they provided the regression model with quadratic terms. They did not consider the effect of subject age on the ESMLA distance since their age range was very small, 17-25 years old. Since they had only male subjects, they also could not address any gender effect on the ESMLA distance.

A CT study by Kumar (1988) included relatively older subjects who were medical patients but did not have LBP. He had 21 male and 11 female subjects for the L3 vertebral level and 8 male and 5 female subjects for the L5 vertebral level. It should be noted that the transverse spinalis muscle group and the erector spinae group were presented in the report as if they were two different muscle groups. The ESMM term in this dissertation includes both muscle groups. Kumar (1988) conducted an ANOVA test to determine the effect of age on the ESMLA distance. Results did not suggest any significant difference between age groups. On the other hand, comparison of males and females revealed that the ESMLA distance was dependent on subject gender; males had larger ESMLA distances. However, gender was not included in the multiple regression model. There was no significant case of regression derived from height, weight, nor the product of height and weight (H*W).

Male LBP patients were studied by Tracy *et al.* (1989). Researchers measured the ESMLA distances on lumbar transverse images, which results in larger values than oblique images may provide. They also used visual determination of centroid points of the ESMM and IVD. Their independent variables were height, weight, trunk depth, trunk width, the product of trunk depth and trunk width, and an "index of fat" in simple regression models. They restricted the number of independent variables used in each regression model to one because they had limited sample size of 26 subjects. Results of their regression analyses did not find any significant relationships between independent variables and the ESMLA distance. They mentioned that the mean value of ESMLA was a better prediction than a function of trunk depth and width.

Chaffin *et al.* (1990) included 96 older female subjects in their CT study. They were interested in determining any significant relationship between the ESMLA and subject anthropometric measurements (height, weight, trunk area, trunk breadth, trunk depth, and combinations of these variables including second order models with interactions). They did not report any significant estimation model for the ESMLA distance.

Three-dimensional orientation of torso muscles including the ESMM was describe by Moga *et al.* (1993) using 11 male and 8 female patients. Researchers determined the centroids of the ESMM and IVD presumably drawing axes visually. To estimate the ESMLA distances, they provided two regression models for each gender. The first model had age, height, weight, and trunk depth and trunk width as independent variables while the second model did not have trunk depth and trunk width variables. It is assumed that their regression models are for the average of all these IVD levels (T10/T11 to L4/L5) since they did not specify the IVD level in the report. Note that they also did not provide any descriptive statistics about subject characteristics and anthropometrics.

The relationships between the ESMLA distance and anthropometric measurements including height, weight, skinfold measurements, limb and torso circumferences, and ratios between variables were investigated in an MRI study (Wood *et al.*, 1996). Transverse MRI scans were taken from 26 male subjects at the L4/L5 IVD level. Results of multiple regression models suggested that the ESMLA distance could be estimated using subject sitting height (Table 4.2). The objective of the study was to investigate the effect of obesity on muscle morphometry. However, there were no significant differences for the ESMLA distances between any BMI categories.

Jorgensen *et al.* (2001) conducted an MRI study with 10 males and 20 females to investigate the relationship between the ESMLA distance and subject external anthropometrics (21 independent variables) including height, weight, trunk depth and width at xyphoid process and iliac crest, and combinations of these measurements. They had transverse scans that were taken from subjects in a supine posture with extended knees. They adjusted all ESMLA measurements for the angle between the spinous process and the vertebral body. They indicated that male subjects had significantly larger ESMLA distances than female subjects. They did not include subject gender and age in their regression models. They found significant regression models for the left ESMLA distances at the L3 and L4 levels for males, but they did not find any significant regression model for the right ESMLA distances at the L3 and L4 levels. For females, it was opposite. They found significant regression models for the right ESMLA distances, but not for the left side. They could not find any regression model for both genders and both sides at the L5/S1 IVD level. Their regression models are provided in Table 4.2.

Jorgensen *et al.* (2003b) also conducted another MRI study. They included 12 males and 12 females to determine the effect of torso flexion on the magnitude of the ESMLA distance. Since they had transverse plane scans, they needed to correct their direct ESMLA measurements to oblique measurements. They applied male lumbar erector spinae fascicle orientation data to both genders for corrections. They suggested that there might be significant gender differences in the fascicle orientations. Since their subjects were lying on their left sides, they measured the ESMLA distances at the right side. They performed hierarchical linear regression analyses (forward selection) to determine the relationship between the ESMM size and independent variables including subject anthropometrics such as weight, product of height and weight, trunk circumference, trunk depths and widths at xyphoid process and iliac crest. In addition to these external anthropometric variables, some internal variables such as the segmental lordosis, L1/L5 lordosis, and L1/S1 lordosis were included in the analyses. Results suggested that male subjects had significantly larger ESMLA distances than female subjects (at least at the L4/L5 and L5/S1 levels). Regression equations are provided in Table 4.2. Note that the equations presented in Table 4.2 are not the original equations presented in Jorgensen *et al.* (2003b). These equations were modified with combining two models into one model and adding a constant for gender. Units were also changed from mm to cm.

An MRI study with a relatively large sample (152 Japanese males and 98 Japanese females) was conducted by Seo *et al.* (2003). They measured the ESMLA distances at the L3/L4 level by assuming the ESMM had an ellipsoid shape. It is presumed that they visually determined the centroid of the ESMM and IVD by drawing two axes since precise methods were not described in their publication. The multiple correlation coefficients of the ESMLA distance were small but significant. For males, age (0.232) and weight (0.250) were significant and for females hight (0.232) and weight (0.276) were significant. Their regression equations for estimating the ESMLA distances included all variables (age, height, and weight) for both genders are presented in Table 4.2.

Retrospectively sampled Korean patients in was included in Lee *et al.*'s (2006) MRI study. The ESMLA distances were measured from the centroid of the IVD to the centroid of the ESMM rather than the anterior-posterior distance, which resulted in larger ESMLA measurements. Their centroid determination method was based on the assumption that the IVD and ESMM had ellipsoid shapes and the intersection of long and short axes was the centroid point of the IVD and ESMM. They also did not include the multifidus muscle in the ESMM. Their results showed that the mean ESMLA distance of 17 LDK patients was significantly smaller than 17 control group who had spinal stenosis and/or disc herniation. Their objective was to determine the relationship between subject BMI and the lever arm distance of the erector spine muscle at the L4/L5 level. Correlations were significant for both groups (0.67, $p = 0.000$ for LDK group and 0.564, $p = 0.018$ for the control group), which means that subjects with higher BMIs were demonstrated to have larger ESMLA distances. They also provided regression models to estimate the ESMLA distances. However, their predictor variable was an interior measurement (the CSA of the erector spinae muscle) rather than externally measurable anthropometrics. Table 4.2 shows the relationship between the CSA of the erector spinae and the ESMLA distance.

Anderson *et al.* (2012) conducted a CT study with a relatively large (51 males, 49 females) sample. They had older subjects (males, mean age 59.4 years old and females, mean age 58.1 years old). Due to limitations of the imaging field, they could not scan the low back musculature of larger subjects. Transverse scans from T6 to L5 vertebral level were taken while subjects in supine posture with arms extended above the head. In addition to direct ESMLA measurements from transverse scans, they provided computed measurements that can be measured from oblique scans. They multiplied the direct measurements with the cosine of the angle between the normal to the scan plane and the muscle line-of-action obtained from the literature. They separated the transversospinalis muscle group (including multifidus) and the erector spinae muscle group. Therefore, direct comparisons between Anderson *et al.* (2012) and other studies including the present study might not be possible. They performed regression analyses to estimate the lever arm distance of the erector spinae muscle with independent variables (subject gender, age, height, and weight). Height was the only variable that was significant. This demonstrates that there was a significant association between subject height and the lever arm distance. They provided regression models that include all parameters in the model even though they were not significant. Other researchers may prefer running regression analyses with only height and presenting estimating models with only intercept and height parameters. The regression analyses to estimate "direct" lever arm distances are given in Table 4.2. Regression models were significant for all three lower vertebral levels (the L3, L4, and L5).

## Table 4.2: Prediction equations for the ESMLA distances

| Study | Subjects | Age | Height | Weight | Level | Regression equations for the ESMLA distance | $R^2$ | S.E. | p-value |
|---|---|---|---|---|---|---|---|---|---|
| Schultz *et al.* (1981; 1982) | - | - | - | - | L3 | = 0.22*TD | - | - | - |
| Reid and Costigan (1985) | 16 Male | 54.6 | 172.6 | 74.7 | L5 | = 0.280*TD | - | - | - |
| *(CT, Healthy)* | 12 Female | 52.1 | 159.4 | 63.8 | L5 | = 0.293*TD | - | - | - |
| Reid *et al.* (1987) | 20 Male | 21.2 | 176.9 | 69.7 | L5 | = 5.61 - 0.11*(CHW - 29.12) + 0.07*(ABLW$^2$ - 748.77) | 0.85 | - | - |
| *(MRI, Healthy)* | | | | | | - 0.34*(TRW - 30.82) + 0.21*(TRW$^2$ - 950.35) | | | |
| Kumar (1988) | 21 Male | 60.2 | 175.1 | 80.0 | L3 | Could not find any regression model for H, W, and H*W | - | - | - |
| *(CT, Supine,* | 11 Female | 62.0 | 158.2 | 68.7 | | | | | |
| *Patients)* | 8 Male | 57.7 | 178.3 | 82.6 | L5 | Could not find any regression model for H, W, and H*W | - | - | - |
| | 5 Female | 55.2 | 162.2 | 65.5 | | | | | |
| Tracy *et al.* (1989) | 26 Male | - | - | - | L2-S1 | Could not find any regression model | - | - | - |
| *(MRI, Supine, LBP)* | | | | | | for H, W, TD, TW, TD*TW, and IF | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | - | Could not find any regression model | - | - | - |
| *(CT, Supine, Healthy)* | | | | | | for H, W, TA, and all combination of these variables | | | |
| Marras and Sommerich (1991) | - | - | - | - | L5 | = 0.22*TD | - | - | - |
| Moga *et al.* (1993) | 11 Male | - | - | - | - | = 5.4 + 0.12*H + 0.23*W + 0.18*A + 0.001*TD + 0.01*TW | 0.26 | 0.86(cm) | - |
| *(CT, Patients* | | | | | | =-10.3 + 0.35*H - 0.02*W - 0.22*A | 0.23 | 0.74(cm) | - |
| *undertaken CT)* | 8 Female | - | - | - | - | = -6.1 + 0.12*H + 0.16*W - 0.25*A + 0.005*TD + 0.0005*TW | 0.91 | 0.31(cm) | - |
| | | | | | | = -9.3 + 0.3*H + 0.1*W - 0.22*A | 0.87 | 0.26(cm) | - |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | L4/L5 | = -4.332 + 0.104*SH | 0.446 | - | 0.001 |
| Jorgensen *et al.* (2001) | 10 Male | 26.4 | 175.9 | 79.8 | Left L3 | = 1.83 - 0.042*H | 0.475 | 0.43 | 0.0276 |
| *(MRI, Supine, Healthy)* | | | | | | = -9.3 - 12.8*(TDX/W) | 0.448 | 0.44 | 0.0344 |
| | | | | | Right L3 | Could not find any regression model | - | - | - |
| | | | | | Left L4 | = -2.33 - 0.046*H | 0.627 | 0.34 | 0.0064 |
| | | | | | | = -9.96 - 14.6*(TDX/W) | 0.652 | 0.33 | 0.0047 |
| | | | | | | = -4.1 + 0.01*(H*W) | 0.415 | 0.43 | 0.0445 |
| | | | | | Right L4 | Could not find any regression model | - | - | - |
| | | | | | Left L5 | Could not find any regression model | - | - | - |
| | | | | | Right L5 | Could not find any regression model | - | - | - |
| | 20 Female | 25.0 | 165.5 | 57.9 | Left L3 | Could not find any regression model | - | - | - |
| | | | | | Right L3 | = -2.48 - 0.043*W | 0.307 | 0.42 | 0.0113 |
| | | | | | | = -2.73 - 0.023*(H*W) | 0.313 | 0.42 | 0.0103 |
| | | | | | | = -7.72 + 0.79*(H/W) | 0.261 | 0.44 | 0.0213 |
| | | | | | Left L4 | = Could not find any regression model | - | - | - |
| | | | | | Right L4 | = -3.02 - 0.095*TDI | 0.261 | 0.35 | 0.0214 |
| | | | | | | = -3.39 - 0.016*(H*W) | 0.229 | 0.36 | 0.0329 |
| | | | | | Left L5 | Could not find any regression model | - | - | - |
| | | | | | Right L5 | Could not find any regression model | - | - | - |
| Jorgensen *et al.* (2003b) | 12 Male | 23.1 | 177.1 | 74.5 | L3/L4 | = 4.474 + 0.006*L1/S1 - 0.106*TDI + 0.042*W | 0.60 | 2.8 | 0.0001 |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | L4/L5 | = 6.985 + 0.523*G + 0.012*L1/S1 - 0.173*TDX + 0.028*W | 0.65 | 2.7 | 0.0001 |
| | | | | | L5/S1 | = 8.389 + 0.768*G + 0.021*L1/S1 - 0.074*IC + 0.034*W | 0.76 | 2.7 | 0.0001 |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | L3/L4 | = 5.01 + 9.68*10$^{-11}$*A*H$^2$*W$^2$ | 0.355 | 0.445 | 0.0001 |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | L3/L4 | = 4.31 - 1.27*10$^{-9}$*A$^2$*W$^3$ + 2.21*10$^{-12}$*A*H$^3$*W$^2$ | 0.364 | 0.444 | 0.0012 |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | LDK | = 5.454 + 0.023*CSA of ES | - | - | - |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | Control | = 5.832 + 0.02*CSA of ES | - | - | - |
| Anderson *et al.* (2012) | 51 Male | 59.4 | 177.6 | 81.3 | L3 | = -0.87 + 0.0912*G - 0.00478*A + 0.0257*H + 0.00492*W | 0.44 | 0.40 | - |
| *(CT, Supine, Healthy)* | 49 Female | 58.1 | 162.2 | 68.4 | L4 | = -1.21 + 0.0922*G - 0.00233*A + 0.0224*H + 0.00332*W | 0.32 | 0.44 | - |
| | | | | | L5 | = 0.33 + -0.16*G - 0.00575*A + 0.0277*H + 0.00432*W | 0.26 | 0.47 | - |

G: Gender (0 for female, 1 for male); A: Age (year); H: Height (cm); W: Weight (kg); CHW: Width at chest; TRW: Width at greater trochanter;
ABLW: Abdominal's least width; TD: Trunk depth; TW: Trunk width; IF: Index of fat; TA: Torso area (cm$^2$); SH: Sitting height (cm);
CSA of ES: cross-sectional area of the erector spinae muscle (cm$^2$); TDX: Trunk depth at xyphoid process (cm); TDI: Trunk depth at iliac crest (cm)

These studies indicate that the ESMLA distance is associated with subject characteristics. The ESMLAs can be estimated by prediction equations. However, the current literature provides different regression models that using different predictors and varying coefficients. These differences are possibly due to different muscle definitions, methodology employed, and subject characteristics. Practitioners should consider these differences before using a prediction model. For example, a prediction model derived from a relatively older female Korean population may not be applicable to a working American male population.

The literature search presented above indicated that previous studies had some limitations. For example, previous studies used;

**(1) limited sample size:** Reid and Costigan, 1985 (10 males and 8 females); Reid *et al.*, 1987 (20 males); McGill *et al.*, 1988 (13 males); Moga *et al.*, 1993 (11 males and 8 females);

**(2) different age groups:**

**(a) younger populations:** Reid *et al.*, 1987 (mean age 21.2 years old); Marras *et al.*, 2001 (mean age 26.4 years old); Jorgensen *et al.*, 2003a and 2003b (male 23.1 and female 23.8 years old mean age),

**(b) older populations:** Reid and Costigan, 1985 (male 52.1 and females 54.6 years old mean age); Chaffin *et al.*, 1990 (mean age 49.6 years old); Lee *et al.*, 2006 (LDK patients 62.5 and controls 63.6 years old mean age); Anderson *et al.*, 2012 (male 59.4 and female 58.1 years old mean age),

**(3) different medical conditions:** Tracy *et al.*, 1989 (LBP patients); Moga *et al.*, 1993 (patients who had undertaken MRI); Lee *et al.*, 2006 (lumbar degenerative kyphosis patients),

**(4) over-simplified measurement techniques (e.g., ellipsoid muscle shape assumption, visual center determination, etc.)**: Reid and Costigan, 1985; Reid *et al.*, 1987; Kumar, 1988; McGill *et al.*, 1988; Tracy *et al.*, 1989; Moga *et al.*, 1993; Seo *et al.*, 2003; Lee *et al.*, 2006,

**(5) single gender:**

**(a) female subjects:** Chaffin *et al.*, 1990; Lee at al., 2006,

**(b) male subjects:** Reid *et al.*, 1987; McGill *et al.*, 1988; Tracy *et al.*, 1989; Wood *et al.*, 1996,

**(6) lumbar data from different vertebral body and IVD levels:**

**(a) only at the L3/L4 IVD level:** Seo *et al.*, 2003,

**(b) only at the L4 vertebral body level:** Cooper *et al.*, 1992,

**(c) only at the L4/L5 IVD level:** McGill *et al.*, 1988; Wood *et al.*, 1996; Lee *et al.*, 2006,

**(d) only at the L5 vertebral body level:** Reid *et al.*, 1987,

**(e) only at the L5/S1 IVD level:** Tracy *et al.*, 1989, and

**(f) only the average across several levels:** Reid and Costigan, 1985.

The limitations of previous studies indicate that there is a need for a study that may address these limitations. This present study proposes to address the limitations of the previous studies by including larger sample sizes, collecting data using high resolution MRI scans, using computerized and reliable measurement techniques, and analyzing data for three IVD levels for both genders. The objective of this study is to provide reliable regression equations that accurately estimate the ESMLA distance and the CSA of the ESMM at the low back region based on subject characteristics and anthropometrics. Easily measured anthropometric variables (subject height and weight) and subject characteristics (gender and age) are utilized in the present study to estimate the ESMLA distance and the CSA of the total ESMM. Estimation models can provide individualized muscle size and lever arm distances for biomechanical models. Individualized morphometric data allow designers to calculate the spinal loading for a particular person, therefore, estimate the LBP risk to *this* person.

## 4.2 Material and Methods

### 4.2.1 Subjects

This study included a total of 112 subjects (54 males and 58 females). They had undertaken an MRI scan at the University of Utah Hospital in Salt Lake City, Utah to help medical doctors explore whether they had any medical abnormalities in their lumbar spinal region. It is unknown whether such abnormalities were associated with the spine itself or to nearby tissues. Researchers were blinded to patient medical history. Before releasing the MRI data from the University of Utah Hospital System, personal identifiers such as name, birth date, and identification number regarding the patients were purged. The subject population of this regression study is a subgroup of the first study presented in Chapter 3. Note that the sample size was 163 (82 males and 81 females) in the first study. Patients with missing anthropometric data (height, weight) were excluded from this regression study, yielding a total of 112 subjects. Remember that there were some subject exclusion criteria, as well. MRI scans were reviewed by an expert with experience analyzing the spine whether there is abnormality in muscles and IVDs (the expert has a Bachelor of Science degree in Physical Therapy and a Doctor of Philosophy degree in Anatomy). Subjects who had (1) degenerative changes in the lumbar spine (e.g., crushed vertebral body, trauma, etc.) and/or erector spinae muscles (e.g., atrophy), (2) obvious spinal deformities, and (3) any known pathology relevant to and likely to alter low back geometry (e.g., scoliosis, tumor) were not included in the study. There were a total of 283 MRI images (135 male MRI images and 148 female images) for three IVD levels; 53 male and 54 female images at the L3/L4 level, 45 male and 51 female images at the L4/L5 level, and 37 male and 43 female images at the L5/S1 level. Note that there were 54 male and 58 female subject in total, however, there were some missing images at some levels. The research protocol of this study was approved by the Institutional Review Board (IRB) at both participating institutions, the University of Utah (Appendix A) and Auburn University (Appendix B).

Demographic properties (gender and age) and anthropometric measurements (height and weight) of patients were recorded in the picture archiving and communication system (PACS) embedded in the MRI scans. Body mass index (BMI) was calculated from subject height and weight. Subjects were categorized into four obesity levels (underweight, less than 18.5 $kg/m^2$; normal, between 18.5 and 24.9 $kg/m^2$; overweight, between 25 and 29.9 $kg/m^2$; and obese, more than 30$kg/m^2$) based on the World Health Organization's BMI classification (WHO, 2012).

The average age was 30.1 (5.7) years for males and 29.3 (5.2) years for females. Male subjects were significantly taller ($p<0.000$) and heavier (but not significant in general, $p = 0.055$) than female subjects at each IVD level. The average height and weight for males were 178.60 (8.78) cm and 84.04 (19.60) kg, while the average height and weight for females were 165.37 (8.91) cm and 76.55 (21.11) kg for females. More detailed descriptive statistics for subject properties are given in Table 4.3.

The average BMI was 26.25 (5.31) $kg/m^2$ for males and 28.09 (8.02) $kg/m^2$ for females (Table 4.3), so the average BMI for both genders fell into the overweight category for BMI classification. Among subjects who had MRI scans of their L3/L4 disc level, 0.9% of subjects were underweight, 43.9% of them were normal, 29.0% of them were overweight, and 26.2% of subjects were in obese category (Table 4.4). At the L4/L5 level, 44.8% of subjects were normal, 27.1% of them were overweight, and 28.1% of them were obese. At the L5/S1 level, underweight, normal, overweight, and obese percentages were 1.3, 43.7, 30, and 25, respectively.

### 4.2.2 Data Collection

#### Device and recording

Low back architecture was investigated with Magnetic Resonance Imaging (MRI). An open-bore 1.5 Tesla MRI scanner (MAGNETOM Avanto, Siemens AG, Erlangen, Germany) at the University of Utah Hospital was used to obtain MR scans of the lumbar

Table 4.3: Demographic properties and anthropometric measurements of subjects (complete data sets only gender, age, height, and weight)

| IVD Level | Variable | Gender | N | Mean | St.d | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|
| **L3/L4** | Age | Female | 54 | 29.2 | 5.4 | -0.846 | 105 | 0.399 |
| | | Male | 53 | 30.1 | 5.7 | | | |
| | | Total | 107 | 29.6 | 5.5 | | | |
| | Height | Female | 54 | 165.29 | 9.01 | -7.680 | 105 | *0.000** |
| | | Male | 53 | 178.57 | 8.86 | | | |
| | | Total | 107 | 171.87 | 11.12 | | | |
| | Weight | Female | 54 | 76.66 | 21.57 | -1.982 | 105 | *0.050** |
| | | Male | 53 | 84.53 | 19.45 | | | |
| | | Total | 107 | 80.56 | 20.83 | | | |
| | BMI | Female | 54 | 28.14 | 8.16 | 1.306 | 105 | 0.194 |
| | | Male | 53 | 26.41 | 5.23 | | | |
| | | Total | 107 | 27.29 | 6.89 | | | |
| **L4/L5** | Age | Female | 51 | 29.1 | 5.4 | -0.476 | 94 | 0.635 |
| | | Male | 45 | 29.6 | 5.4 | | | |
| | | Total | 96 | 29.3 | 5.4 | | | |
| | Height | Female | 51 | 164.8 | 8.8 | -7.496 | 94 | *0.000** |
| | | Male | 45 | 178.53 | 9.04 | | | |
| | | Total | 96 | 171.24 | 11.26 | | | |
| | Weight | Female | 51 | 76.84 | 21.9 | -2.026 | 94 | *0.046** |
| | | Male | 45 | 85.39 | 19.06 | | | |
| | | Total | 96 | 80.85 | 20.95 | | | |
| | BMI | Female | 51 | 28.39 | 8.34 | 1.151 | 94 | 0.253 |
| | | Male | 45 | 26.74 | 5.17 | | | |
| | | Total | 96 | 27.62 | 7.05 | | | |
| **L5/S1** | Age | Female | 43 | 30.0 | 5.4 | -0.082 | 78 | 0.935 |
| | | Male | 37 | 30.1 | 5.6 | | | |
| | | Total | 80 | 30.0 | 5.4 | | | |
| | Height | Female | 43 | 165.87 | 9.46 | -5.785 | 78 | *0.000** |
| | | Male | 37 | 178 | 9.22 | | | |
| | | Total | 80 | 171.48 | 11.11 | | | |
| | Weight | Female | 43 | 75.22 | 21.06 | -2.128 | 78 | *0.036** |
| | | Male | 37 | 84.88 | 19.25 | | | |
| | | Total | 80 | 79.69 | 20.69 | | | |
| | BMI | Female | 43 | 27.46 | 8.01 | 0.434 | 78 | 0.665 |
| | | Male | 43 | 26.78 | 5.47 | | | |
| | | Total | 80 | 27.15 | 6.91 | | | |
| **Total** | Age | Female | 58 | 29.3 | 5.2 | -0.812 | 110 | 0.418 |
| | | Male | 54 | 30.1 | 5.7 | | | |
| | | Total | 112 | 29.7 | 5.4 | | | |
| | Height | Female | 58 | 165.37 | 8.91 | -7.909 | 110 | *0.000** |
| | | Male | 54 | 178.60 | 8.78 | | | |
| | | Total | 112 | 171.75 | 11.03 | | | |
| | Weight | Female | 58 | 76.55 | 21.11 | -1.943 | 110 | 0.055 |
| | | Male | 54 | 84.04 | 19.60 | | | |
| | | Total | 112 | 80.16 | 20.65 | | | |
| | BMI | Female | 58 | 28.09 | 8.02 | 1.418 | 110 | 0.159 |
| | | Male | 54 | 26.25 | 5.31 | | | |
| | | Total | 112 | 27.20 | 6.88 | | | |

Age (years); Height (cm); Weight (kg); BMI (kg/m$^2$)

region. Subjects were placed in head-first-supine (HFS) posture in the MRI machine. T2-weighted standard soft-tissue MRI scans were taken in both axial and sagittal planes. T2-weighted scans were preferred over T1-weighted scans because of its superiority in

Table 4.4: Subject BMI categories

| | | L3/L4 | | L4/L5 | | L5/S1 | |
|---|---|---|---|---|---|---|---|
| **BMI Category** | **Gender** | **N** | **%** | **N** | **%** | **N** | **%** |
| **Underweight** | Female | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 |
| | Male | 1 | 0.9 | 0 | 0.0 | 1 | 1.3 |
| | **Total** | **1** | **0.9** | **0** | **0.0** | **1** | **1.3** |
| **Normal** | Female | 25 | 23.3 | 24 | 25.0 | 21 | 26.2 |
| | Male | 22 | 20.6 | 19 | 19.8 | 14 | 17.5 |
| | **Total** | **47** | **43.9** | **43** | **44.8** | **35** | **43.7** |
| **Overweight** | Female | 11 | 10.3 | 9 | 9.4 | 10 | 12.5 |
| | Male | 20 | 18.7 | 17 | 17.7 | 14 | 17.5 |
| | **Total** | **31** | **29.0** | **26** | **27.1** | **24** | **30.0** |
| **Obese** | Female | 18 | 16.8 | 18 | 18.8 | 12 | 15.0 |
| | Male | 10 | 9.4 | 9 | 9.4 | 8 | 10.0 |
| | **Total** | **28** | **26.2** | **27** | **28.1** | **20** | **25.0** |

distinguishing muscles from fat tissues. One oblique (parallel to the vertebral disc) scan was taken for each IVD level (Figure 4.2).

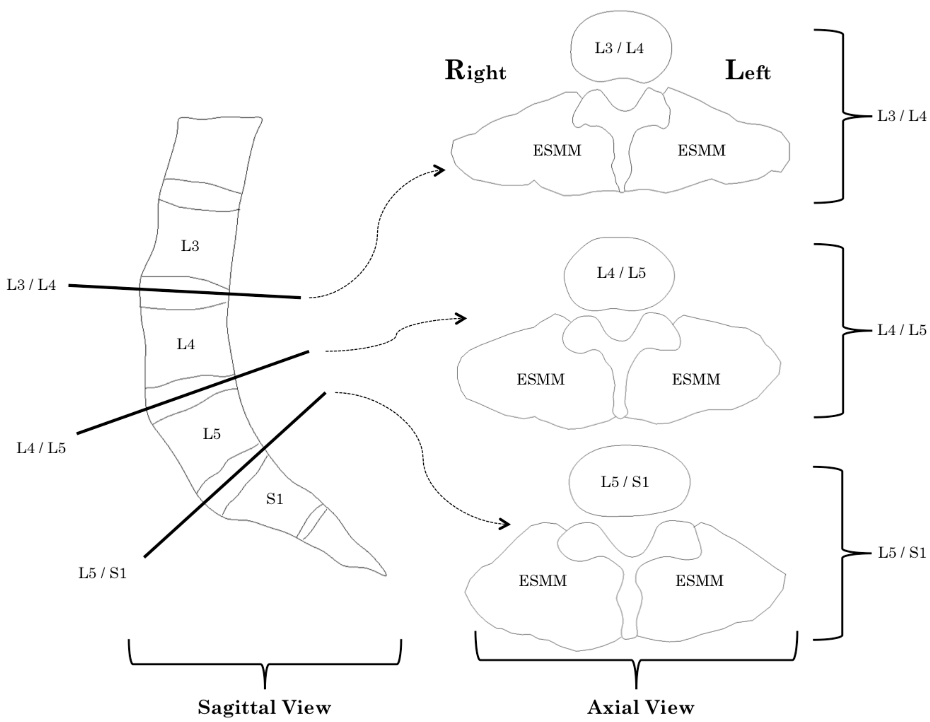



Figure 4.2: Oblique scans at the L3/L4, L4/L5, L5/S1 IVD levels

### The erector spinae muscle mass (ESMM)

The erector spinae muscle mass (ESMM) can be described as the whole muscle structure posterior to the spinal column, filling the space between the spinous and transverse processes, and laying longitudinally throughout the torso. The ESMM in the low back region consists of the erector spinae muscle (ESM) group (the spinalis thoracis, longissimus thoracis, and iliocostalis lumborum), the transversospinalis group (the multifidus, semispinalis, and rotatores), and the segmental muscles (the interspinales, intertransversarii). The prevalence and percentages of these muscles are dependent upon the vertebral level. The longissimus thoracis, iliocostalis lumborum, and multifidus are the major muscles in the low back region (Figure 4.3), and they constitute the main focus of the present study since they are the major muscles responsible for concentric extension and eccentric flexion of the trunk. Note that, the psoas major, quadratus lumborum, and latissumus dorsi are excluded from the present study due to their minimal role in sagittal plane lifting tasks compared to the erector spinae muscles.

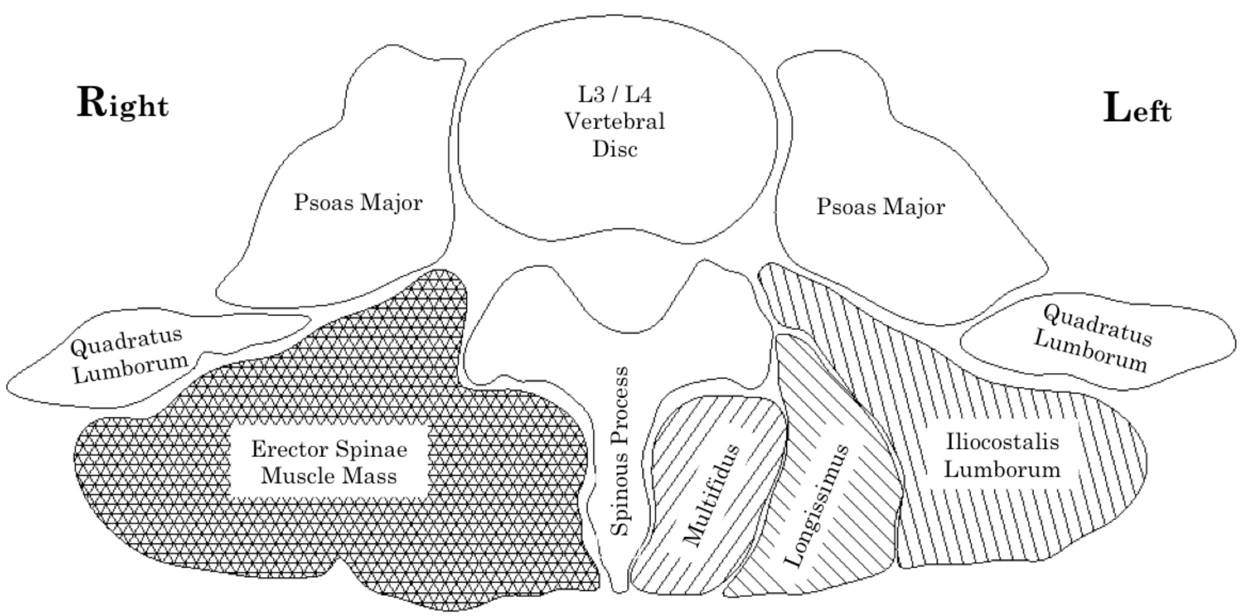



Figure 4.3: Muscles in the ESMM at the L3/L4 IVD level

### The CSA and lever arm measurement techniques

MR images were transfered to an open source DICOM image analysis software, OsiriX® (v4.0, 2011, Antoine Rosset, Bernex, Switzerland). Sagittal and axial plane images of the spine were carefully evaluated using OsiriX®. Figure 4.4 shows sagittal (on the left) and axial (on the right) MR images in OsiriX® software. One oblique image was selected for each IVD level (the L3/L4, L4/L5, and L5/S1). Selected images were transferred to an architectural design software, Rhinoceros (known as Rhino) (v4.0). Rhino was selected as the main measurement instrument because it can accurately estimate the centroid of an irregular shape such as the muscle mass and IVD. Images were scaled with the scale given in the raw OsiriX® images. Contours of the right and left ESMMs and IVDs were manually traced on a high resolution computer screen (1280 X 1024 pixels, 60 Hz, Dell 1905FP, Dell Inc., Round Rock, TX). A Grasshopper model was created to (1) compute the centroid points of the ESMMs from contour traces, (2) draw "a connector line" between the centroid point of the right ESMM to the centroid point of the left ESMM, (3) compute the centroid point of the IVD, and (4) draw a perpendicular line from the disc centroid to the connector line, which is the definition of the ESMLA used in the present study. Figure 4.5 illustrates the ESMLA distance measurements. Grasshopper software provided the measurements regarding muscle and disc CSAs, as well as the corresponding ESMLA distance.

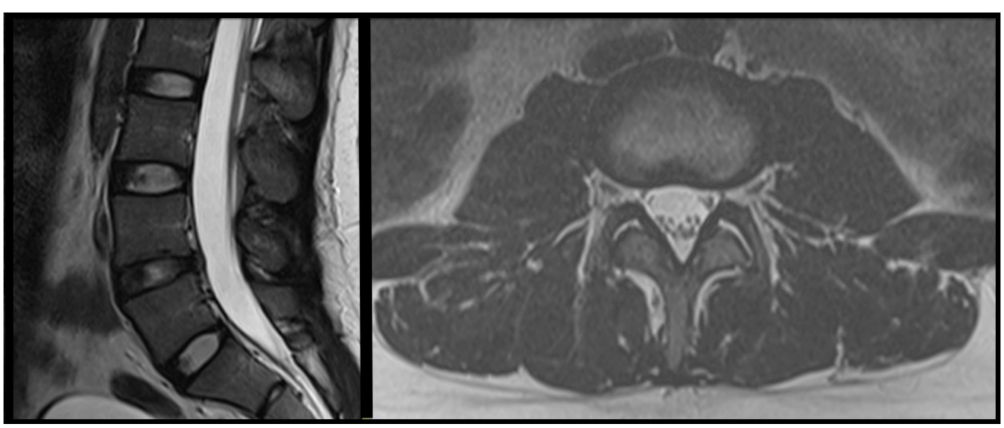


Figure 4.4: Image selection in OsiriX® software

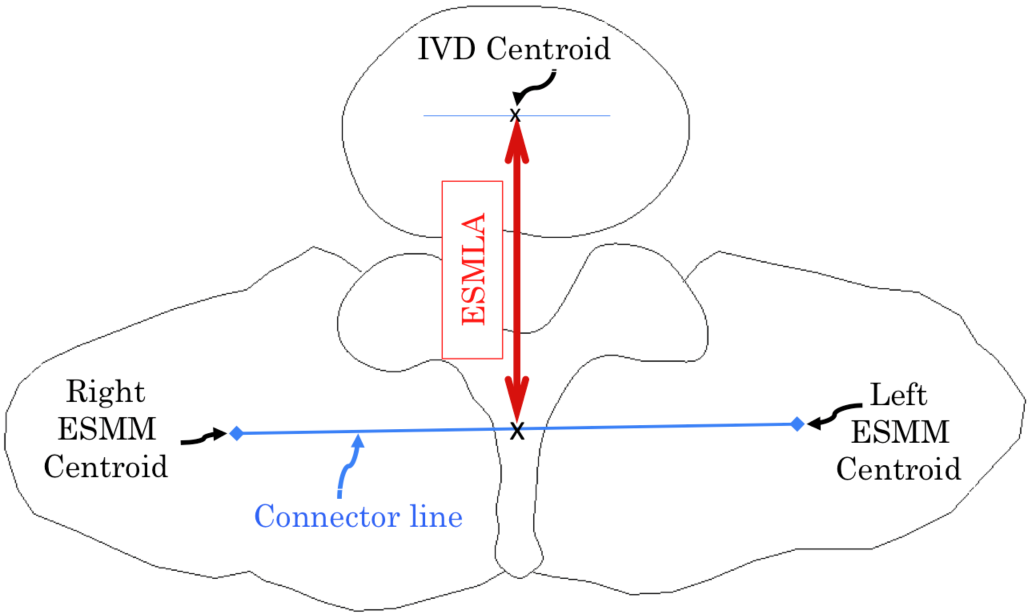



Figure 4.5: The ESMLA distance measurement

### 4.2.3 Statistical Tests

Independent samples T-tests were used to compare descriptives statistics such as male and female heights. Tukey's outlier labeling methodology was used to detect univariate outliers in the dependent variables. The Kolmogorov-Smirnov and the Shapiro-Wilk tests were used to evaluate the normality of dependent variables. Skewness and kurtosis were also evaluated to better understand the data distribution. Paired-samples T-tests were used to compare the right and left CSAs of the ESMM to determine if any asymmetry exists between muscle sizes. Split plot factorial design (SPF) ANOVA tests were used to determine the effect of gender, IVD level, and interaction of these two factors on the CSA of the total ESMM and the ESMLA distance. Post-hocs tests were performed for the main effects with three categories, if they were significant, to understand the relationship to the response value. Independent T-tests were performed for the main effects with two categories. Backward stepwise regression analyses were performed to determine prediction models for the CSA of the total ESMM and the ESMLA distance. Correlation coefficients for the dependent variables (the CSA of the total ESMM and the ESMLA) were determined at each IVD level. Model assumptions such as linearity, normality, and constant variance for error terms were evaluated using residual plots. Collinearity statistics for predictor variables were also performed. Statistical tests were performed using IBM SPSS Statistics (version 19.0) and Minitab (version 15.1).

### 4.2.4 Preliminary Model Investigations for Regression Analyses

The total CSA of ESMM ($Y_{ESMM}$) and ESMLA ($Y_{ESMLA}$) distance are the dependent (or response) variables. They were tested for whether they can be estimated by some independent (or predictor, estimator) variables such as subject gender ($X_G$), age ($X_A$), height ($X_H$), and weight ($X_W$). Since BMI is highly correlated with height ($p = 0.005$) and weight ($p = 0.000$), it was removed from the estimator list. Otherwise, it may have caused multicollinearity problems. Highly correlated variables means that the coefficient estimates may change dramatically with small changes in the data, as well as result in reduced prediction power and reliability of the model. Some preliminary model investigations were performed to understand the data set and check outliers and multiple linear regression assumptions regarding normality.

**Check for univariate outliers on the dependent variables**

The slope and intercept of regression line is very sensitive to extreme values, outliers (note that sensitivity is depend on where these outliers are). Outliers can distort estimates of regression coefficients. Outliers should be removed from the data set (e.g. trimming, Winsorizing) in order to produce a normally distributed data set on which to perform parametric statistical analyses such as regression analyses. Tukey's fences/hinges outlier labeling methodology (Tukey, 1977; Hoaglin, Iglewicz, and Tukey, 1986) was applied for identifying possible outliers in the present study. Lower ($C_L$) and upper ($C_U$) cutoff points (demarcation points) for outliers are calculated with the formula given below:

$F_L$ - $k(F_U$ - $F_L)$ *and* $F_U + k(F_U$ - $F_L)$;

where $F_L$ is lower forth (approximate first (lower) quartile ($Q_1$)), $F_U$ is the upper forth (approximate third (upper) quartile ($Q_3$)), ($F_U$ - $F_L$) is the inter-quartile range (IQR), which is the interval between Q1 and Q3, and $k$ is the multiplier for the IQR. The multiplier $k$ for the (inner) fence calculations is considered 1.5 (as for the three sigma method). By using $k = 1.5$; the lower and upper demarcation points were calculated for the total CSA of ESMM (Table 4.5) and ESMLA distance (Table 4.6).

Table 4.5: Outlier detection methodology for **the total CSA of ESMM**

| **IVD Level** | **Q1** | **Q3** | **$C_L$** | **$C_U$** |
|---|---|---|---|---|
| L3/L4 | 45.40 | 61.25 | 21.63 | 85.03 |
| L4/L5 | 46.30 | 57.44 | 29.59 | 74.15 |
| L5/S1 | 41.23 | 56.97 | 17.62 | 80.58 |

Table 4.6: Outlier detection methodology for **the ESMLA distance**

| **IVD Level** | **Q1** | **Q3** | **$C_L$** | **$C_U$** |
|---|---|---|---|---|
| L3/L4 | 4.99 | 5.69 | 3.94 | 6.74 |
| L4/L5 | 4.90 | 5.57 | 3.90 | 6.58 |
| L5/S1 | 4.99 | 5.63 | 4.03 | 6.59 |

The outlier detection method for the CSA of the total ESMM suggested that there were 2 outliers at the L4/L5 level and 1 outlier at the L5/S1 level. For the L4/L5 level, a female subject with a 29.56 $cm^2$ total ESMM CSA (Age: 25, Height: 160.0 cm, Weight: 58.97 kg, BMI: 23.0 $kg/m^2$) was the outside of the lower demarcation point, and a male subject with 79.85 $cm^2$ total ESMM CSA (Age: 28, Height: 182.9 cm, Weight: 97.52 kg, BMI: 29.2 $kg/m^2$) was the outside of the upper demarcation point. At the L5/S1 level, a female subject with a total of 84.37 $cm^2$ ESMM CSA (Age: 31, Height: 172.7 cm, Weight: 131.54 kg, BMI: 44.1 $kg/m^2$) was an outlier.

After the data set was carefully investigated, three outlier ESMLA distances were detected for the L5/S1 level. A female subject with a 4.03 cm ESMLA distance (Age: 21, Height: 150.0 cm, Weight: 52.16 kg, BMI: 23.2 kg/m$^2$), a male subject with a 7.68 cm ESMLA distance (Age: 28, Height: 182.9 cm, Weight: 97.52 kg, BMI: 29.2 kg/m$^2$; note that he was also outlier for the total ESMM CSA), and another male subject with a 7.04 cm ESMLA distance (Age: 35, Height: 170.2 cm, Weight: 77.11 kg, BMI: 26.6 kg/m$^2$) were removed from the ESMLA distance data set at the L5/S1 level.

Descriptive statistics after removing these 5 subjects (3 subjects for ESMLA distances and 3 subjects for the total CSA of ESMM, one subject was outlier for both) are given in Table 4.7. Note that the data set given in Table 4.7 is the data set used in subsequent statistical analyses.

**Normality tests**

An assessment of the normality of data is a prerequisite for many statistical tests as normally distributed data is an underlying assumption in parametric tests. There are the two main methods of assessing normality: graphically and numerically (statistical tests). Numerical (statistical) tests provide objective results but might be over or under sensitive. On the other hand, graphical methods requires subjective judgements with experience in interpreting normality graphically. The Kolmogorov-Smirnov test and the Shapiro-Wilk test are two most common statistical tests for the normality of data. Shapiro-Wilk is more appropriate for small sample sizes ($< 50$ samples) (Razali and Wah, 2011). Both statistical tests were performed to evaluate whether the ESMLA distances and the total CSAs of ESMMs distribute normally. The results of two numerical tests are given in Table 4.8.

The significance level for both normality tests (Kolmogorov-Smirnov and Shapiro-Wilk) regarding the ESMLA distances and the total CSAs of the ESMMs were larger than 0.05 at each IVD level. Therefore, it can be concluded that the results of normality tests indicated that the data were normally distributed. In addition to numeric

Table 4.7: Descriptive statistics of the research sample to be used for regression analyses

| IVD Level | Variable | Gender | N | Mean | St.d | Min | Max |
|---|---|---|---|---|---|---|---|
| **L3/L4** | Age | Female | 54 | 29.2 | 5.4 | 21.0 | 39.0 |
| | | Male | 53 | 30.1 | 5.7 | 21.0 | 39.0 |
| | | Total | 107 | 29.6 | 5.5 | 21.0 | 39.0 |
| | Height | Female | 54 | 165.29 | 9.01 | 142.20 | 195.60 |
| | | Male | 53 | 178.57 | 8.86 | 157.50 | 200.70 |
| | | Total | 107 | 171.87 | 11.12 | 142.20 | 200.70 |
| | Weight | Female | 54 | 76.66 | 21.57 | 45.46 | 136.08 |
| | | Male | 53 | 84.53 | 19.45 | 36.29 | 178.71 |
| | | Total | 107 | 80.56 | 20.83 | 36.29 | 178.71 |
| | BMI | Female | 54 | 28.14 | 8.16 | 19.10 | 53.20 |
| | | Male | 53 | 26.41 | 5.23 | 13.70 | 52.00 |
| | | Total | 107 | 27.29 | 6.89 | 13.70 | 53.20 |
| **L4/L5** | Age | Female | 50 | 29.2 | 5.4 | 21.0 | 39.0 |
| | | Male | 44 | 29.7 | 5.5 | 21.0 | 39.0 |
| | | Total | 94 | 29.4 | 5.4 | 21.0 | 39.0 |
| | Height | Female | 50 | 164.90 | 8.94 | 142.20 | 195.60 |
| | | Male | 44 | 178.43 | 9.12 | 157.50 | 200.70 |
| | | Total | 94 | 171.24 | 11.26 | 142.20 | 200.70 |
| | Weight | Female | 50 | 77.20 | 21.97 | 45.36 | 136.08 |
| | | Male | 44 | 85.11 | 19.19 | 58.97 | 178.71 |
| | | Total | 94 | 80.90 | 20.98 | 45.36 | 178.71 |
| | BMI | Female | 50 | 28.50 | 8.39 | 19.10 | 53.20 |
| | | Male | 44 | 26.68 | 5.22 | 19.20 | 52.00 |
| | | Total | 94 | 27.65 | 7.11 | 19.10 | 53.20 |
| **L5/S1** | Age | Female | 41 | 30.1 | 5.3 | 22.0 | 39.0 |
| | | Male | 35 | 30.0 | 5.7 | 21.0 | 39.0 |
| | | Total | 76 | 30.1 | 5.5 | 21.0 | 39.0 |
| | Height | Female | 41 | 166.09 | 9.30 | 142.20 | 195.60 |
| | | Male | 35 | 178.09 | 9.36 | 157.50 | 200.70 |
| | | Total | 76 | 171.61 | 11.05 | 142.20 | 200.70 |
| | Weight | Female | 41 | 74.41 | 19.30 | 45.36 | 136.08 |
| | | Male | 35 | 84.74 | 19.64 | 58.06 | 178.71 |
| | | Total | 76 | 79.17 | 20.01 | 45.36 | 178.71 |
| | BMI | Female | 41 | 27.16 | 7.73 | 19.10 | 53.20 |
| | | Male | 35 | 26.72 | 5.61 | 17.90 | 52.00 |
| | | Total | 76 | 26.95 | 6.80 | 17.90 | 53.20 |
| **Total** | Age | Female | 58 | 29.3 | 5.2 | 21.0 | 39.0 |
| | | Male | 54 | 30.1 | 5.7 | 21.0 | 39.0 |
| | | Total | 112 | 29.7 | 5.4 | 21.0 | 39.0 |
| | Height | Female | 58 | 165.37 | 8.91 | 142.20 | 195.60 |
| | | Male | 54 | 178.60 | 8.78 | 157.50 | 200.70 |
| | | Total | 112 | 171.75 | 11.03 | 142.20 | 200.70 |
| | Weight | Female | 58 | 76.55 | 21.11 | 45.36 | 136.08 |
| | | Male | 54 | 84.04 | 19.60 | 36.29 | 178.71 |
| | | Total | 112 | 80.16 | 20.65 | 36.29 | 178.71 |
| | BMI | Female | 58 | 28.09 | 8.02 | 19.10 | 53.20 |
| | | Male | 54 | 26.25 | 5.31 | 13.70 | 52.00 |
| | | Total | 112 | 27.20 | 6.88 | 13.70 | 53.20 |

tests, normal quantile-quantile (Q-Q) plots also provide information to graphically assess normality. Normal Q-Q plots for both the ESMLA distance and total CSA of ESMM were drawn for each IVD level. The output for Q-Q plots is given in Figure 4.6. The data points plot in a linear fashion for both variables at each IVD level. It can be concluded that

Table 4.8: Normality test results

| IVD Level | Variable | Kolmogorov-Smirnov | | | Shapiro-Wilk | | |
|---|---|---|---|---|---|---|---|
| | | Statistic | df | Sig. | Statistic | df | Sig. |
| **L3/L4** | ESMLA | 0.040 | 107 | 0.200 | 0.995 | 107 | 0.964 |
| | CSA of ESMM | 0.070 | 107 | 0.200 | 0.988 | 107 | 0.479 |
| **L4/L5** | ESMLA | 0.083 | 94 | 0.113 | 0.990 | 94 | 0.699 |
| | CSA of ESMM | 0.059 | 94 | 0.200 | 0.984 | 94 | 0.307 |
| **L5/S1** | ESMLA | 0.069 | 76 | 0.200 | 0.993 | 76 | 0.952 |
| | CSA of ESMM | 0.076 | 76 | 0.200 | 0.982 | 76 | 0.359 |

graphical method, in addition to numerical method, indicated that the dependent variables (the ESMLA distance and the CSA of the total ESMM) are normally distributed.

**Skewness and kurtosis**

Skewness and kurtosis are two measures that provides information about the shape and symmetry of a distribution. The skewness of a distribution refers to how much a distribution's shape is deviating from a symmetrical shape. A perfectly symmetrical shape has zero skewness. If skewness is less than -1 or greater than +1, the distribution is highly skewed. If skewness is between -1 and -0.5 or between +0.5 and +1, the distribution is moderately skewed. If skewness is between -0.5 and +0.5, the distribution is approximately symmetric. If skewness is positive, the data are positively skewed or "right" skewed, meaning that the right tail of the distribution is longer than the left tail. A negative skewness, on the other hand, means the shape of the distribution appears skewed to the "left" and the left tail is longer.

The kurtosis of a distribution refers to the peakedness or flatness of the distribution: whether the shape is high and sharp or short and broad. A negative kurtosis (platykurtic) means a flatter distribution with thick and heavy tails and a positive kurtosis (leptokurtic) means a sharp and high peak in the center and thick and heavy tails. If kurtosis is less

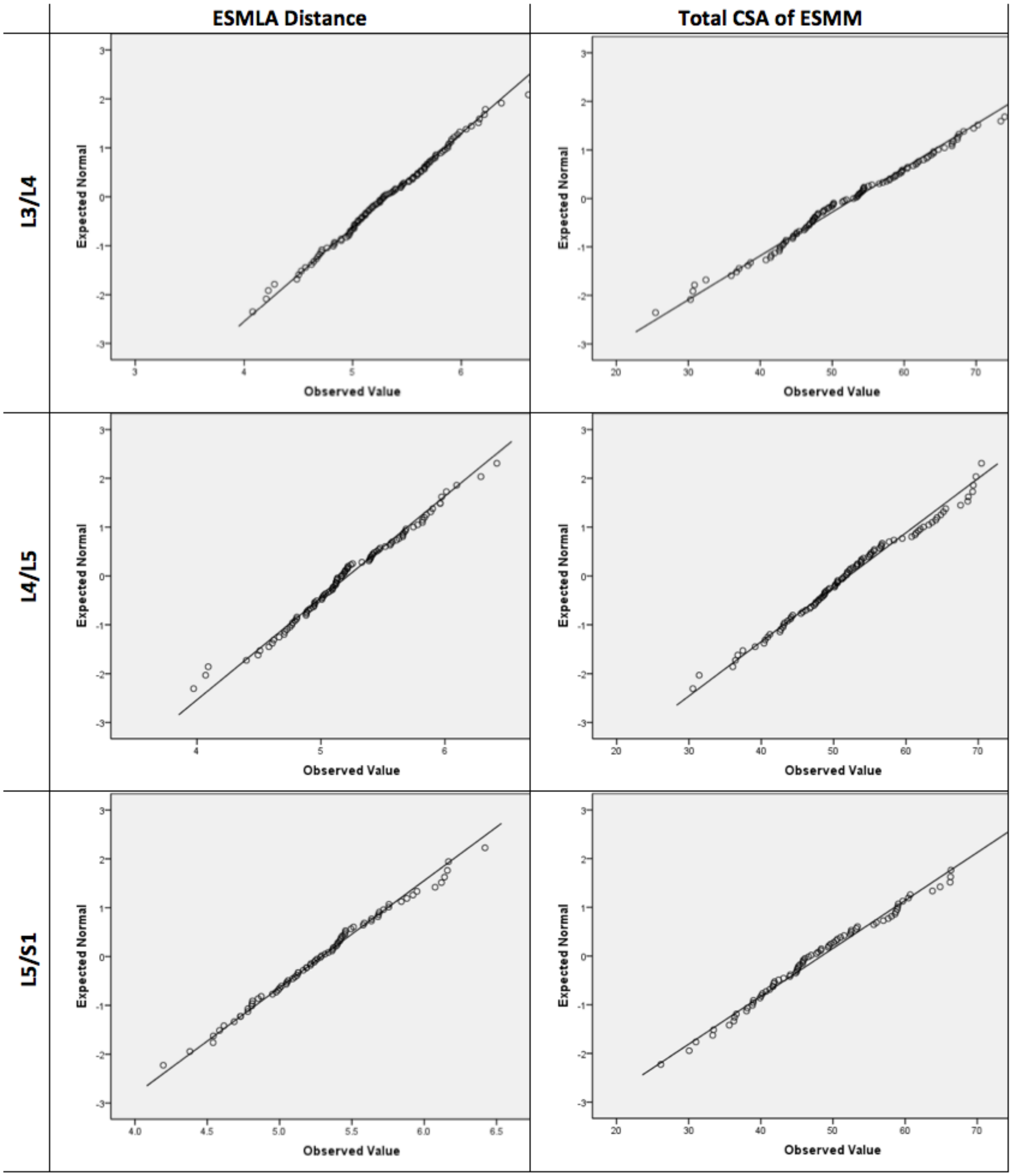



Figure 4.6: Normal quantile-quantile (Q-Q) plots

than -3 or greater than +3, the distribution demonstrates excess kurtosis. Table 4.9 shows the results of skewness and kurtosis investigation analyses.

Table 4.9: Skewness and kurtosis of the data

| | Level | Skewness | St. Err. | Kurtosis | St. Err. |
|---|---|---|---|---|---|
| **Area** | L3/L4 | 0.059 | 0.234 | -0.301 | 0.463 |
| | L4/L5 | 0.083 | 0.249 | -0.287 | 0.493 |
| | L5/S1 | 0.434 | 0.276 | 0.089 | 0.545 |
| **ESMLA** | L3/L4 | 0.049 | 0.234 | -0.123 | 0.463 |
| | L4/L5 | -0.007 | 0.249 | 0.068 | 0.493 |
| | L5/S1 | 0.128 | 0.276 | -0.147 | 0.545 |

Since all skewness values are between -0.5 and +0.5 at each IVD level for both the CSA of the ESMM and the ESMLA distance, it can be concluded that the skewness is relatively low, and the distribution is approximately symmetric. In addition, all kurtosis values are *not* less than -3 or greater than +3 at each IVD level for both the CSA of the ESMM and the ESMLA distance. Therefore, it can be concluded that the kurtosis is not significant and the distribution is approximately normal (mesokurtic).

An alternative method to evaluate the skewness and kurtosis is the statistical t-test. If the critical value (which is calculated by dividing the skewness or kurtosis by the standard error of skewness or kurtosis) is smaller than -2 or larger than +2, there may be a skewness or kurtosis problem. Note that the critical value of skewness or kurtosis is selected as approximately 2 since a two-tailed T-test is roughly equal to 2 at the 0.05 significance level (df $\approx$ 30 - 60). Since none of the skewness and kurtosis values are twice large as the standard error of skewness or kurtosis, it is concluded that skewness and kurtosis are not significant, as concluded earlier. Therefore, the normality assumptions necessary for regression analysis have been satisfied. Other model assumptions will be evaluated in the regression analyses part.

## 4.3 Results

### 4.3.1 Reproducibility Tests

#### Intra-rater reliability

Two researchers measured the CSA of the IVD, right ESMM, and left ESMM, and the ESMLA distance from 40 randomly selected images (20 males and 20 females) at the L5/S1 level. Each researcher repeated measurements after 4-weeks. To test the level of agreement between the two measurements of both researchers, statistical tests for intra-class correlation coefficients (ICC) were performed. The results of the intra-rater reliability tests (Table 4.10) indicate that there was a highly significant correlation (excellent ICC, ranging from 0.968 to 0.998) between the first and second measurements of both researchers. Interpretations of ICC results are based on Portney's and Watkins's (2000) descriptions presented in Table 4.11.

Table 4.10: Intra- and inter-reliability tests

| Measurement | Intra-rater reliability | | Inter-rater reliability | | | |
|---|---|---|---|---|---|---|
| | R1M1-R1M2 | R2M1-R2M2 | R1M1-R2M1 | R1M1-R2M2 | R1M2-R1M1 | R1M2-R1M2 |
| Right ESMM | 0.982 | 0.988 | 0.870 | 0.875 | 0.891 | 0.885 |
| Left ESMM | 0.968 | 0.990 | 0.820 | 0.811 | 0.870 | 0.857 |
| IVD | 0.997 | 0.998 | 0.995 | 0.993 | 0.997 | 0.994 |
| ESMLA | 0.990 | 0.995 | 0.990 | 0.986 | 0.995 | 0.990 |

R1: first researcher; R2: second researcher; M1: first measurement; M2: second measurement

Table 4.11: Interpretation of ICC reliability

| | ICC |
|---|---|
| Excellent | 0.900 and over |
| Good | 0.800 - 0.899 |
| Fair | 0.700 - 0.799 |
| Poor | 0.699 and less |

### Inter-rater reliability

Statistical tests for inter-class correlation coefficients performed to test how much agreement there was between the two researchers. Results of the first and second measurements of the first researcher were compared with results of the first and second measurements of the second researcher. Results of inter-rater reliability tests (Table 4.10) indicated that there was a highly significant correlation (ranging from 0.811 to 0.997) between the two researchers.

## 4.3.2 Descriptive Statistics

### Cross-sectional area (CSA) of the erector spinae muscle mass (ESMM) and inter-vertebral disc (IVD)

Descriptive statistics for cross-sectional areas (CSA) of the right, left, and total erector spinae muscle masses (ESMMs) and the inter-vertebral discs (IVDs) are presented in Table 4.12 and Table 4.13, respectively. The average CSA of ESMM was the largest at the L3/L4 vertebral disc level; the average CSA for the ESMM at the L3/L4 level was 26.55 $cm^2$ for the right side, 26.53 $cm^2$ for the left side, and 53.08 $cm^2$ for the total of both sides. The average CSA of IVD was also larger at the L3/L4 disc level, 16.38 $cm^2$. The average CSA for the ESMM at the L4/L5 level was approximately 1-3% smaller than the L3/L4 level, 25.88 $cm^2$ for the right side, 26.18 $cm^2$ for the left side, and 53.08 $cm^2$ for the total of both sides. The average CSA of ESMMs and IVDs were the smallest at the lowest vertebral disc level (L5/S1). The total CSA of ESMM at the L5/S1 level (48.41 $cm^2$) was approximately 9% smaller than the L3/L4 level and 7% smaller than the L4/L5 level. The CSA of IVD at the L5/S1 level (14.89 $cm^2$) was approximately 9% smaller than the L3/L4 (16.38 $cm^2$) and and 8% smaller than the L4/L5 level (16.18 $cm^2$). Note that these interpretations were for the overall population, not for a specific gender. However, males had sharp reductions in muscle sizes with lower disc levels. The CSA of the total ESMM for male subjects at the L5/S1 level, for instance, was approximately 19% smaller than the L3/L4 level and 14%

Table 4.12: Cross-sectional areas (CSAs) of the erector spinae muscle masses (ESMMs)

| | | | CSA of Right ESMM (cm$^2$) | | | | CSA of Left ESMM (cm$^2$) | | | | CSA of Total ESMM (cm$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Min | Max | Mean | St.d. | Min | Max | Mean | St.d. | Min | Max |
| L3/L4 | Female | 54 | 23.62 | 4.35 | 15.07 | 35.56 | 23.50 | 3.98 | 14.78 | 32.70 | 47.12 | 8.17 | 30.30 | 68.26 |
| | Male | 53 | 29.53 | 5.22 | 13.56 | 39.34 | 29.62 | 5.23 | 11.89 | 39.11 | 59.15 | 10.28 | 25.45 | 76.60 |
| | Total | 107 | 26.55 | 5.62 | 13.56 | 39.34 | 26.53 | 5.55 | 11.89 | 39.11 | 53.08 | 11.03 | 25.45 | 76.60 |
| L4/L5 | Female | 50 | 24.39 | 4.19 | 15.76 | 33.92 | 24.62 | 4.23 | 14.71 | 36.52 | 49.01 | 8.29 | 30.54 | 70.44 |
| | Male | 44 | 27.58 | 4.15 | 17.95 | 36.10 | 27.95 | 4.62 | 19.50 | 38.19 | 55.52 | 8.54 | 37.45 | 69.68 |
| | Total | 94 | 25.88 | 4.45 | 15.76 | 36.10 | 26.18 | 4.70 | 14.71 | 38.19 | 52.06 | 8.98 | 30.54 | 70.44 |
| L5/S1 | Female | 41 | 24.08 | 4.75 | 12.40 | 32.66 | 24.86 | 5.68 | 13.73 | 44.61 | 48.93 | 10.02 | 26.13 | 75.89 |
| | Male | 35 | 23.50 | 4.82 | 15.72 | 37.91 | 24.29 | 5.97 | 15.29 | 37.83 | 47.79 | 10.43 | 31.01 | 74.93 |
| | Total | 76 | 23.81 | 4.76 | 12.40 | 37.91 | 24.59 | 5.78 | 13.73 | 44.61 | 48.41 | 10.16 | 26.13 | 75.89 |

Table 4.13: Cross-sectional areas (CSAs) of the inter-vertebral discs (IVDs)

| | | | CSA of IVD (cm$^2$) | | | |
|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Min | Max |
| L3/L4 | Female | 54 | 14.60 | 1.64 | 11.09 | 18.33 |
| | Male | 53 | 18.19 | 2.59 | 13.39 | 27.96 |
| | Total | 107 | 16.38 | 2.81 | 11.09 | 27.96 |
| L4/L5 | Female | 50 | 14.43 | 1.60 | 11.31 | 17.83 |
| | Male | 44 | 18.16 | 2.07 | 13.63 | 24.55 |
| | Total | 94 | 16.18 | 2.61 | 11.31 | 24.55 |
| L5/S1 | Female | 41 | 13.15 | 2.05 | 9.99 | 17.74 |
| | Male | 35 | 16.94 | 2.77 | 13.64 | 27.12 |
| | Total | 76 | 14.89 | 3.05 | 9.99 | 27.12 |

smaller than the L4/L5 disc level. On the contrary, the total CSA of ESMM was the largest at the L4/L5 level in female subjects and was approximately 4% larger than the L3/L4 level. the CSA of the total ESMM at the L4/L5 was almost equal to the CSA of the total ESMM at the L5/S1 level. The CSA of IVD for female subjects follow the same trend. The average CSA of IVD for both males and females were the largest at the L3/L4 level and the smallest at the lowest lumbar disc level. Figure 4.7 graphically summarize the descriptive statistics of the CSA of the right (a), left (b), and total (c) ESMMs and the CSA of IVD (d) at each IVD level. Note that bars represent the 95% confidence intervals (CI).

Paired-samples T-tests were performed to determine whether there was any significant size difference between the CSAs of the right and left ESMMs. Statistical analyses revealed that the CSAs of the right and left ESMMs were highly correlated (correlation coefficients ranging from 0.845 to 0.938) and there was not any significant difference between muscle sizes for both genders at all IVD levels (Table 4.14). It can be concluded that the side where measurements were taken was not important, both sides are statistically equal to each other.

Table 4.14: Comparisons of CSAs of the right and left ESMMs

| | | | Right ($cm^2$) | | Left ($cm^2$) | | Correlations | | Paired Samples Tests | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Mean | St.d. | Coeff. | Sig. | t | df | Sig. |
| L3/L4 | Female | 54 | 23.62 | 4.35 | 23.50 | 3.98 | 0.926 | 0.000 | 0.523 | 53 | 0.603 |
| | Male | 53 | 29.53 | 5.22 | 29.62 | 5.23 | 0.937 | 0.000 | -0.330 | 52 | 0.743 |
| L4/L5 | Female | 50 | 24.39 | 4.19 | 24.62 | 4.23 | 0.938 | 0.000 | -1.110 | 49 | 0.272 |
| | Male | 44 | 27.58 | 4.15 | 27.95 | 4.62 | 0.897 | 0.000 | -1.206 | 43 | 0.234 |
| L5/S1 | Female | 41 | 24.08 | 4.75 | 24.86 | 5.68 | 0.845 | 0.000 | -1.647 | 40 | 0.107 |
| | Male | 35 | 23.50 | 4.82 | 24.29 | 5.97 | 0.866 | 0.000 | -1.550 | 34 | 0.130 |

To test the effect of gender and IVD level on the CSA of the total ESMM, a split plot factorial (SPF) analysis of variance test was performed. The SPF ANOVA tested two independent main effects at the same time; whether the main effects and the interaction between main effects were significant. A subgroup of research subjects were selected for

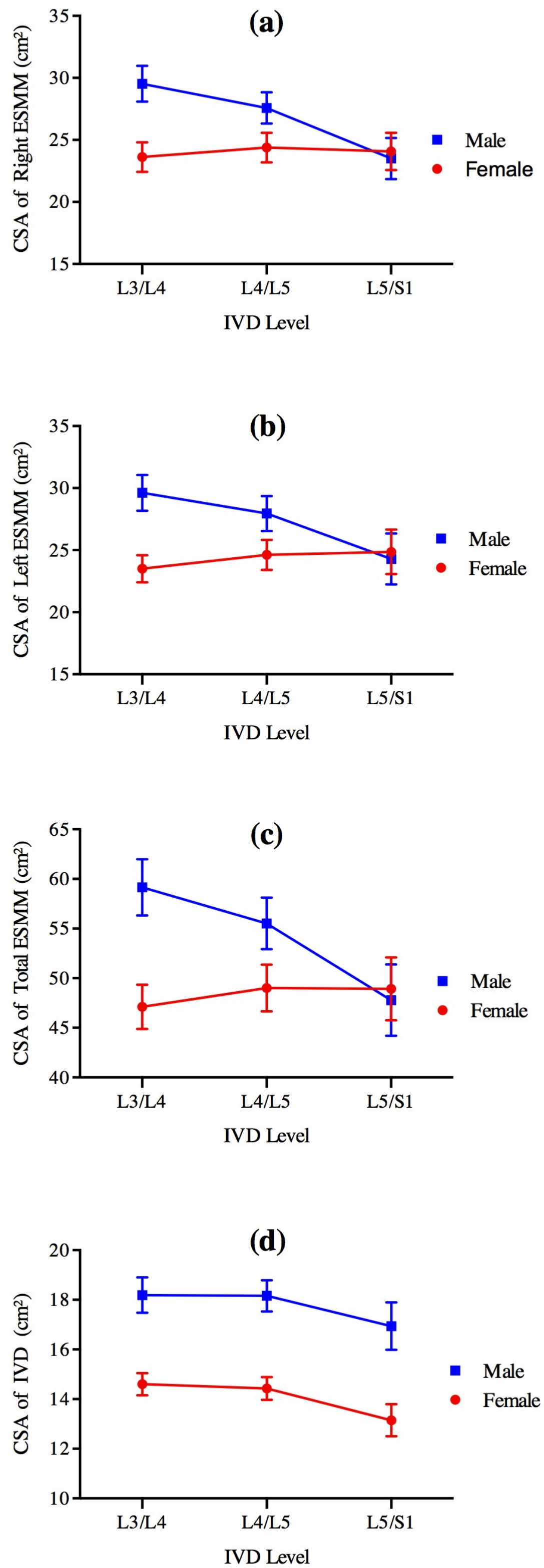



Figure 4.7: Gender comparisons on the CSAs of ESMMs (a: Right ESMM, b: Left ESMM, and c: Total ESMM) and IVDs (d)

SPF analysis; a total of 69 subjects, 35 males and 34 females. Note that there should not be any missing observation for a subject to be able to perform SPF analysis. These 69 subjects had measurements at all three IVD levels. SPF analyses were performed with these 69 subjects. Results of the SPF ANOVA analysis for the total ESMM size are given in Table 4.15. The ANOVA found a main effect of gender ($p = 0.021$) and a main effect of the IVD level ($p = 0.000$). The effect of interaction between gender and IVD level on the total ESMM size was also significant. Figure 4.7.c demonstrates how gender and IVD level affect the size of the ESMM's CSA.

Table 4.15: ANOVA summary table for main and interaction effects of gender and IVD level on the total ESMM size

| **Source** | **SS** | **df** | **MS** | **F-stat** | **Sig.** |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 1158.31 | 1 | 1158.31 | 5.57 | *0.021** |
| Subject(Gender) | 13936.32 | 67 | 208.00 | 9.52 | |
| **Within Subjects** | | | | | |
| IVD Level | 718.47 | 2 | 371.56 | 17.01 | *0.000** |
| Gender*IVD Level | 1084.42 | 2 | 542.21 | 24.82 | *0.000** |
| IVD Level * Subject(Gender) | 2927.88 | 134 | 21.85 | | |
| Total | 19825.4 | 206 | | | |

### The erector spinae muscle mass lever arm (ESMLA) distance

Descriptive statistics for the erector spinae muscle mass lever arm (ESMLA) distances are presented in Table 4.16. The ESMLA distance was 5.08 cm for females and 5.58 cm for males at the L3/L4 IVD level. The lever arm length decreased at the L4/L5 IVD level; 5.00 cm for females and 5.47 cm for males which were the smallest ESMLAs among the three lumbar IVD levels studied. The ESMLA distance was 5.10 cm for females and 5.51 cm for males at the L5/S1 IVD level. The average ESMLA distances for each gender and all subjects are given in Figure 4.8.a. The average ESMLA distance along with the 95% confidence intervals (CI) for each gender are given in Figure 4.8.b.

Table 4.16: Descriptives for the erector spinae muscle mass lever arm (ESMLA) distance

| | | | ESMLA (cm) | | | |
|---|---|---|---|---|---|---|
| | | **N** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 54 | 5.08 | 0.43 | 4.08 | 5.91 |
| | Male | 53 | 5.58 | 0.48 | 4.22 | 6.65 |
| | Total | 107 | 5.33 | 0.52 | 4.08 | 6.65 |
| **L4/L5** | Female | 50 | 5.00 | 0.42 | 3.97 | 5.89 |
| | Male | 44 | 5.47 | 0.42 | 4.66 | 6.42 |
| | Total | 94 | 5.22 | 0.48 | 3.97 | 6.42 |
| **L5/S1** | Female | 41 | 5.10 | 0.42 | 4.20 | 6.14 |
| | Male | 35 | 5.51 | 0.39 | 4.81 | 6.42 |
| | Total | 76 | 5.29 | 0.46 | 4.20 | 6.42 |
| **Total** | Female | 145 | 5.06 | 0.43 | 3.97 | 6.14 |
| | Male | 132 | 5.52 | 0.44 | 4.22 | 6.65 |
| | Total | 277 | 5.28 | 0.49 | 3.97 | 6.65 |

A SPF ANOVA test was performed to evaluate the effect of gender, IVD level, and the interaction between gender and IVD level on the ESMLA distance (Table 4.17). The ANOVA found a main effect of gender ($p = 0.000$). There was not a main effect of IVD level ($p = 0.060$) on the ESMLA distance. However, the interaction between gender and IVD level was statistically significant ($p = 0.003$). Figure 4.8.a and 4.8.b graphically demonstrate the effect of gender and the interaction between gender and IVD level on the ESMLA distances.

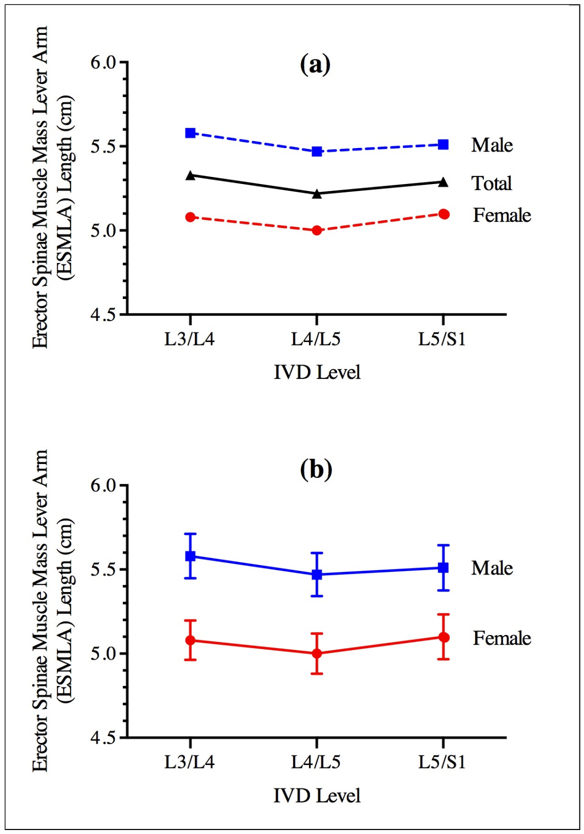



Figure 4.8: ESMLA distances for both genders and at each IVD level

Table 4.17: ANOVA summary table for main and interaction effects of gender and IVD level on the ESMLA distance

| Source | SS | df | MS | F-stat | Sig. |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 6.42 | 1 | 6.42 1 | 4.18 | *0.000** |
| Subject(Gender) | 30.32 | 67 | 0.45 | 16.89 | |
| **Within Subjects** | | | | | |
| IVD Level | 0.15 | 2 | 0.08 | 2.88 | 0.060 |
| Gender*IVD Level | 0.32 | 2 | 0.16 | 6.01 | *0.003** |
| IVD Level * Subject(Gender) | 3.59 | 134 | 0.03 | | |
| Total | 40.80 | 206 | | | |

### 4.3.3 Regression Analyses

**Regression analyses for the cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM)**

A backward regression analysis was performed to determine the estimation equation for each cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM). The dependent variable, the total ESMM ($Y_{ESMM}$), was predicted by the independent variables: gender ($X_G$), age ($X_A$), height ($X_H$), and weight ($X_W$). The estimated model for the CSA of the total ESMM is given below.

$Y_{ESMMi} = \beta_0 + \beta_G X_G + \beta_A X_A + \beta_H X_H + \beta_W X_W + \epsilon_i$; where $\beta_0$ is the constant, $\beta$'s are the coefficient of the independent variables and $\epsilon_i$ is the error term.

One regression analysis was performed for each IVD level, yielding three regression models in total. ANOVA tests revealed that all three regression models were significant ($p \leq 0.05$). This means that the dependent variable can be estimated by independent variables at $p \leq 0.05$ and at least one predictor variable will be included in the model to explain the variability in the total ESMM size. Table 4.18 shows the results of ANOVA tests.

Table 4.18: ANOVA results for the total ESMM regression models

| **ANOVA results** | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | | **SS** | **df** | **MS** | **F** | **Sig.** |
| **L3/L4** | Regression | 6933.948 | 3 | 2311.316 | 39.873 | *0.000** |
| | Residual | 5970.565 | 103 | 57.967 | - | - |
| | Total | 12904.513 | 106 | - | - | - |
| **L4/L5** | Regression | 2985.459 | 2 | 1492.730 | 30.110 | *0.000** |
| | Residual | 4511.380 | 91 | 49.576 | - | - |
| | Total | 7496.839 | 93 | - | - | - |
| **L5/S1** | Regression | 1618.599 | 3 | 539.533 | 6.343 | *0.001** |
| | Residual | 6124.017 | 72 | 85.056 | - | - |
| | Total | 7742.617 | 75 | - | - | - |

The result of the regression analyses to determine the coefficients are given in Table 4.19. The regression model was created in 2 iterations for the L3/L4 level. In the first iteration, all independent variables were included in the model. Since subject age was not significant at the L3/L4 level, it was removed in the second iteration. All remaining independent variables (gender, height, and weight) were significant. At the L4/L5 level, 3 iterations were performed. Height and weight were the only remaining independent variables that were significant. Two backward elimination iterations yielded gender, height, and weight in the regression equation at the L5/S1 level. Note that the "use of probability of F" was selected as 0.05 for entry, and 0.0501 for removal in IBM SPSS. This means that only independent variables whose p-value is less than 0.05 can enter the final model. Further details about iterations are found in Appendix C.

Table 4.19: Coefficients of independent variables in the total ESMM prediction equations

| **Model** | | $\beta_i$ | **Unst. Coeff.** | | **St. Coef.** | **t** | **Sig.** |
|---|---|---|---|---|---|---|---|
| | | | **B** | **St.Err.** | **Beta** | | |
| **L3/L4** | Constant | $\beta_0$ | -9.262 | 13.882 | - | -0.667 | 0.506 |
| | Gender | $\beta_G$ | 7.146 | 1.841 | 0.325 | 3.882 | *0.000* |
| | Height | $\beta_H$ | 0.244 | 0.088 | 0.246 | 2.785 | *0.006* |
| | Weight | $\beta_W$ | 0.209 | 0.038 | 0.394 | 5.474 | *0.000* |
| **L4/L5** | Constant | $\beta_0$ | -20.378 | 11.160 | - | -1.826 | 0.071 |
| | Height | $\beta_H$ | 0.358 | 0.069 | 0.449 | 5.224 | *0.000* |
| | Weight | $\beta_W$ | 0.138 | 0.037 | 0.322 | 3.753 | *0.000* |
| **L5/S1** | Constant | $\beta_0$ | -20.300 | 19.146 | - | -1.060 | 0.293 |
| | Gender | $\beta_G$ | -6.811 | 2.548 | -0.336 | -2.674 | *0.009* |
| | Height | $\beta_H$ | 0.356 | 0.117 | 0.388 | 3.034 | *0.003* |
| | Weight | $\beta_W$ | 0.135 | 0.056 | 0.265 | 2.392 | *0.019* |

Regression equations to estimate the total ESMM are given in Table 4.20. Recall Figure 4.7.c., the CSA of the total ESMM for male subjects was decreasing with the IVD level while it was increasing for female subjects. The CSA of the total ESMM of female subjects was larger than male subjects at the L5/S1 level. That is why the coefficient for gender is positive at the L3/L4 level and negative at the L5/S1 level. Note that the gender multiplier is 0 for females and 1 for males. The response functions having gender effect will produce two parallel lines with different intercepts. Height and weight had positive values (positive linear relationships with the CSA of the total ESMM). This means that the CSA of the total ESMM is increasing for each additional height and weight. For example, the CSA of the total ESMM at the L5/S1 level increases by 0.356 $cm^2$ per cm increase in subject height; and increases by 0.135 $cm^2$ per kg increase in subject weight.

Table 4.20: Prediction equations for the CSA of the total ESMM

| Level | Equations for the total ESMM's CSA | $R^2$ | Adj.$R^2$ | S.E. | p-value |
|---|---|---|---|---|---|
| **L3/L4** | = -9.262 + 7.146*G + 0.244*H + 0.209*W | 0.537 | 0.524 | 7.61 | *0.000** |
| **L4/L5** | = -20.378 + 0.358*H + 0.138*W | 0.398 | 0.385 | 7.04 | *0.000** |
| **L5/S1** | = -20.300 - 6.811*G + 0.356*H + 0.135*W | 0.209 | 0.176 | 9.22 | *0.001** |

CSA ($cm^2$); G: Gender (0 for female, 1 for male); H: Height (cm); W: Weight (kg)

All regression models were linear models. $R^2$ and Adjusted-$R^2$ values were relatively small. Other fitted regression models such as quadratic and exponential regression models might be more appropriate for the data set. To test other model types, more independent variables in the model (two-way interactions between all four independent variables and square-term of all four independent variables) were included in regression analyses. Regression analyses with interactions and square-terms revealed that the following factors should be included in regression models:

(1) age, height, weight-square, product of height and age, weight and age, weight and gender at the L3/L4 level ($R^2 = 0.602$, p = 0.000),

(2) height, product of height and weight, and product of height and age at the L4/L5 level ($R^2 = 0.396$, p = 0.000), and

(3) height, weight, and gender-square at the L5/S1 level ($R^2 = 0.209$, p = 0.001).

However, adding square terms and interaction terms did not significantly alter $R^2$'s and/or Adjusted-$R^2$'s. The added complexity of quadratic and exponential regressions were not deemed worth the trade-off for potentially slightly improved $R^2$ values. Slight improvements in $R^2$ associated with these models were more likely due to an increase in the number of explanatory variables rather than the explanatory power of these variables. These terms made the models more complex to understand. Therefore, first-order regression models with only simple independent variables (gender, age, height, and weight) are presented in the present study. Since regression models are first order models, predictor variables are additive. Since there is no interaction effect, these models are called simple models. The models presented in Table 4.20 are simple linear regression models.

Correlations among independent variables and the CSA of the ESMM are given in Table 4.21. Higher correlations among independent variables result in multicollinearity problems in the data set. Multicollinearity inflates the standard error (and the variance) of a regression coefficient, which results in insignificancy of some independent variables that should be in the model. Variance inflation factor (VIF) helps to detect the presence of multicollinearity in the model. The VIF is defined as $(1 / (1 - R^2))$. In practice, it is assumed that there is a multicollinearity problem if VIF exceeds 5 (or 10). There is no table of critical VIF values to evaluate results. The rule of thumb is if VIF is larger than 5 then multicollinearity may be an issue. VIF values of 5 and higher need further investigation and may result in erroneous removal of the independent variable. Therefore, a VIF of 5 represents a multiple correlation coefficient of 0.8 and a VIF of 10 represent a multiple correlation coefficient of 0.9. The ideal VIF value is 1; meaning that there is no correlation at all. In addition to VIF, tolerance is also used to detect multicollinearity problems. Tolerance is simply the reciprocal of VIF, and therefore, larger tolerance values are desired. The results of collinearity statistics for the present study are provided in Table 4.22. All VIF values only slightly depart from 1 and are between 1.155 and 1.738, which indicates that multicollinearity is not a problem for the present study.

The residual plots against fitted values (Figure 4.9) were drawn for the CSA of the total ESMM at (a) the L3/L4, (b) L4/L5, and (c) L5/S1 levels. Plots did not suggest any

Table 4.21: Correlations among subject variables and the CSA of the total ESMM

| Level | Variables | Statistics | Gender | Age | Height | Weight |
|---|---|---|---|---|---|---|
| **L3/L4 (n = 107)** | **CSA of ESMM** | Pearson Correlation | *0.548** | 0.020 | *0.585** | *0.546** |
| | | Sig. (2-tailed) | 0.000 | 0.842 | 0.000 | 0.000 |
| | **Gender** | Pearson Correlation | | 0.082 | *0.600** | *0.190** |
| | | Sig. (2-tailed) | | 0.399 | 0.000 | 0.050 |
| | **Age** | Pearson Correlation | | | -0.038 | 0.031 |
| | | Sig. (2-tailed) | | | 0.698 | 0.751 |
| | **Height** | Pearson Correlation | | | | *0.364** |
| | | Sig. (2-tailed) | | | | 0.000 |
| | | | **Gender** | **Age** | **Height** | **Weight** |
| **L4/L5 (n = 94)** | **CSA of ESMM** | Pearson Correlation | *0.364** | 0.011 | *0.552** | *0.467** |
| | | Sig. (2-tailed) | 0.000 | 0.917 | 0.000 | 0.000 |
| | **Gender** | Pearson Correlation | | 0.045 | *0.603** | 0.189 |
| | | Sig. (2-tailed) | | 0.670 | 0.000 | 0.068 |
| | **Age** | Pearson Correlation | | | -0.050 | 0.106 |
| | | Sig. (2-tailed) | | | 0.631 | 0.310 |
| | **Height** | Pearson Correlation | | | | *0.322** |
| | | Sig. (2-tailed) | | | | 0.002 |
| | | | **Gender** | **Age** | **Height** | **Weight** |
| **L5/S1 (n = 76)** | **CSA of ESMM** | Pearson Correlation | -0.056 | -0.154 | *0.286** | *0.298** |
| | | Sig. (2-tailed) | 0.628 | 0.183 | 0.012 | 0.009 |
| | **Gender** | Pearson Correlation | | -0.016 | *0.545** | *0.259** |
| | | Sig. (2-tailed) | | 0.890 | 0.000 | 0.024 |
| | **Age** | Pearson Correlation | | | -0.156 | -0.040 |
| | | Sig. (2-tailed) | | | 0.178 | 0.731 |
| | **Height** | Pearson Correlation | | | | *0.309** |
| | | Sig. (2-tailed) | | | | 0.007 |

(*) indicates a significant correlation at the 0.05 level (2-tailed)

Table 4.22: Collinearity statistics for the coefficients of the total ESMM size regression equations

| Model | | Collinearity Statistics | |
|---|---|---|---|
| | | **Tolerance** | **VIF** |
| L3/L4 | Constant | - | - |
| | Gender | 0.639 | 1.564 |
| | Height | 0.575 | 1.738 |
| | Weight | 0.866 | 1.155 |
| L4/L5 | Constant | - | - |
| | Height | 0.896 | 1.115 |
| | Weight | 0.896 | 1.115 |
| L5/S1 | Constant | - | - |
| | Gender | 0.694 | 1.441 |
| | Height | 0.673 | 1.486 |
| | Weight | 0.893 | 1.120 |

systematic deviations from the response planes. Residuals were distributed randomly and did not have a specific pattern; therefore, the linearity assumption holds. There is no need to transform any predictor variables (e.g., logarithmic transformation) to explain model variability.

The error terms are reasonably distributed. The variances of the error terms did not vary with the level of the fitted values. Therefore, the constant variance assumption held for all three IVD levels.

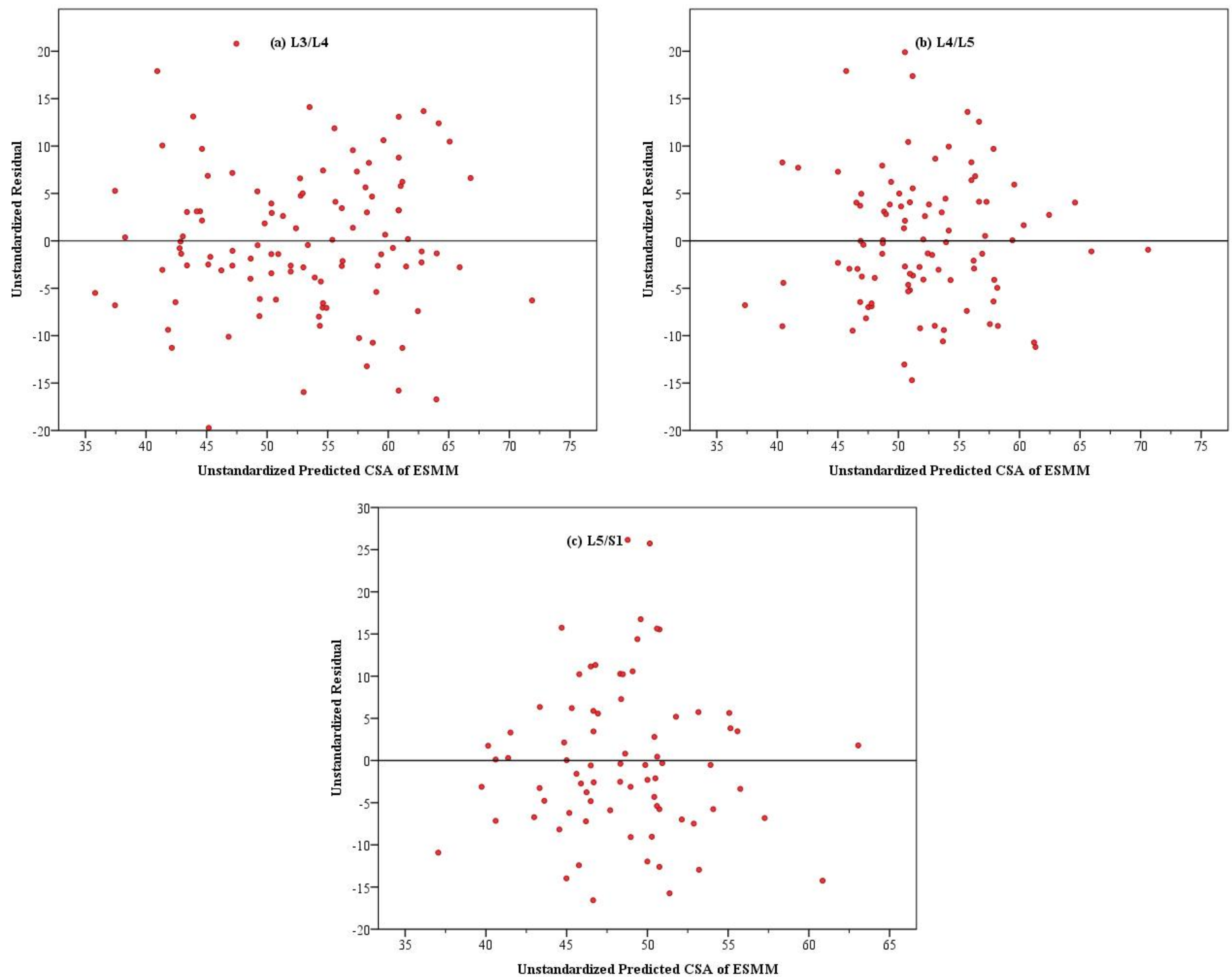



Figure 4.9: The residual plots against the fitted CSA of ESMM values

***Validation of regression models for the cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM)***

To assess how well the regression models estimate the CSA of the total ESMM, 20 male subjects from a new MRI study were selected. Further details about subjects and the data collection process about the new MRI study can be found in Chapter 5. Note that female subjects were not included in model validations since they had statistically different anthropometrics than the female subjects in the present study. Comparisons of the present (historical) study and the new study regarding subject anthropometrics are given in Table 4.23. Statistical tests revealed that subjects in both studies had the same anthropometrics. Therefore, it is expected that regression models derived from the present study should closely estimate the CSA of the total ESMM for the new sample.

Paired samples T-tests were performed to test whether there is any significant difference between the "observed" values measured from MRI scans and the "estimated" values estimated from the regression models. Results suggested that there was no significant difference between the observed and estimated values. This means that the regression models are valid and estimate the CSA of the total ESMM very closely. The mean values of the CSA of total ESMM of male subjects, the mean differences ($\Delta$) between the observed and estimated values at each IVD level, and standard deviations of the mean differences are presented in Table 4.24.

Note that paired T-tests provide comparisons of the two techniques (observed and estimated using regression equations) using the same subject twice. However, a T-test does not report the absolute difference between the observed and estimated values. The mean absolute differences between the observed and estimated CSAs of the total ESMMs are given in Table 4.25. Note that these averages were calculated by subtracting the estimated value from the observed value. Absolute values are preferred to eliminate the direction of the difference (smaller or larger).

Table 4.23: Comparison of subject anthropometrics of the present study and the new study

| Level | Variable | Study | N | Mean | St.d. | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|
| **L3/L4** | Height | Present | 53 | 178.57 | 8.86 | 0.672 | 71 | 0.504 |
| | | New | 20 | 177.04 | 8.06 | | | |
| | Weight | Present | 53 | 84.53 | 19.45 | 0.124 | 71 | 0.902 |
| | | New | 20 | 83.96 | 10.43 | | | |
| | BMI | Present | 53 | 26.41 | 5.23 | -0.274 | 71 | 0.785 |
| | | New | 20 | 26.74 | 2.34 | | | |
| **L4/L5** | Height | Present | 44 | 178.43 | 9.12 | 0.587 | 62 | 0.559 |
| | | New | 20 | 177.04 | 8.06 | | | |
| | Weight | Present | 44 | 85.11 | 19.19 | 0.251 | 62 | 0.803 |
| | | New | 20 | 83.96 | 10.43 | | | |
| | BMI | Present | 44 | 26.68 | 5.22 | -0.049 | 62 | 0.961 |
| | | New | 20 | 26.74 | 2.34 | | | |
| **L5/S1** | Height | Present | 35 | 178.09 | 9.36 | 0.418 | 53 | 0.677 |
| | | New | 20 | 177.04 | 8.06 | | | |
| | Weight | Present | 35 | 84.74 | 19.64 | 0.165 | 53 | 0.870 |
| | | New | 20 | 83.96 | 10.43 | | | |
| | BMI | Present | 35 | 26.72 | 5.61 | -0.018 | 53 | 0.985 |
| | | New | 20 | 26.74 | 2.34 | | | |

Height: cm; Weight: kg, BMI: kg/cm$^2$

The error percentages for the regression models for the ESMM sizes were 11%, 12%, and 15% at the L3/L4, L4/L5, and L5/S1 level, respectively. For example, the average difference between the actual measurement and the estimated value at the L4/L5 level is expected to be 12%. The minimum and maximum values indicate that the closest prediction had 1.01 cm$^2$ difference, and the maximum difference was 28.61 cm$^2$. This means that the regression model made a maximum of approximately 50% error (= 28.61 cm$^2$ / 59.49 cm$^2$) in estimating the CSA of the total ESMM at the L4/L5 level. This large difference suggests that the model does not work well for all circumferences. However, descriptive statistics about absolute differences do not explain the whole scenario here.

Table 4.24: Comparisons of the observed and estimated total ESMM CSAs

| | | CSA of ESMM ($cm^2$) | | | Paired Samples T-tests | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Measurement** | **Mean CSA** | **Δ** | **St.d.** | **t** | **df** | **Sig.** |
| **L3/L4** | Observed | 59.49 | 0.86 | 8.56 | 0.448 | 19 | 0.659 |
| | Estimated | 58.63 | | | | | |
| **L4/L5** | Observed | 56.78 | 2.19 | 9.43 | 1.040 | 19 | 0.311 |
| | Estimated | 54.59 | | | | | |
| **L5/S1** | Observed | 50.89 | 3.64 | 9.31 | 1.747 | 19 | 0.097 |
| | Estimated | 47.25 | | | | | |

Table 4.25: Absolute differences between the observed and estimated CSAs of the ESMMs

| | | | "Absolute" CSA of ESMM ($cm^2$) | | | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Measurement** | **Mean ($cm^2$)** | **Mean Δ** | **St.d.** | **Min** | **Max** | **%** |
| **L3/L4** | Observed | 59.49 | 6.57 | 5.35 | 0.09 | 20.93 | 11.0 |
| | Estimated | 58.63 | | | | | |
| **L4/L5** | Observed | 56.78 | 7.00 | 6.51 | 1.01 | 28.61 | 12.3 |
| | Estimated | 54.59 | | | | | |
| **L5/S1** | Observed | 50.89 | 7.80 | 6.04 | 0.17 | 21.41 | 15.3 |
| | Estimated | 47.25 | | | | | |

Figures showing frequencies of subjects in terms of absolute difference between the observed and estimated CSAs of the total ESMMs may provide better understanding (see Figure 4.10). Figure 4.10.a indicates that the difference between the observed and estimated values at the L3/L4 level were primarily less than 10 $cm^2$ (15 subjects had less than 7.56 $cm^2$ absolute difference). On the other hand, one subject had 20.93 $cm^2$ absolute difference. However, it is known by the researchers that this subject was a weight lifting enthusiast with significant musculature. He had the maximum absolute difference at the L4/L5 level, as well. Twelve subjects had less than 5.21 $cm^2$ absolute difference at the L4/L5 level (approximately 9% error difference). The subject who is a weight lifter had the

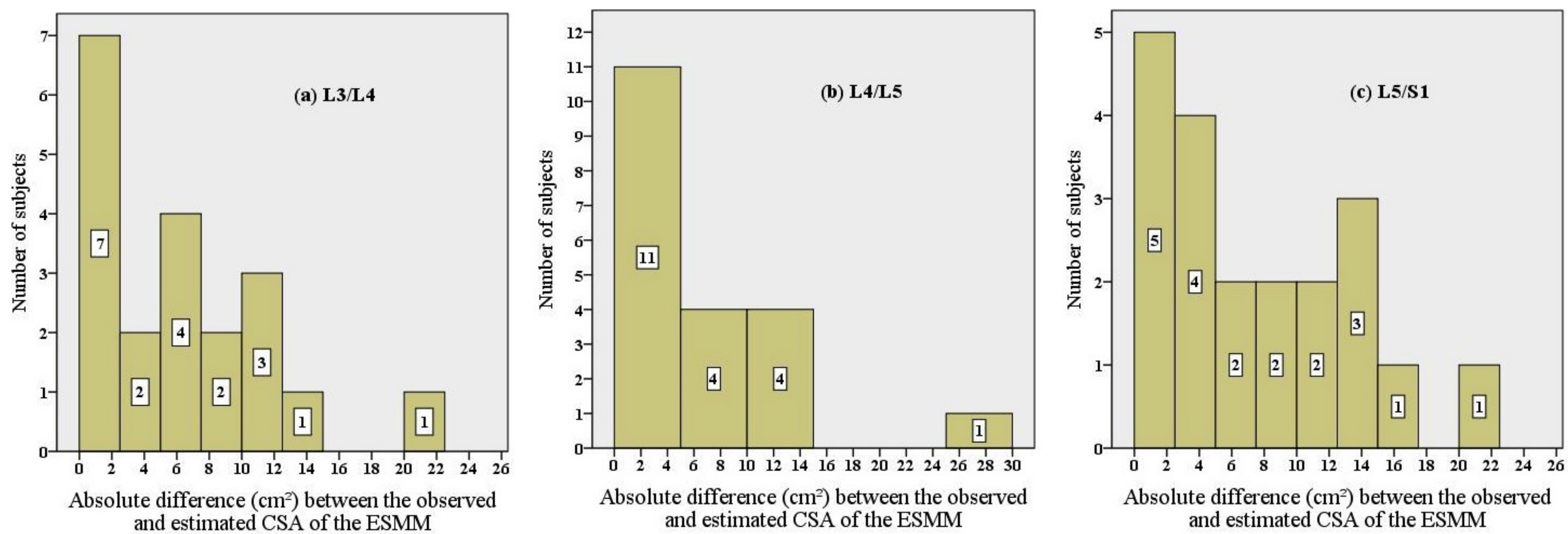



Figure 4.10: Subject frequencies for the absolute differences between the observed and estimated CSA of the total ESMM values

second largest absolute difference at the L5/S1 level; however, the subject who had the largest absolute difference was also a weight lifter. These conclusions indicate that the predictor variables (gender, height, and weight) are not sufficient to explain the variability among subjects. Future studies should investigate further subject characteristics such as the frequency, intensity, and duration of physical exercises. Future studies should include these characteristics in the predictor variable list. For example, lean body mass may be a good predictor of subject muscularity. Perhaps, an interaction of lean body mass and BMI might predict such muscularity.

### Regression analyses for the erector spinae muscle mass lever arm (ESMLA) distance

Backward stepwise regression analyses were performed to determine prediction models for the erector spinae muscle mass lever arm (ESMLA) distances at each IVD level. The dependent variable, the ESMLA ($Y_{ESMLA}$), was predicted by independent variables, gender ($X_G$), age ($X_A$), height ($X_H$), and weight ($X_W$). The fitted model for the ESMLA distance is given below.

$Y_{ESMLAi} = \beta_0 + \beta_1 X_G + \beta_2 X_A + \beta_3 X_H + \beta_4 X_W + \epsilon_i$; where $\beta_i$ is the coefficient of the independent variable and $\epsilon_i$ is the error term.

Regression model were developed for each IVD level. ANOVA tests were performed to test whether the dependent variable ($Y_{ESMLAi}$) can be estimated by the independent variables. The results of ANOVA tests suggested that regression models at all three IVD levels were significant (Table 4.26). This means that the ESMLA distance can be estimated by at least one of the independent variables at $\alpha = 0.05$ significance level.

The results of regression analyses are given in Table 4.27. Regression models at all IVD level were developed after 4 iterations. Iterations are provided in Appendix D. In the first iteration, all estimators were included in the model. One non-significant predictor was removed in each iteration. After 4 iterations, height was the only remaining variable in all

Table 4.26: ANOVA results for the ESMLA distance regression models

| ANOVA results | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | | **SS** | **df** | **MS** | **F** | **Sig.** |
| **L3/L4** | Regression | 12.509 | 1 | 12.509 | 81.539 | *0.000** |
| | Residual | 16.108 | 105 | 0.153 | - | - |
| | Total | 28.618 | 106 | - | - | - |
| **L4/L5** | Regression | 8.882 | 1 | 8.882 | 65.376 | *0.000** |
| | Residual | 12.499 | 92 | 0.136 | - | - |
| | Total | 21.380 | 93 | - | - | - |
| **L5/S1** | Regression | 5.554 | 1 | 5.554 | 40.841 | *0.001** |
| | Residual | 10.063 | 74 | 0.136 | - | - |
| | Total | 15.617 | 75 | - | - | - |

three regression models. Note that the forward selection criteria also provided the same results as the backward selection criteria given below.

Table 4.27: Coefficients of independent variables in prediction equations of the ESMLA distance

| **Model** | | $\beta_i$ | **Unst. Coeff.** | | **St. Coef.** | **t** | **Sig.** |
|---|---|---|---|---|---|---|---|
| | | | **B** | **St.Err.** | **Beta** | | |
| **L3/L4** | Constant | $\beta_0$ | 0.160 | 0.589 | - | 0.027 | 0.978 |
| | Height | $\beta_H$ | 0.031 | 0.003 | 0.661 | 9.030 | 0.000 |
| **L4/L5** | Constant | $\beta_0$ | 0.515 | 0.583 | - | 0.884 | 0.379 |
| | Height | $\beta_H$ | 0.027 | 0.003 | 0.645 | 8.086 | 0.000 |
| **L5/S1** | Constant | $\beta_0$ | 1.063 | 0.663 | - | 1.604 | 0.113 |
| | Height | $\beta_H$ | 0.025 | 0.004 | 0.596 | 6.391 | 0.000 |

Regression equations to estimate the ESMLA distances are given in Table 4.28. Height was the only estimator that was included in the models. The marginal effect of each additional increase in height (cm) was the highest at the L3/L4 level and lowest at the L5/S1 level. The ESMLA distance at the L3/L4 level will incase by 0.031 cm per cm increase in subject height while the increase will be 0.025 cm at the L5/S1 level. The constant value, on the other hand, was the largest at the L5/S1 level and smallest at the L3/L4 level. Higher coefficients reduce the dependency of the dependent variable on the independent variables. The determination of coefficient ($R^2$) values reduce, as well. The L3/L4 level had the largest $R^2$ value (0.437) while the L5/S1 level had the smallest $R^2$ value (0.347). Note that $R^2$ is the measure of the "goodness of fit" of a (linear) model. The relationship between the ESMLA distance and subject height is given in Figure 4.11.

Table 4.28: Prediction equations for ESMLA distances

| **Level** | **Equations for the ESMLA distance** | $\mathbf{R^2}$ | **Adj.** $\mathbf{R^2}$ | **S.E.** | **p-value** |
|---|---|---|---|---|---|
| L3/L4 | = 0.016 + 0.031*H | 0.437 | 0.432 | 0.39 | *0.000** |
| L4/L5 | = 0.515 + 0.027*H | 0.415 | 0.409 | 0.37 | *0.000** |
| L5/S1 | = 1.063 + 0.025*H | 0.356 | 0.347 | 0.37 | *0.000** |

ESMLA (cm); H: Height (cm)

Correlations among subject variables and the ESMLA distances at each IVD level are given in Table 4.29. VIF values were investigated to detect multicollinearity caused by higher correlations among independent variables. The variance of the regression coefficients are inflated with higher multicollinearity, resulting in small t-values and unstable regression coefficients. Since there is only one independent variable (height) in all three regression models, multicollinearity is not a problem for the ESMLA prediction models in the present study. Note that VIF equals 1 if there is only one predictor in a model.

Residual plots against the fitted ESMLA values are given in Figure 4.12. Residuals distribute randomly in plots for (a) the L3/L4, (b) L4/L5, and (c) L5/S1 IVD levels. They do not have any pattern, which is a sign of non-linearity. Therefore, it can be concluded that residual plots against the fitted values suggest that linear regression functions are appropriate at each IVD level. Current predictors appear to be enough to explain the model variability. In addition to the linearity assumption, the constant variance assumption held for each IVD level since the residuals do not have any pattern. Residuals are random; and they do not change with the magnitude of the predicted value. As discussed in the preliminary model investigation section, the residual plots support that there was no serious outliers in the data sets. Therefore, no observations play a significant role in biasing the regression results or in influencing conclusions.

Table 4.29: Correlations among subject variables and ESMLA distances

| **Level** | **Variables** | **Statistics** | **Gender** | **Age** | **Height** | **Weight** |
|---|---|---|---|---|---|---|
| **L3/L4 (n = 107)** | **ESMLA** | Pearson Correlation | *0.477** | 0.057 | *0.661** | *0.311** |
| | | Sig. (2-tailed) | 0.000 | 0.556 | 0.000 | 0.001 |
| | **Gender** | Pearson Correlation | | 0.082 | *0.600** | *0.190** |
| | | Sig. (2-tailed) | | 0.399 | 0.000 | 0.050 |
| | **Age** | Pearson Correlation | | | -0.038 | 0.031 |
| | | Sig. (2-tailed) | | | 0.698 | 0.751 |
| | **Height** | Pearson Correlation | | | | *0.364** |
| | | Sig. (2-tailed) | | | | 0.000 |
| | | | **Gender** | **Age** | **Height** | **Weight** |
| **L4/L5 (n = 94)** | **ESMLA** | Pearson Correlation | *0.494** | 0.076 | *0.645** | 0.157 |
| | | Sig. (2-tailed) | 0.000 | 0.464 | 0.000 | 0.130 |
| | **Gender** | Pearson Correlation | | 0.045 | *0.603** | 0.189 |
| | | Sig. (2-tailed) | | 0.670 | 0.000 | 0.068 |
| | **Age** | Pearson Correlation | | | -0.050 | 0.106 |
| | | Sig. (2-tailed) | | | 0.631 | 0.310 |
| | **Height** | Pearson Correlation | | | | *0.322** |
| | | Sig. (2-tailed) | | | | 0.002 |
| | | | **Gender** | **Age** | **Height** | **Weight** |
| **L5/S1 (n = 76)** | **ESMLA** | Pearson Correlation | *0.457** | -0.054 | *0.596** | *0.322** |
| | | Sig. (2-tailed) | 0.628 | 0.644 | 0.000 | 0.005 |
| | **Gender** | Pearson Correlation | | -0.016 | *0.545** | *0.259** |
| | | Sig. (2-tailed) | | 0.890 | 0.000 | 0.024 |
| | **Age** | Pearson Correlation | | | -0.156 | -0.040 |
| | | Sig. (2-tailed) | | | 0.178 | 0.731 |
| | **Height** | Pearson Correlation | | | | *0.309** |
| | | Sig. (2-tailed) | | | | 0.007 |

(*) indicates a significant correlation at the 0.05 level (2-tailed)

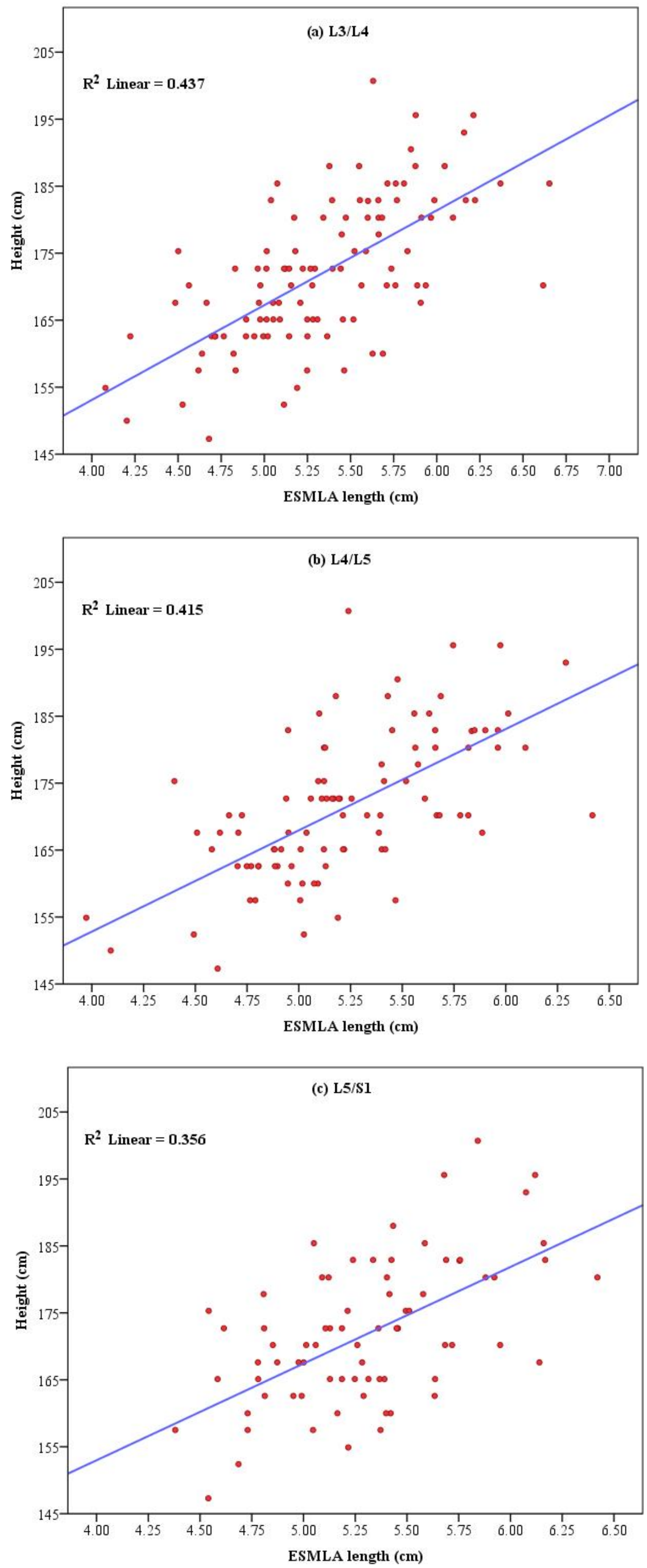



Figure 4.11: Correlations between subject height and the ESMLA distance at each IVD level

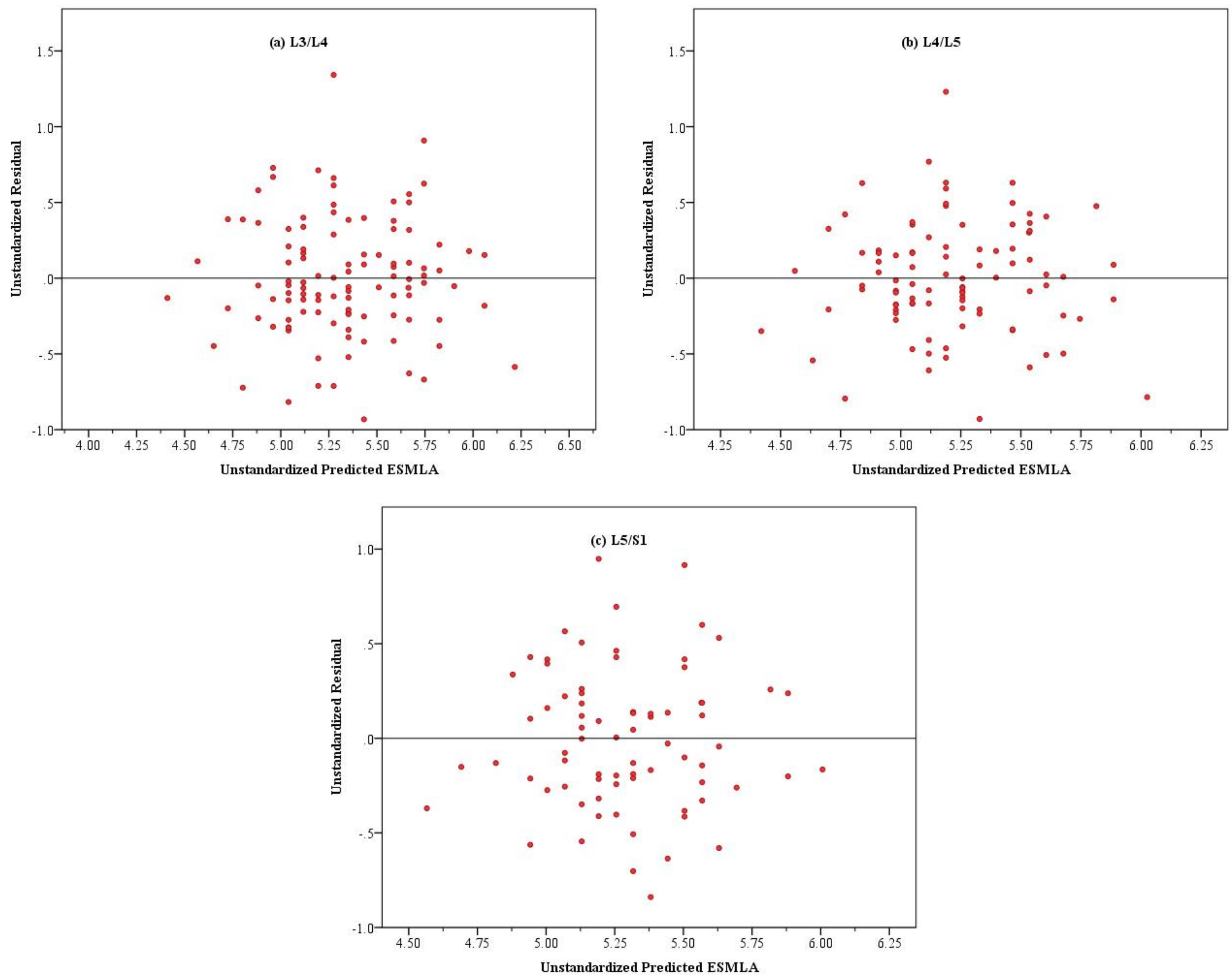



Figure 4.12: Residual plots against the fitted ESMLA values

Scatter plots of the fitted ESMLA values against to the measured ESMLA values are given in Figure 4.13. These plots demonstrate the strength of the linear relationship between the response variable (the ESMLA distance) and the predictors (only subject height in this case). Note that the black solid lines depict the fitted lines and blue dotted lines depict the 95% confidence intervals (CI) for the fitted lines. There are some data points outside the 95% CI, but they are acceptable at $\alpha = 0.05$. If the relationship between the fitted values and observed values is perfect ($R^2 = 1$), all data points will be on the regression line. However, plots in the present study suggest that the relationship is not perfect and there are some variations between the fitted and observed values.

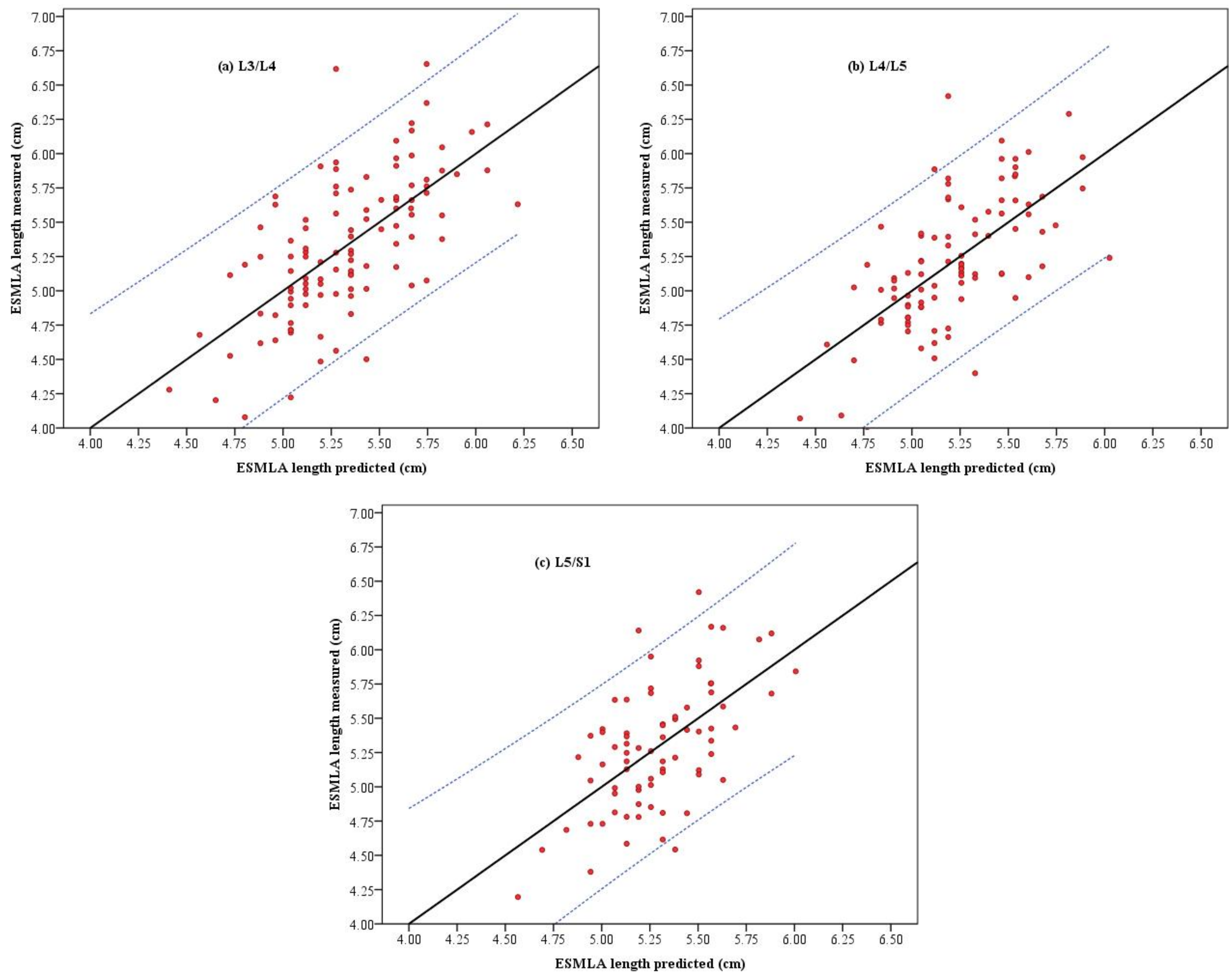



Figure 4.13: The fitted ESMLA values against the observed ESMLA values

***Validation of regression models for the erector spinae muscle mass lever arm (ESMLA) distance***

Twenty male subjects from a new MRI study were used to assess how well the regression models predict the ESMLA distances. Anthropometrics for the male subjects were statistically similar to the male subjects of the present study (see Table 4.23). Therefore, it is expected that regression models derived from the present study should closely estimate the ESMLA distances for these 20 male subjects.

Paired samples T-tests were performed to test whether there was any significant difference between the "observed" and "estimated" ESMLA distances. Results indicate that there was no significant difference between the observed and estimated ESMLA distances (Table 4.30), which means that regression models to estimate the ESMLA distance were valid and there was not a statistically significant difference between the observed and estimated ESMLA distances.

Table 4.30: Comparisons of the observed and estimated ESMLA distances

| | | **ESMLA distance (cm)** | | | **Paired Samples T-tests** | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Measurement** | **Mean** | **Δ** | **St.d.** | **t** | **df** | **Sig.** |
| **L3/L4** | Observed | 5.43 | -0.07 | 0.26 | -1.282 | 19 | 0.215 |
| | Estimated | 5.50 | | | | | |
| **L4/L5** | Observed | 5.34 | 0.04 | 0.26 | 0.706 | 19 | 0.489 |
| | Estimated | 5.30 | | | | | |
| **L5/S1** | Observed | 5.57 | 0.08 | 0.30 | 1.145 | 19 | 0.267 |
| | Estimated | 5.49 | | | | | |

Absolute differences between the observed and estimated ESMLA distances at each IVD level were also calculated (Table 4.31). The error percentages for regression models for the ESMLA are 3.9%, 4.1%, and 4.2% at the L3/L4, L4/L5, and L5/S1 level, respectively. This means that an average of 4% difference between the observed and estimated ESMLA distances are expected.

Table 4.31: Absolute differences between the observed and estimated ESMLA distances

| | | | Absolute ESMLA (cm) | | | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Measurement** | **Mean (cm)** | **Mean Δ** | **St.d.** | **Min** | **Max** | **%** |
| **L3/L4** | Observed | 5.43 | 0.21 | 0.16 | 0.00 | 0.47 | 3.9 |
| | Estimated | 5.50 | | | | | |
| **L4/L5** | Observed | 5.34 | 0.22 | 0.13 | 0.02 | 0.52 | 4.1 |
| | Estimated | 5.30 | | | | | |
| **L5/S1** | Observed | 5.57 | 0.23 | 0.20 | 0.01 | 0.71 | 4.2 |
| | Estimated | 5.49 | | | | | |

The mean absolute difference between the observed and the fixed (5 cm) ESMLA distances were calculated at each level (Table 4.32). The average percent of the absolute errors are 7.9%, 7.2%, and 10.2% at the L3/L4, L4/L5, and L5/S1 level, respectively. These errors are approximately twice as the absolute errors resulting from the regression estimations, 3.9%, 4.1%, and 4.2%, respectively. Note that these numbers are averages and the error terms of the fixed number do not seem as very large. However, these errors are very high for extreme (very small and large) ESMLA distances. Regression models provided in the present study will decrease the amount of error for these extremes. Table 4.32 also provides the comparison of the observed ESMLA distances and the mean value of the ESMLA distances. The average ESMLA distance for these 20 male subjects were 5.43, 5.34, and 5.57 cm for the L3/L4, L4/L5, and L5/S1 level, respectively. The average errors for use of these averages are smaller than the errors resulting use of the fixed ESMLA (5 cm). However, the use of the regression model results in less error than a fixed ESMLA assumption. Figure 4.14 illustrates the errors in the ESMLA distances for these three methods.

Table 4.32: Comparisons of absolute differences between the observed ESMLA value and the estimated, average, and fixed (5 cm) ESMLA values

| | | Δ in ESMLA distances (cm) | | | | |
|---|---|---|---|---|---|---|
| | ***Observed vs.*** | **Mean** | **St. d.** | **Min** | **Max** | **Error** |
| **L3/L4** | Regression estimates | 0.21 | 0.16 | 0.00 | 0.47 | 3.9% |
| | Use of averages | 0.27 | 0.16 | 0.05 | 0.61 | 5.0% |
| | Fixed number (5 cm) | 0.43 | 0.32 | 0.02 | 1.04 | 7.9% |
| **L4/L5** | Regression estimates | 0.22 | 0.13 | 0.02 | 0.52 | 4.1% |
| | Use of averages | 0.26 | 0.20 | 0.01 | 0.66 | 4.8% |
| | Fixed number (5 cm) | 0.38 | 0.27 | 0.13 | 1.00 | 7.2% |
| **L5/S1** | Regression estimates | 0.23 | 0.20 | 0.01 | 0.71 | 4.2% |
| | Use of averages | 0.27 | 0.22 | 0.01 | 0.71 | 4.9% |
| | Fixed number (5 cm) | 0.57 | 0.36 | 0.06 | 1.28 | 10.2% |

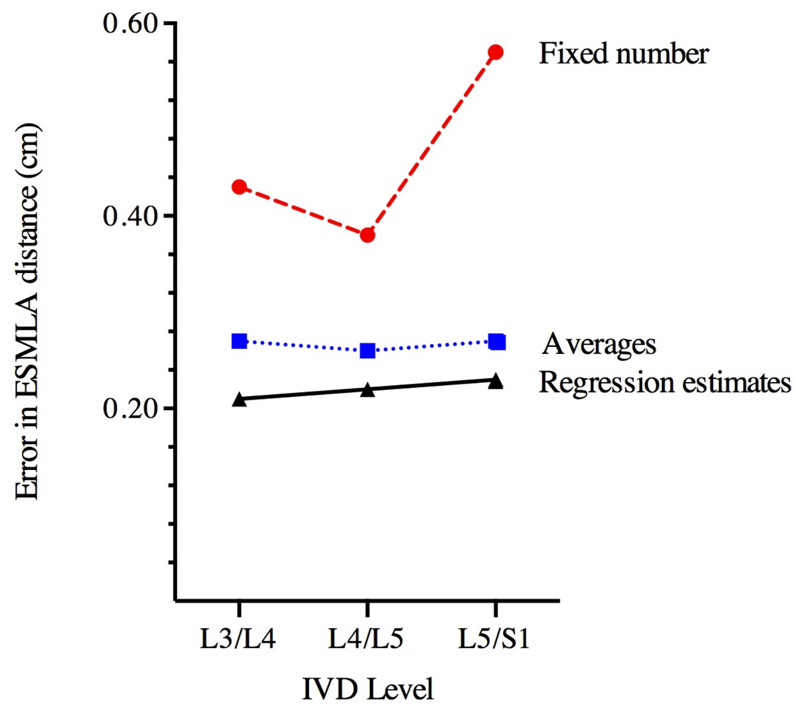



Figure 4.14: Error comparisons between the observed ESMLA value and the estimated, average for gender and level, and fixed (5 cm) ESMLA values

## 4.4 Discussion

The purpose of this MRI study was to provide prediction models for the cross-sectional area (CSA) of the erector spinae muscle mass (ESMM) and the erector spinae muscle mass lever arm (ESMLA). Prediction models may decrease the error in prediction of spinal forces that can result from over-simplification of the musculoskeletal structure (e.g., using a fixed ESMLA). The relationship between the morphology of the low back musculature and individual characteristics (i.e., age and gender) and anthropometrics (i.e., height, weight) has been studied by other researchers. However, prediction models that estimate a subject's ESMM size using these characteristics have been elusive (Reid *et al.*, 1987; McGill *et al.*, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990; Cooper *et al.*, 1992; Wood *et al.*, 1996; Marras *et al.*, 2001; Jorgensen *et al.*, 2003a; Seo *et al.*, 2003; Anderson *et al.*, 2012) and ESMLA distance (Reid and Costigan, 1985; Reid *et al.*, 1987; Kumar, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990; Moga *et al.*, 1993; Wood *et al.*, 1996; Jorgensen *et al.*, 2001 and 2003b; Seo *et al.*, 2003; Lee *et al.*, 2006; Anderson *et al.*, 2012).

The present study included a relatively larger sample size [107 subjects (54 females, 53 males) at the L3/L4 level, 94 subjects (50 females, 44 males) at the L4/L5 level, and 76 subjects (41 females, 36 males) at the L5/S1 level] compared to most previous studies (Reid and Costigan, 1985 (12 females, 16 males); Reid *et al.*, 1987 (20 males); Kumar, 1988 (11 females, 21 males); McGill *et al.*, 1988 (13 males); Tracy *et al.*, 1989 (26 males); Moga *et al.*, 1993 (8 females, 11 males); Wood *et al.*, 1996 (26 males); Jorgensen *et al.*, 2001 (20 females, 10 males); Marras *et al.*, 2001 (20 females, 10 males); Jorgensen *et al.*, 2003a and 2003b (12 females, 12 males); Lee *et al.*, 2006 (34 females). The average age was 29.3 years for females and 30.1 years for males. Males were significantly heavier and taller than females when compared at each IVD level at $\alpha = 0.05$. The average BMI of female subjects (28.09 kg/m$^2$) was larger than male subjects (26.17 kg/m$^2$), but this difference was not statistically significant.

The measurement technique used in the present study was highly reliable and repeatable. The CSA of the ESMMs and IVD and the ESMLA from 40 randomly selected subject images were measured by two researchers. Intra-class correlation coefficients (ICC) were excellent (ranging from 0.968 to 0.998) (see Table 4.11 for the interpretation of ICC score). These two researchers also reported measurements after 4 weeks with the order of measurements randomized for both sets of observations. The inter-class correlation coefficients for the first and second measurements were in good agreement (ranging from 0.811 to 0.997).

Results of paired-samples T-tests indicated that there was not a significant difference between the right and left ESMMs. Correlations between both ESMMs at each level were also very high (ranging from 0.845 to 0.938). Therefore, it was concluded that there is no asymmetry between the right and left muscle sizes. Reid and Costigan (1985), Kumar (1988), Millerchip, Savage, and Edwards (1988), Chaffin *et al.* (1990), Moga *et al.* (1993), McGill *et al.* (1993), Guzik *et al.* (1996), and Jorgensen *et al.* (2001) also found that there was no significant difference between the right and left CSAs of the ESMM. However, it should be noted that these asymmetry comparisons were made for the right and left side, and presumably based on the assumption that people are mostly right-hand dominant. Studies that investigate the asymmetry of the dominate and non-dominant hand sides may provide better understanding of muscle symmetries.

## Prediction models for the cross sectional areas (CSA) of the erector spinae muscle mass (ESMM)

### *Age and the CSA of the ESMM*

In the present study, regression analyses indicated that gender, height, and weight were predictors that estimate the CSA of the total ESMM. Subject age was not significant at any IVD level. It should be noted that subject age was limited in range (21 - 39 years), which may be the reason why age was not distinctive for the ESMM size. The association between the decrease in the muscle mass and aging has been reported in the literature (Lexell *et al.*,1988, Brooks and Faulkner, 1994, and Faulkner *et al.*, 2007). However, some previous researchers did not include subject age as a predictor in their regression models (McGill *et al.*, 1988; Cooper *et al.*, 1992). Other studies did not find any relationship with the subject age and the ESMM size (Seo *et al.*, 2003). Age was included in Anderson *et al.*'s (2012) regression models. However, they included all variables even though they were not significant. Their regression analyses reported that the coefficient of the subject age was not significant, but they did not remove age from their model. Reid *et al.* (1987) could not determine whether there is an age effect on the ESMM size since the age range of their subjects was relatively small.

*Gender and the CSA of the ESMM*

Gender was a significant predictor in determining the ESMM CSA at the L3/L5 and L5/S1 levels in the present study. Correlation analyses revealed that the CSA of the total ESMM was correlated with subject gender at the L3/L4 and L4/L5 levels. Cooper *et al.* (1992) investigated the effect of gender on the ESMM size at the L4 level. They found that male subjects had approximately 2 $cm^2$ larger CSAs. Marras *et al.* (2001) found that male subjects had significantly larger ESMMs than female subjects. They provided different regression models for males and females. Jorgensen *et al.* (2003) had 12 males and 12 females in the MRI study to determine the effect of torso flexion on the CSA of the ESMM. Gender was included in their regression models at the L3/L4 and L4/L5 levels, but not for the L5/S1 level. Note that gender in the present study was in models at the L3/L4 and L5/S1 levels. Seo *et al.* (2003) provided one regression model for each gender to estimate the CSA of the ESMM at the L3/L4 level. A recent study with a relatively large sample size was conducted by Anderson *et al.* (2012). They provided regression models for each vertebral level. Gender was significant at the L3 level and not significant at the L4 and L5 levels. Note that their regression model at the L5 level was not significant at all. In the present study, gender was significant for the L3/L4 level and L5/S1 level, but not significant at the L4/L5 level. It can be concluded that both the present study and Anderson *et al.*'s (2012) study agree that gender has an effect on the muscle size at the L3 or L3/L4 level, but not significantly at L4 or L4/L5 level. A major difference between their study and the present study was that their regression model was not significant at the L5 level while the regression model of the present study was significant at the L5/S1 level.

In general, it can be concluded that gender impacts ESMM size. However, the IVD levels were such gender effects occur vary among studies. This may be the result of different subject anthropometrics and characteristics and of limited sample sizes. Measurement techniques, ESMM definition, scanning posture, and scan plane may be other reasons that cause some variation among studies.

Since Reid *et al.* (1987), McGill *et al.* (1988), Tracy *et al.* (1989), and Wood *et al.* (1996) studied only male subjects and Chaffin *et al.* (1990) studied only female subjects, they could not investigate gender effects on the ESMM size.

*Height and the CSA of the ESMM*

Results from the present study indicated that height was a significant variable predicting the ESMM CSAs at all IVD levels studied. However, some previous researchers did not find a significant relationship between the CSA of the ESMM and subject height. Reid *et al.* (1987) investigated the CSA of the ESMM at the L5 level and could not find any correlation between height and the ESMM size. Note that they had a small sample size of 20 males. McGill *et al.* (1988) also could not find any relationship between subject height and the ESMM size. They also had a small sample size of 13 males. Tracy *et al.* (1989) also could not find any regression model for the ESMM size for 26 male subjects. They limited their regression models to only one constant and one estimator, which may have resulted in failure to determine synergetic relationships. In the present study, gender, height, and weight were all included together in the model. Wood *et al.* (1996) could not find any relationship between height and the ESMM size at the L4/L5 level. They had 26 males in their study. Seo *et al.* (2003) found significant correlation between height and ESMM size for male subject, but not for female subjects. Their regression equations were limited to only one variable in the model. They provided a model with the largest $R^2$ value, which only included weight. Therefore, it is unknown whether they could have obtained a regression model including height.

On the other hand, some researchers found significant relationships between height and the ESMM size, as the present study did. Chaffin *et al.* (1990) found a significant correlation between subject height and the ESMM size, and then included a height variable in their regression model to estimate the CSA of the ESMM. The coefficient of determination, however, for their regression model was 0.26. The coefficients of determination ($R^2$) in the present study was larger for the L3/L4 and L4/L5 levels; 0.54 and 0.40, respectively. However, $R^2$ was smaller than Chaffin *et al.*'s (1990) average value; 0.21 at the L5/S1 level. Marras *et al.*'s (2001) study included ratios of height to weight and weight to height in the regression models. Jorgensen *et al.* (2003) included height in the regression models at the L3/L5 and L5/S1 levels, but not at L4/L5 level. Height was included in Anderson *et al.*'s (2012) regression models. However, height was not significant at any of the low vertebral levels even though it was in the models.

As with gender, height was not consistently evaluated across studies. Some researchers found relationships between height and the ESMM size, but some researchers did not. This may be the result of differences in sampling and/or methods used. For example, Anderson *et al.* (2012) separated the erector spinae and transversospinalis muscle groups while both muscle groups are combined in the present study and most of the previous studies.

*Weight and the CSA of the ESMM*

Subject weight was significantly correlated with the CSA of the ESMM at all IVD levels in the present study. Weight was also used in regression models estimating the

ESMM size. Several researchers also found significant associations between subject weight and ESMM size. Reid *et al.* (1987) studied 20 male subjects and found a significant correlation between weight and the CSA of the ESMM. Chaffin *et al.* (1990) studied 96 female subjects and also found a significant correlation between subject weight and the ESMM size and included weight in the regression model to estimate the CSA of the ESMM. Their regression equation (Table 4.1) indicated that the ESMM size increases approximately 0.12 $cm^2$ per kg increase in the weight. Cooper *et al.* (1992) also found significant correlation between subject weight and the CSA of the ESMM. Marras *et al.* (2001) conducted an MRI study with 10 males and 20 females. They provided three regression models for each gender and each side (the left and right ESMMs). All their regression equations included weight. They had higher $R^2$'s (ranging from 0.47 to 0.72) compared to the present study (ranging from 0.176 to 0.524). Jorgensen *et al.* (2003a) also reported that weight was a significant predictor to estimate the ESMM size at the L3/L4, L4/L5, and L5/S1 levels. Seo *et al.* (2003) reported two regression models at the L3/L4 level, one model for each gender. The model for male subjects included weight and the model for the female subjects included weight-squared in the model. Anderson *et al.* (2012) found that subject weight was significant at the L3 and L4 vertebral levels. However, weight was not significant at the L5 level. It should be noted that the regression model at the L5 level was not significant at all ($R^2 = 0.04$).

On the other hand, some researchers indicated that the CSA of the ESMM was not associated with subject weight. McGill *et al.* (1988) studied 13 male subjects and could not find any significant regression model for the ESMM size. Tracy *et al.* (1989) also could not find any relationship between weight and ESMM size for 26 male subjects. Wood *et al.* (1996) regressed anthropometric variables including weight and could not find any regression model to estimate the ESMM size. After they normalized their BMI data, they found that obese subjects had smaller ESMM sizes compared to lean subjects.

Among predictor variables, it seems that subject weight was the most promising variable to estimate the CSA of the ESMM. In the present study, subject weight was in regression models at all levels. McGill *et al.* (1988) and Tracy *et al.* (1989) were the only two studies that did not find any relationship between the ESMM size and weight. Wood *et al.* (1996) found the relationship after they normalized BMIs. It should be noted that the mean weight was 89.1 kg in McGill *et al.*'s (1988) study and 87.3 kg in Wood *et al.*'s (1996) study, which were the two heaviest sample populations among the studies compared here (Table 4.1). These subjects were significantly heavier (more obese) than subjects in the other studies and this, along with relatively small sample size, may have impeded their ability to find a relationship with height. Tracy *et al.* (1989), unfortunately, did not provide any anthropometric measurements regarding subject weight. Therefore, it is not possible to interpret the relationship between subject weight and the ESMM size.

*Other predictor variables and the CSA of the ESMM*

Some researchers found significant relationships between the CSA of the ESMM and predictor variables such as trunk circumference (Reid *et al.* 1987), trunk depth and width (Jorgensen *et al.*, 2003a), and trunk area (Chaffin *et al.*, 1990). These measurements were not recorded in the present study; therefore, the relationships between these measurements and the CSA of the ESMM could not be investigated. These relationships should be studied in future studies by taking more anthropometric measurements from subjects.

### Prediction models for the erector spinae muscle mass lever arm (ESMLA) distance

*Age and the ESMLA distance*

Reid *et al.* (1987) and Kumar (1988) could not address possible age effects on the ESMLA distance. Reid *et al.* (1987) had young 20 males ($\bar{x} = 21.2$ years) and Kumar (1988) had relatively older subjects (mean age ranging from 55.2 to 62.2 years old).

Jorgensen *et al.* (2001) did not include age in their regression analyses. On the other hand, Moga *et al.* (1993), Seo *et al.* (2003), and Anderson *et al.* (2012) included age in the ESMLA distance prediction models. Note that Moga *et al.* (1993) did not provide any descriptive statistics about their subjects. Moreover, they included all predictor variables in regression models and did not consider whether they were significantly correlated with the ESMLA. Age was correlated only with male subjects in Seo *et al.*'s (2003) study and the coefficient of correlation was modest (0.232). Anderson *et al.* (2012) reported that age was not significant, however, it was included in the ESMLA prediction equations. To conclude, age was significant only in Seo *et al.*'s (2003) study and only significant for male subjects with a small correlation coefficient. Age was included in the regression analyses in the present study, but it was removed from prediction equations since it did not show any ability to estimate the ESMLA distance.

*Gender and the ESMLA distance*

Some researchers could not address any gender effect on the ESMLA distance since they had only one gender in their studies [only male subjects (Reid *et al.*, 1987; Tracy *et al.*, 1989; Wood *et al.*, 1996) or female subjects (Chaffin *et al.*, 1990; Lee at al., 2006)]. Kumar (1988) found that the ESMLA distance is dependent on gender. However, gender was not included in the multiple regression analyses as a possible estimator. Moga *et al.* (1993), Jorgensen *et al.* (2001), and Seo *et al.* (2003) did not include gender in the regression models, but they provided different regression models for each gender to emphasize the gender effect on ESMLA distance. It should be noted that $R^2$ values were larger in female subjects (ranging from 0.87 to 0.91) than male subjects (ranging from 0.23 to 0.26) in Moga *et al.*'s (1993) study while $R^2$ values were smaller in female subjects (ranging from 0.229 to 0.313) than male subjects (ranging from 0.415 to 0.652) in Jorgensen *et al.*'s (2001) study. Therefore, it can be concluded that the effect of gender on the ESMLA distance is not consistent across studies. In the present study, male subjects had larger ESMLA distances at each IVD level. ANOVA tests found a main effect of gender ($p = 0.000$) on the ESMLA distance. Independent T-tests also supported the same conclusion that males had larger ESMLA distances than females. However, gender was not statistically significant in the regression models; therefore, it was removed from the regression equations. It can be questionable that T-tests found gender effect, but regression analyses found no gender effect. This could be a result of not having matched male and female subjects regarding their anthropometrics. Height and weight are possibly confounding factors for gender difference. All regression equations revealed that height was the only predictor to estimate the ESMLA distance. Therefore, it can be concluded that the difference between males and females may actually have resulted the height difference between the genders. Height might be a confounding factor in ANOVA and T-tests seeking a gender effect. It is suggested that future studies should select matched pairs (male-female pair with similar anthropometrics) to address the gender effect alone.

*Height and the ESMLA distance*

Reid *et al.* (1987) studied 20 young male subjects to determine the relationship between anthropometric measurements and the ESMLA distance. They concluded that height was significantly correlated ($r = 0.40$) with the ESMLA distance. However, their regression model for the ESMLA distance at the L5 level did not include height as a predictor. It should be noted that they determined centroid points by drawing axes (an oversimplification). Kumar (1988) and Chaffin *et al.* (1990) found that there was no significant case of regression derived from height. Subjects in both studies were relatively older. Tracy *et al.* (1989) studied 26 males. Results of their regression analyses did not find any significant relationship between the ESMLA distance and anthropometrics including height. It should be noted that they had transverse scans and visually determined the centroid points. Since they did not provide any anthropometrics about subjects, it is not possible to compare their results with other studies including the present study. In the present study, the only predictor in regression equations to estimate the ESMLA distance was subject height. Correlation coefficients between the ESMLA distance and height were 0.661, 0.645, and 0.596 at the L3/L4, L4/L5, and L5/S1, respectively. All regression models were significant (p = 0.000). Moga *et al.* (1993), Jorgensen *et al.* (2001), Seo *et al.* (2003), and Anderson *et al.* (2012) also included the subject height in their regression models. Anderson *et al.* (2012) included other variables (age, gender, and weight) in their regression models; however, height was the only variable that was significant (as found in the present study). Their sample size was relatively large (51 males and 49 females), as well.

*Weight and the ESMLA distance*

Reid *et al.*'s (1987) study found both height and weight were significantly correlated (r = 0.54) with the ESMLA distance; however, neither was included in their prediction model. Their regression model for the ESMLA distance at the L5 level included other anthropometric variables such as chest and greater trochanter width. Moga *et al.* (1993) included weight in their model, but they did not provide subject anthropometrics so that it is not possible to compare their results with the present study. They also included all independent variables in their models so that there is a possibility that some variables were not statistically significant in their estimate of the ESMLA. Wood *et al.* (1996) studied 26 male subjects to determine the relationship between BMI and the ESMLA distance. They concluded that there was no any significant difference between BMI categories. Lee *et al.* (2006), on the other hand, reported significant association between the ESMLA distance and BMI. However, they did not provide a regression equation including BMI in the model. Jorgensen *et al.* (2001) included weight in their regression equations in the form of a multiplier or denominator of another predictor variable. However, Jorgensen et al's (2001) results were not consistent throughout vertebral levels and sides. Regression models for the left L3 and L4 ESMLA were significant for males but not for females. Regression models for the right side were vice versa. Regression models for the L5 ESMLA was not significant for any side and any gender. In the present study, the ESMLA measurements were measured from the center of the IVD to the connector line. Therefore, only one ESMLA measurement was provided. Seo *et al.* (2003) found that weight was significantly correlated with the ESMLA distance with small correlation coefficients. Weight was included in their models. Jorgensen (2003b) also include weight in their regression models. Anderson *et al.* (2012) included weight in their model, but it was not significant. Kumar (1988), Tracy *et al.* (1989), Chaffin *et al.* (1990), and Wood *et al.* (1996) did not find any significant regression model to estimate the ESMLA distance for anthropometric variables including weight. The present study also did not include weight in prediction models since weight was not statistically significant in regression analyses. However, subject weight should not be completely ignored. Several other researchers found that weight and/or BMI can predict ESMLA distance. Weight is highly correlated with gender and height; therefore, there might be a confounding effect and/or combination effect among other variables. A future factorial design study with a large range of weight may answer whether subject weight has any effect on the ESMLA distance.

*Other predictor variables and the ESMLA distance*

Some researchers found significant relationships between the ESMLA distance and predictor variables such as trunk depth (Reid and Costigan, 1985; Moga *et al.*, 1993; Jorgensen *et al.*, 2001; Jorgensen *et al.*, 2003b) and trunk width (Moga *et al.*, 1993; Jorgensen *et al.*, 2003b). Note that Shultz *et al.* (1981 and 1982) and Marras and Somerrich (1991) also used torso depth to estimate the ESMLA distance in their low back models. The ESMLA distance was predicted with subject sitting height in Wood *et al.*'s (1996) study. Some internal measurements were also studied to determine their relationships with the ESMLA distance. For example, Lee *et al.* (2006) suggested using the CSA of the ESMM to predict the ESMLA. Jorgensen *et al.* (2003b) included the L1/L5 lordosis in their model since they were studying torso flexion on the ESMLA distance.

However, the purpose of the present study is to provide ESMLA estimation equations with some external variables that biomechanists can easily measure. After measuring these external anthropometrics, they can calculate the ESMLA distance for a specific subject and use this distance in biomechanical force and moment calculations.

## 4.5 Conclusion

The purpose of the present study was to suggest regression models that can estimate an individual's the cross-sectional area (CSA) of the erector spinae muscle mass (ESMM) and the erector spinae muscle mass lever arm (ESMLA) distance which, in turn, provides individualization of biomechanical force and moment calculations. Individual factors such as gender, age, height, and weight were investigated to determine whether they could help estimate the CSA of the total ESMM and the ESMLA distance.

The results of the present study found that subject gender, height, and weight are predictors for the total ESMM size. These results agree with some previous studies that found significant relationships with these measurements and subject gender (Cooper *et al.*, 1992; Marras *et al.*, 2001; Jorgensen *et al.*, 2003a; Seo *et al.*, 2003; Anderson *et al.*, 2012), height (Chaffin *et al.*, 1990; Marras *et al.*, 2001; Jorgensen *et al.*, 2003a; Anderson *et al.*, 2012), and weight (Reid *et al.*, 1987; Chaffin *et al.*, 1990; Cooper *et al.*, 1992; Marras *et al.*, 2001; Jorgensen *et al.*, 2003; Seo *et al.*, 2003; Anderson *et al.*, 2012). It should be noted that these studies had mostly larger sample sizes compared other previous studies. Variations among studies might be explained by the differences in muscle definitions, measurement techniques, and subject anthropometrics.

Regression models to estimate the CSA of the total ESMM are given below:

$ESMM_{L3/L4}$ = - 9.262 + 7.146*$X_G$ + 0.244*$X_H$ + 0.209*$X_W$ ($R^2 = 0.537$)

$ESMM_{L4/L5}$ = - 20.378 + 0.358*$X_H$ + 0.138*$X_W$ ($R^2 = 0.398$)

$ESMM_{L5/S1}$ = - 20.300 - 6.811*$X_G$ + 0.356*$X_H$ + 0.135*$X_W$ ($R^2 = 0.209$)

Note that the coefficients of multiple correlation, $R^2$'s, were not very high in the present study. To minimize this deficiency, future studies should investigate the relationships between the CSA of the ESMM and other anthropometric measurements and/or some subject features such as exercise level and health conditions. For example, the regression models suggested in the present study had an approximately 50% error in estimation of the ESMM size of one of the research subject used in model validations. It is known that the subject is a weight lifter with significant muscularity. Current predictors (age, gender, height, and weight) are not sufficient to explain the difference between this subject and other subjects. Chaffin *et al.* (1990) indicated that the size of ESMM may not correlate with body weight because the size of the ESMM depends more on the physical requirements placed on the muscle during normal manual activities and not on simple gross body weight. Therefore, the relationship between lean body mass and the ESMM size should be investigated. Future studies should measure lean body mass perhaps (by skinfold measurements) of subjects.

Validation of regression models provided in the present study were performed with 20 new male subjects. Paired samples T-tests indicated that the observed and estimated values were not statistically different. An average of 11%, 12.3%, and 15.3% (absolute) error is expected from the regression model at the L3/L4, L4/L5, and L5/S1 levels, respectively. Future studies with larger sample sizes and additional independent variables may provide better estimates.

The subject height was the only predictor for the ESMLA distance prediction models. Moga *et al.* (1993), Jorgensen *et al.* (2001), Seo *et al.* (2003), and Anderson *et al.* (2012) also found significant relationship between height and the ESMLA distance. Male subjects had larger ESMLA distances than female subjects; approximately 10% at the L3/L4 level, 9% at the L4/L5 level, and 8% at the L5/S1 level. Even though gender was correlated with the ESMLA distance, it was not included in prediction models. To investigate gender effect itself, future studies should select matching subjects in terms of height and weight from both genders.

Regression models to estimate the ESMLA distance (cm) are given below:

$ESMLA_{L3/L4} = 0.016 + 0.031*X_H$ ($R^2 = 0.437$)

$ESMLA_{L4/L5} = 0.515 + 0.027*X_H$ ($R^2 = 0.415$)

$ESMLA_{L5/S1} = 1.063 + 0.025*X_H$ ($R^2 = 0.356$)

To test the validity of ESMLA distance prediction models, the ESMLA distances for 20 new subjects were calculated by regression models provided in the present study. Their ESMLA distances were measured with the same methodology suggested in the present study. The results of statistical analyses indicated that the observed and estimated ESMLAs were significantly correlated, and there was no statistical difference between the observed and estimated ESMLA distances. The average prediction error of the regression models was approximately 4%. Smaller ESMLA prediction errors can result in smaller errors in the calculation of spinal loading for a particular subject.

For the subjects in the present study, weight was not a predictor for their ESMLA distances. However, it may enter regression models for another sample population. It can be concluded that future studies should investigate the effect of the subject weight by selecting subjects with several weight classifications and body composition levels.

The results of the present study did not find any significant relationship between subject age and the ESMM and ESMLA sizes. Subjects in the present study ranged from 21 years old to 39 years old (average 29.7 (5.4) years old). Future studies should include subjects with different ages and larger age ranges to address possible aging affects on ESMM size.

In addition to predictor variables studied in the present study (age, gender, height, and weight), some other variables should be measured from subjects to determine whether these variables can estimate the ESMLA distance. For example, sitting height (Wood *et* *al.*, 1996), trunk depth (Reid and Costigan,, 1985; Moga *et al.*, 1993; Jorgensen *et al.*, 2001 and 2003b), trunk width (Moga *et al.*, 1993; Jorgensen *et al.*, 2003b) are some promising predictor variables that should be investigated in future studies.

Comparisons between the right and left ESMM sizes indicated that there was no significant difference between the two sides of ESMM. However, it was unknown whether these subjects were right- or left-handed. Comparison of dominant side to non-dominant side may provide a better understanding of the training effect on muscle size than a simple comparison of the right side to the left side (which assumes "most" subjects are right-hand dominant).

To conclude, the CSA of the total ESMM and the ESMLA distance can be accurately estimated by regression models provided in the present study. This study included a relatively larger sample size compared to most studies in the literature. The morphological measurements were taken from MRI scans. MRI scans provide much higher resolution than CT scans. Three IVD levels were investigated in the present study to understand low back structures. The computerized centroid determination and ESMLA measurement techniques provide much more accurate and repeatable measurements compared to visual determination or tape measurement techniques. The intra-rater and inter-rater reliability tests indicated that the measurement technique was highly repeatable (good inter-rater reliability ranging from 0.811 to 0.997 and excellent intra-rater reliability ranging from 0.968 to 0.998). Although the multiple correlation coefficients of the regression models were relatively smalls, like those in other studies (McGill *et al.*, 1988; Chaffin *et al.*, 1990; Seo *et al.*, 2003), the equations could be useful in minimizing the effect of individual differences. The present study provided regression models for the CSA of the total ESMM and the ESMLA distances at three IVD levels. These regression equations can be used by biomechanists to construct subject specific biomechanical models to calculate spinal loading. As a crude straight forward example, the ESMLA distance is considered 5 cm in some biomechanical low back models, which results in an average of 7 to 10% error in muscle force calculations. However, regression models decreased this error to 4% in average. Note that these are averages, and the assumptions of using the fixed number or average number will result in larger errors with extremes while the proposed regression equations will estimate much closer values for these extreme subjects. Finally, anthropometrics of subject sample should be considered before using the regression equations. The regression equations provided in the present study may not be applicable for adolescent or older subjects, obese subjects, or trained athletes. It also be noted that MRI scans were taken while subjects in supine posture, which may not represent the standing posture. The subjects in the present study were medical patients with low back symptoms; therefore, the results of the present study may differ for healthy subjects. Future studies should determine whether the results of the present study are applicable for asymptomatic subject populations.

Chapter 5

# MORPHOLOGICAL ANALYSIS OF ERECTOR SPINAE MUSCLE MASS LEVER ARM (ESMLA) DISTANCE: BEST SUBSET REGRESSION MODELS FOR AN ASYMPTOMATIC SUBJECT POPULATION

## 5.1 Introduction

Accuracy of biomechanical input data is very important for calculating the forces and moments loading the spine. However, some biomechanical inputs are limited by assumptions. For example, the length of the erector spinae muscle mass lever arm (ESMLA) is assumed to be 5 cm (2 inches) in some biomechanical low back models (Bradford and Spurling, 1945; Bartelink, 1957; Morris *et al.*, 1961; Muchinger, 1962; Nachemson, 1968; Chaffin, 1969; Ayoub and El-Bassoussi, 1976; Poulsen, 1981; Schultz and Anderson, 1981; McGill and Norman, 1985; Ayoub and Mital 1989; Vincent, 1991; Garg, 1997; Chaffin *et al.*, 2006; DeSantis *et al.*, 2010). On the other hand, some studies used empirically derived average ESMLA values [Eie, 1966 (6.5 cm); McGill and Norman, 1987a (7.5 cm); Schultz and Anderson, 1981 (4.4 cm); Hutton and Adams, 1982 (6.1 cm); Tracy and Munro, 1991 (5.8 cm); Merryweather *et al.*, 2009 (6.6 cm for females and 6.9 cm for males); 3DSSPP (5.9 cm for males and 5.4 cm and 5.2 cm for females for the right and left side, respectively); Waters and Garg, 2010 (6.0 cm for males and 5.6 cm for females); Bean *et al.*, 1988 (7.4 cm)]. However, these ESMLA distances are not subject specific. For example, those studies do not differentiate a young tall heavy male subject from an old short light female subject. Comparisons of using a fixed (5 cm) ESMLA distance with using a subject specific ESMLA distance estimation model showed that force and moment calculations had approximately 9% error for a fixed number (5 cm) while the error was approximately 4% when a subject specific prediction model was used (see Chapter 4). Use of an average ESMLA number resulted in approximately 5% error. It should be noted that these error terms represent averages. The magnitude of the average error is higher for "extreme" subjects (very tall or very short). Subject specific regression models decrease the error in the ESMLA estimate, which yields more accurate force and moment estimations on the spine.

Subject specific regression models for both the CSA of the ESMM and the ESMLA distance are provided in the previous chapter on this dissertation (Chapter 4). The purpose of Chapter 4 was to address some limitations of previous studies such as using small sample sizes, including only one gender, having younger or older subjects, using over-simplified measurement methods, and reporting only one vertebral or inter-vertebral disc (IVD) level. The data used in Chapter 4 was obtained from a relatively large sample size (54 males and 58 females). Both genders were investigated and reported in this chapter. MRI scans were preferred due to their superior soft tissue resolution over CT scans. Having oblique axial images for morphological investigations was a strength of the data over transverse images which requires conversion of transverse measurements to oblique measurements. The main differentiation of this study from previous studies was the computerized measurement techniques, which minimizes over-simplification of the musculoskeletal structure of the low back.

However, subjects in Chapter 4 had undertaken an MRI scan to help medical doctors to explore whether they had medical abnormalities in their lumbar spinal region. It is unknown whether such abnormalities were associated with the spine itself or nearby tissues. Researchers were blinded to patient medical history. This means that subjects might have low back pain (LBP). Including medical patients in muscle morphological studies may mislead the results. For instance, Cooper *et al.* (1992), Lee *et al.* (2006), Kamaz *et al.* (2007), and Lee *et al.* (2011) reported that LBP patients had statistically smaller muscle sizes than healthy subjects. The purpose of this present study is to investigate low back morphology of asymptomatic subjects and to understand whether the musculoskeletal structures of asymptomatic subjects are similar to those who had visited medical doctors in the previous study.

Subject characteristics in Chapter 4 were limited to gender, age, height, and weight. However, some previous studies found some other relationships between muscle sizes and subject characteristics. For example, Wood *et al.* (1996) reported a significant relationship between the ESMLA distance and subject sitting height. Trunk depth (Reid and Costigan, 1985; Moga *et al.*, 1993; Jorgensen *et al.*, 2001; Jorgensen *et al.*, 2003b) and trunk width (Moga *et al.*, 1993; Jorgensen *et al.*, 2003b) have been also reported in previous studies to estimate the ESMLA distance. Trunk circumference (Reid *et al.* 1987), trunk depth and width (Jorgensen *et al.*, 2003a), and trunk area (Chaffin *et al.*, 1990) were used to estimate the CSA of the ESMM. The present study investigated these relationships. Several anthropometrics such as head, elbow, wrist, hand, knee, and ankle width and circumferences were measured in the present study. Sitting height, shoulder width, chest breath and depth, head depth, and hand and arm lengths were also measured. The relationships between these anthropometrics and the erector spinae muscle mass morphology are investigated in the present study, in addition to gender, age, height, and weight. Note that the previous study presented in Chapter 4 had anthropometrics in integer British units (inch and pound). However, the present study use metric units (cm and kg) in one decimal, which results in higher resolution when constructing prediction models.

In Chapter 4, subject weight was used in correlations and regression models. However, the size of ESMM may not correlate with body weight because the size of the ESMM depends more on the physical requirements placed on the muscle during normal manual activities and not on simple gross body weight (Chaffin *et al.*, 1990). Lean body mass measured by skinfold measurements should be taken into consideration in addition to weight. In the present study, the relationship between lean body mass and the ESMM and ESMLA sizes was also investigated. Lean body mass and the ESMM size may be related to the frequency of physical activity (e.g., resistance training, occupational exposure, etc.). To address this relationship, the present study investigated the relationships between the muscle sizes and the frequency of weight lifting and cardiovascular exercises.

The present study investigates the asymmetry between the right and left ESMMs. The present study also investigates dominate and non-dominant hand sides as the difference between right and left CSAs as this phenomenon is likely due to asymmetric loading of the body. Since most subjects are right hand dominant, the left side low back musculature would likely be more developed particularly for subjects who wield tools primarily in one hand or perform unilateral overhead activities such as tennis.

Reid and Costigan (1985), Kumar (1988), Millerchip *et al.* (1988), Chaffin *et al.* (1990), Moga *et al.* (1993), McGill *et al.* (1993), Guzik *et al.* (1996), and Jorgensen *et al.* (2001) found that there was no significant difference between the right and left CSAs of the ESMM. The previous study (Chapter 4) also found that there was not a significant difference between the right and left ESMMs. However, it was unknown whether these subjects were right- or left-handed. Asymmetry comparisons between the right and left CSAs were made for the right and left side, and presumably based on the assumption that most people are right-hand dominant. The present study compared the dominant and non-dominant hand sides to provide better understanding of muscle symmetries.

To summarize, the objective of present study is to provide accurate and reliable biomechanical model input data (ESMLA distance and CSA of the ESMM) and investigate the relationships between the model inputs and subject characteristics. In addition to predictor variables studied in Chapter 4, several promising new predictors are included in the present study. Including asymptomatic subjects in the present study can provide the opportunity to compare the results of the present study with the results of symptomatic subject studies including previous studies.

## 5.2 Material and Methods

### 5.2.1 Subjects

A total of 35 subjects (22 males and 13 females) were included in the present study. They were given an MRI scan at the Auburn University MRI Research Center in Auburn, Alabama. Subjects were healthy, young, and were primarily university students. Subjects did not have any low back pain (LBP) history. Subject identifiers such as name, birth date, and student identification number were purged from the data set. The research protocol of this study was approved by the Institutional Review Board (IRB) at Auburn University (Appendix B).

### 5.2.2 Data Collection

#### Magnetic Resonance Imaging (MRI) scans

Magnetic Resonance Imaging (MRI) was used to study the low back architecture in the present study. MR scans were performed on a 70 cm Open Bore 3 Tesla MRI scanner (MAGNETOM Verio, Siemens AG, Erlangen, Germany) at the Auburn University MRI Research Center. Subjects were placed in head-first-supine (HFS) posture with knee flexed (cushion under the legs) in the MRI machine. Due to its superiority in distinguishing muscles from fat tissues over T1-weighted scans, T2-weighted scans were collected. Axial (including transverse and oblique views) and sagittal scans were captured for each subjects. A spin-echo sequence with a 4400-msec repetition time (TR) and 100-msec echo time (TE) was used for sagittal plane MR scans and 7880-msec TR and 94-msec TE for the axial plane MR scans. Image slice thickness was 4.5 mm for sagittal plane scans and 3 mm for axial scans. Sagittal scans were used to determine the IVD level. One axial MR scan was selected for each IVD level. Figure 5.1 shows sagittal and axial scans. Morphometric measurements were taken from T2-weighted axial MRI scans.

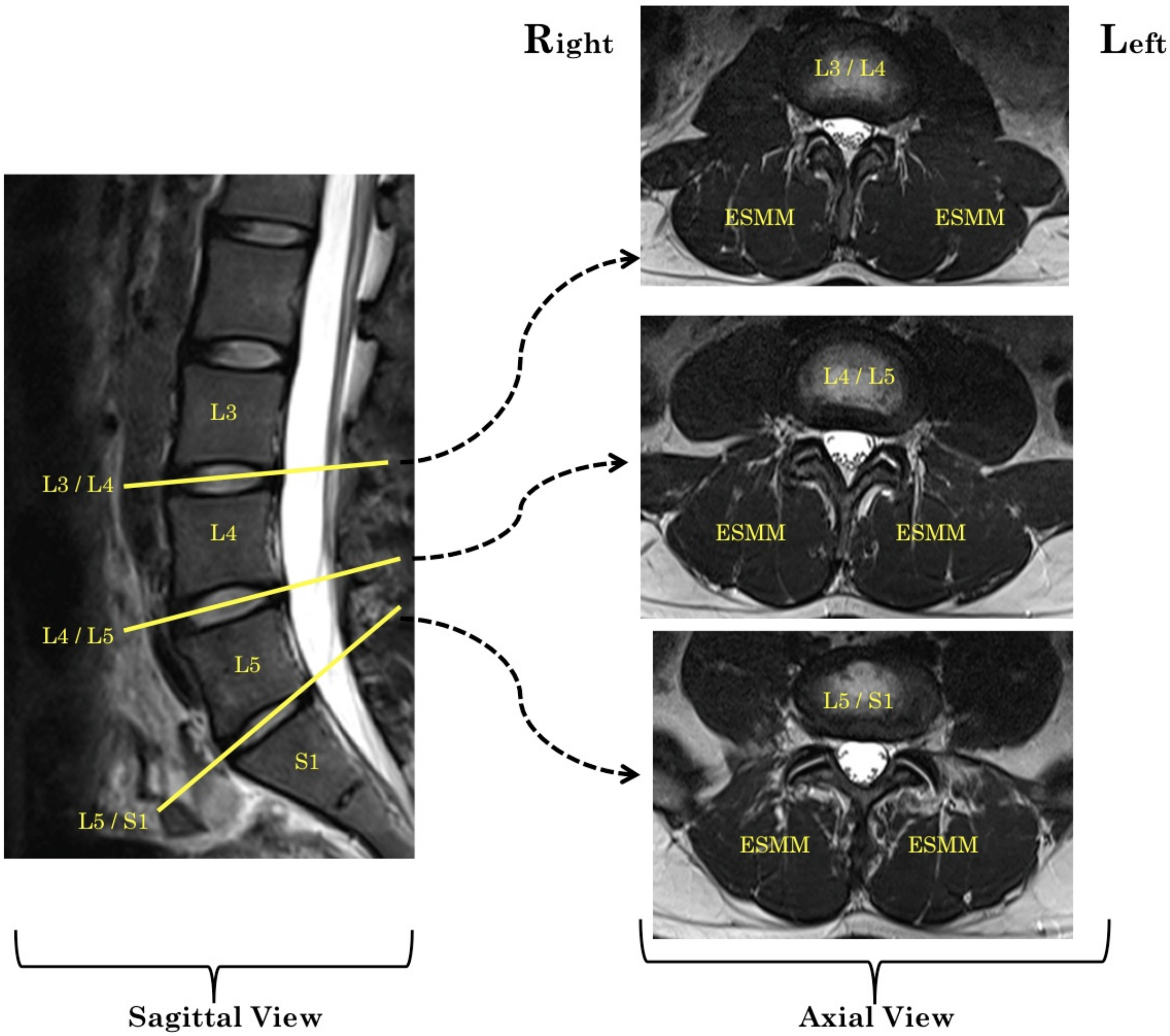
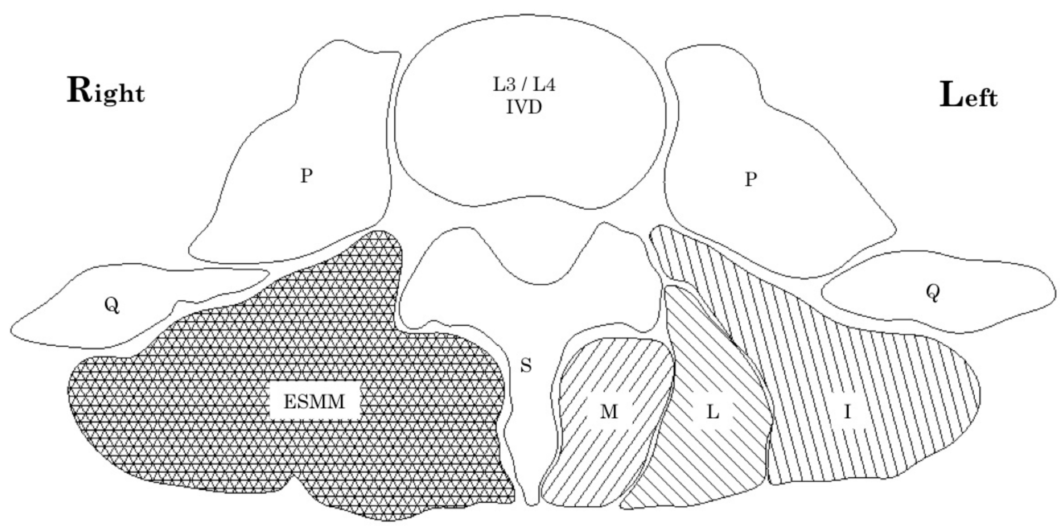



Figure 5.1: Sagittal and Axial MRI scans at the L3/L4, L4/L5, L5/S1 IVD levels
Note: MRI images are viewed inferiorly (from the feet), therefore, the right side appears on the left and vice-versa.

### The erector spinae muscle mass (ESMM)

The erector spinae muscle mass (ESMM) is described as the whole muscle structure posterior to the spine that lays longitudinally throughout the torso. The ESMM fills the space between the spinous and transverse processes. The ESMM consists of the erector spinae muscle (ESM) group (the spinalis thoracis, longissimus thoracis, and iliocostalis lumborum), the transversospinalis group (the multifidus, semispinalis, and rotatores), and the segmental muscles (the interspinales and intertransversarii) in the low back region. The prevalence and percentages of these muscles are dependent upon the vertebral level. The longissimus thoracis (pars lumborum and pars thoracis), iliocostalis lumborum (pars lumborum and pars thoracis), and multifidus are the major muscles in the low back region (the L3/L4, L4/L5, and L5/S1 levels). These muscles constitute the main focus of the present study since they are the major muscles responsible for concentric extension and eccentric flexion of the trunk. Other muscles such as the psoas major, quadratus lumborum, and latissumus dorsi are excluded from the present study due to their minimal role in sagittal plane lifting tasks compared to the erector spinae muscles. Figure 5.2 depicts the ESMM muscles and spinal structures at the L3/L4 IVD level.




**ESMM**: Erector Spinae Muscle Mass
1. Erector Spinae Muscle Group
   - **L**: Longissimus Thoracis
   - **I**: Iliocostalis Lumborum
2. Transversospinalis Group
   - **M**: Multifidus

Other muscles in the low back region
- **Q**: Quadratus Lumborum
- **P**: Psoas Major

Spinal Structures
- **IVD**: Inter-vertebral disc
- **S**: Spinous Process

Figure 5.2: ESMM Muscles and spinal structures at the L3/L4 IVD level
Note: MRI images are viewed inferiorly (from the feet), therefore, the right side appears on the left and vice-versa.

### The CSA and lever arm measurement techniques

Images collected from the MRI machine were transfered to OsiriX® (v4.0, 2011, Antoine Rosset, Bernex, Switzerland), an open source DICOM image analysis software. Sagittal and axial plane images of the spine were analyzed using OsiriX®. Figure 5.1 shows sagittal (on the left) and axial (on the right) MR images in OsiriX® software. One oblique image was selected for each IVD level (the L3/L4, L4/L5, and L5/S1). Selected images were transferred to Rhinoceros (also known as Rhino) (v4.0), an architectural design software. Rhino can accurately estimate the centroid of an irregular shape such as the muscle mass and IVD. Images were scaled using the scale given in the raw OsiriX® images. Contours of the ESMMs and IVDs were manually traced on a high resolution computer screen (1280 X 1024 pixels, 60 Hertz, Dell 1905FP, Dell Inc., Round Rock, TX). A Grasshopper model was created to (1) compute the centroid points of the ESMMs from contour traces, (2) draw "a connector line" between the centroid point of the right ESMM to the centroid point of the left ESMM, (3) compute the centroid point of the IVD, and (4) draw a perpendicular line from the disc centroid to the connector line, which is the definition of the ESMLA used in the present study. The Grasshopper software model produced the measurements regarding muscle and disc CSAs, as well as the corresponding ESMLA distance (See Appendix E for data collection sheet).

### Subject characteristics and anthropometrics

#### *Subject characteristics*

Subject gender and age were recorded. Subjects were asked their dominant hand side (right-, left-hand dominate, or ambidextrous). Subjects were also asked about the frequency and intensity of their physical activities. They were asked whether they regularly perform weight lifting (or any other resistance exercises) or cardiovascular exercise. If they regularly perform weight lifting and/or cardiovascular exercise, they were asked how often they perform these exercises (i.e., everyday, every 2 to 3 days, and every week).

### *Anthropometric measurements*

Anthropometric measurements were taken while subjects were wearing appropriate clothing (i.e., sleeveless shirts and tight/sport shorts). Subjects were weighed using a metric unit (kg) scale. Other anthropometric measurements were taken with an anthropological instrument kit (GPM, Switzerland). An anthropometer was used to measure subject sitting and standing height, chest breadth and depth, shoulder width, head depth, and arm length. Figure 5.3 shows how these anthropometric measurements are defined. Sliding (Martin type) and spreading calipers were used to measure head, elbow, wrist, hand, knee, and ankle widths and hand length. Head, elbow, wrist, hand, knee, and ankle circumferences were taken using a Gulick anthropometric tape. Sitting height, chest breadth and depth, and head width, depth, and circumference were taken while subjects were sitting on a chair and their upper and lower legs form a right angle ($90^o$, thigh parallel to the floor). Standing height, shoulder width, arm length, hand length, and elbow, wrist, hand, knee, and ankle widths and circumferences were taken while subjects were in a standing posture. All anthropometric measurements were taken from both the right and left side.

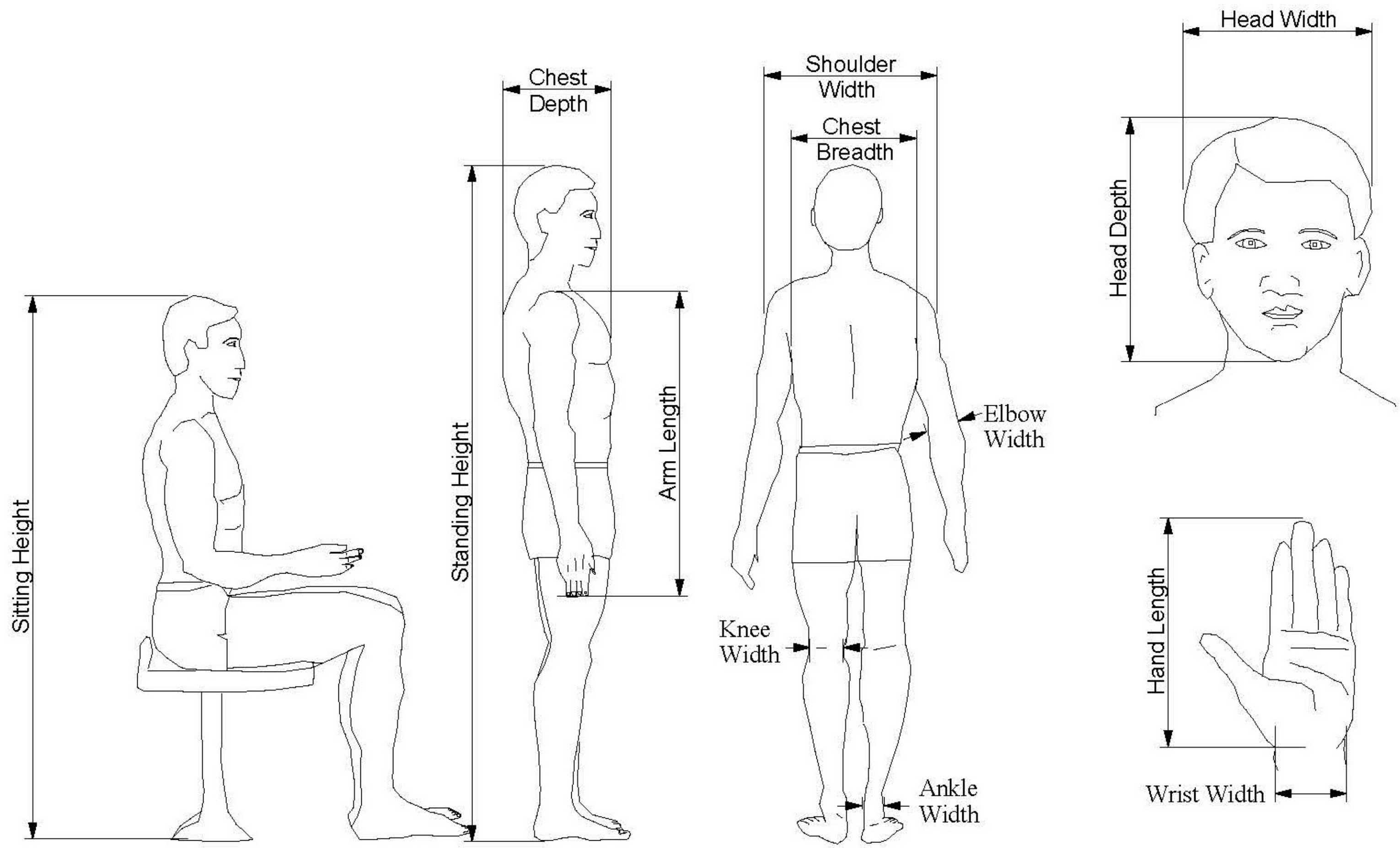



Figure 5.3: Anthropometric measurements

**Body composition**

Lean body mass (LBM) is "fat-free" mass which is composed of all of the body's nonfat tissues including bones, muscles, and connective tissues. Body composition is the relative percentage of body weight in terms of fat and fat-free mass. Body composition can be determined by under water weighing (hydrodensitometry), bioelectrical impedance (BIA), dual-energy x-ray absorptiometry (DEXA), and near-infrader interactance. Skinfold measurement is a simple, quick, and cheap alternative to those methods. Body composition determined from skinfold measurements correlates very well with body composition determined by hydrodensitometry (ACSM, 2009). The principle behind skinfold measurement is that the amount of adipose tissue under the skin is proportional to the total amount of body fat.

Tracy *et al.* (1989) and Parkkola *et al.* (1992) suggested using skinfold measurements to estimate the variation in lever arms and areas of trunk muscles. The accuracy of predicting percent fat from skinfold measurements is very high (±3.5%) when appropriate skinfold site, technique, and equations are used (ACSM, 2009). In the present study, three measurements from each site (abdominal, chest-pectoral, and thigh for males; superiliac, triceps, and thigh for females) were obtained by using a calibrated Lange Skinfold Caliper (Beta Technologies, Santa Cruz, CA, USA). ACSM's (2009) standard description of skinfold sites and procedures are given below.

**Anatomical locations for skinfold sites and procedures:**

***Abdominal (male)*:** vertical fold; 2 cm to the right of the umbilicus (Figure 5.4.a),

***Suprailiac (female)*:** diagonal fold; in line with the natural angle of the iliac crest taken in the anterior axillary line immediately superior to the iliac crest (Figure 5.4.b),

***Chest-pectoral (male)*:** diagonal fold; half the distance between the anterior axillary line and the nipple (Figure 5.4.c),

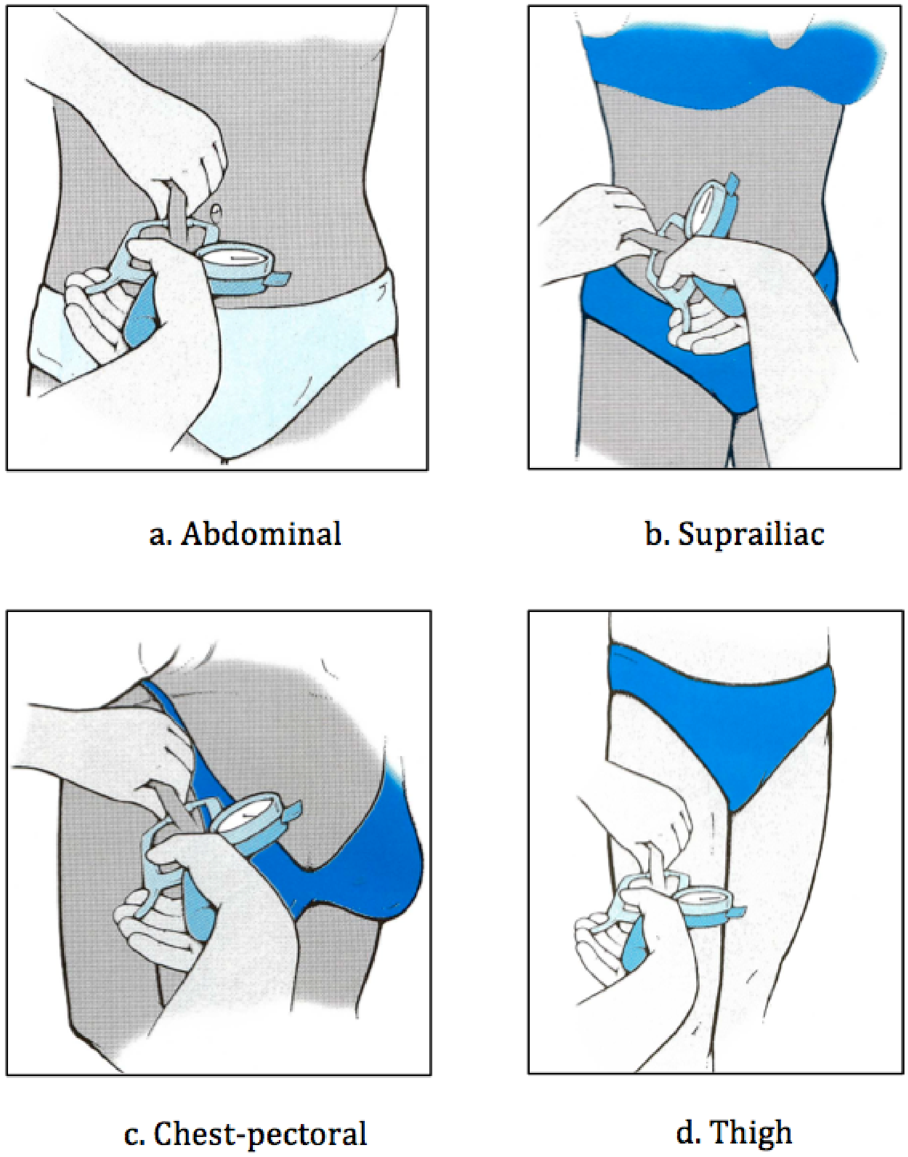



Figure 5.4: Anatomical locations for skinfold sites
Retrieved from ACSM, American College of Sports Medicine: Thompson, W. R., American College of Sports Medicine, Gordon, N. F., and Pescatello, L. S. (2009). ACSM's Guidelines for Exercise Testing and Prescription. Lippincott Williams and Wilkins.

***Triceps (female)*:** vertical fold; on the posterior midline of the upper arm, halfway between the acromion and olecranon processes, with the arm held freely to the side of the body,

***Thigh (male and female)*:** vertical fold; on the anterior midline of the thigh midway between the proximal border of the patella and the inguinal fold (Figure 5.4.d).

In this study, all skinfolds were taken on subjects' dominant sides while in a standing upright posture. Three duplicate measures at each site were taken, and if duplicate measurements were not within 1 to 2 mm, they were retested as ACSM (2009) suggests. The average of three measurements recorded as the skinfold thickness for the site. Generalized prediction skinfold equations (three-site formulas) for both gender (given below) were used to calculate the body density:

***Body Density for Male*** *(chest, abdomen, thigh) = 1.10938 - 0.0008267*(Sum of Three Skinfolds) + 0.0000016*(Sum of Three Skinfolds)*$^2$ *- 0.0002574*(Age)*

***Body Density for Female*** *(triceps, suprailiac, thigh) = 1.099421 - 0.0009929*(Sum of Three Skinfolds) + 0.0000023*(Sum of Three Skinfolds)*$^2$ *- 0.0001392*(Age)*

Body density values were converted to body composition by using the generalized formula:

***Percent Fat*** *= (495 ÷ Body density) - 450*

As mentioned earlier, LBM is "fat-free" mass and can be calculated using the formula:

***LBM = Total Mass - (Percent Fat * Total Mass)***

### 5.2.3 Statistical Tests

Independent samples T-tests were used to compare subject characteristics and anthropometrics such as male and female heights. Independent Student's T-tests were also used to compare subjects regularly performing physical exercise and non-regular exercise groups. The results of the present study and the previous study presented in Chapter 3 in terms of their ESMM CSAs and ESMLA distances. Paired-samples T-tests were used to compare (1) the right and left limb anthropometrics, (2) the right and left CSAs of the ESMM, and (3) the dominant- and non-dominant hand side CSAs of the ESMM to determine if any asymmetry exists. The Split-Plot Designs (2X3) were used to determine the effect of gender, IVD level, and interaction of these two on the CSA of the total ESMM and the ESMLA. Post-hocs tests were performed for the main effects with three categories, if they were significant, to understand the relationship to the response value. Independent T-tests were performed for the main effects with two categories. Correlation analyses were performed to understand the association between subject variables and the ESMM size and ESMLA distance. Correlations among subject variables (characteristics and anthropometrics) were also conducted to determine highly correlated variables so that they may be removed from analyses or combined to form an index variable. Variable reduction was preferred to minimize multicollinearity among independent variables. Correlations between the right and left and dominant as well as non-dominant sides of ESMM sizes were also calculated. Best subsets regression analyses were performed to determine "the best subsets" for the CSA of the total ESMM and the ESMLA distance. After determining "the best subsets," an Enter Method regression analysis was performed for each regression model to determine the coefficients and significance of each predictor variable. Note that Enter Method regression analysis included all predictor variables in the model without considering their significancy levels. ANOVA tests were performed to test whether the regression model was significant. Backward stepwise regression analyses were also performed for easy-to-measure subject variables so that the results of the present study could be compared to the results of the previous study presented in Chapter 4. Minitab (version 15.1) was used for best subset regression analyses and split-plot factorial design analyses. Other statistical tests were performed using IBM SPSS Statistics (version 19.0).

## 5.3 Results

### 5.3.1 Descriptive Statistics

#### Subject characteristics and anthropometrics

***Subject characteristics***

There were 22 male and 13 female subjects in the present study. The average age was 26.9 years old ranging from 21 to 35 years old. The average age for male subjects was 27.8 years old ranging from 22 to 35 years old, and the average age for female subjects was 25.5 years old ranging from 21 to 34 years old. Male subjects were generally older than female subjects, but the difference was not statistically significant.

Descriptive statistics for subject characteristics including the frequency of physical activities and dominant hand-sides are presented in Table 5.1. Approximately half (54%) of subjects do not regularly perform any weight lifting or resistance exercise. Twenty percent of subjects perform weekly and approximately 23% of them perform every 2 or 3 days. There was only one subject (3%) who daily performs lifting exercise. Percentages of subjects who perform and do not perform lifting exercises were similar across genders.

Table 5.1 also shows subjects' dominant hand sides. Eighty-eight percent of subjects were right-handed, 9% were left-handed, and 3% were ambidextrous. None of female subjects were left-hand dominant or ambidextrous. Three male subjects were left-hand dominant and only one male subject was ambidextrous.

Table 5.1: Subject characteristics: Physical activities and dominant hand side

| | | Female | | | | Male | | | | Total | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **N** | | **Percent** | | **N** | | **Percent** | | **N** | | **Percent** | |
| Lifting | No | 7 | 7 | 53.8 % | 53.8 % | 12 | 12 | 54.5 % | 54.5 % | 19 | 19 | 54.3 % | 54.3 % |
| | Every week | 3 | 6 | 23.1 % | 46.2 % | 4 | 10 | 18.2 % | 45.5 % | 7 | 16 | 20.0 % | 45.7 % |
| | Every 2 to 3 days | 2 | | 15.4 % | | 6 | | 27.3 % | | 8 | | 22.9 % | |
| | Everyday | 1 | | 7.7 % | | 0 | | 0.0 % | | 1 | | 2.9 % | |
| Cardio | No | 3 | 3 | 23.1 % | 23.0 % | 4 | 4 | 18.2 % | 18.0 % | 7 | 7 | 20.0 % | 20.0 % |
| | Every week | 6 | 10 | 46.2 % | 77.0 % | 6 | 18 | 27.3 % | 82.0 % | 12 | 28 | 34.3 % | 80.0 % |
| | Every 2 to 3 days | 3 | | 23.1 % | | 11 | | 50.0 % | | 14 | | 40.0 % | |
| | Everyday | 1 | | 7.7 % | | 1 | | 4.5 % | | 2 | | 5.7 % | |
| Dexterity | Right-Handed | 13 | | 100.0 % | | 18 | | 81.8 % | | 31 | | 88.6 % | |
| | Left-Handed | 0 | | 0.0 % | | 3 | | 13.6 % | | 3 | | 8.6 % | |
| | Ambidextrous | 0 | | 0.0 % | | 1 | | 4.5 % | | 1 | | 2.9 % | |

***Subject anthropometrics***

Descriptive statistics for subject anthropometrics are presented in Table 5.2. Male subjects were significantly taller than female subjects (p = 0.000). The average height was 177.1 (7.7) cm for male subjects and 160.9 (7.8) cm for female subjects. Note that numbers in parentheses are standard deviations. Male subjects were also significantly heavier than female subjects (p = 0.000). The average weight was 82.7 (10.8) kg for male subjects and 57.2 (10.2) kg for female subjects. The average BMI was 26.3 (2.6) $kg/m^2$ for males and 22.0 (2.6) $kg/m^2$ for females, so males fell into the "overweight" category and females fell into the "normal" category in BMI classification (according to World Health Organizations BMI classification (WHO, 2012): underweight, less than 18.5 $kg/m^2$; normal, between 18.5 $kg/m^2$ and 24.9 $kg/m^2$; overweight, between 25.0 $kg/m^2$ and 29.9 $kg/m^2$; and obese, more than 30.0 $kg/m^2$). BMI difference between genders was statistically significant (p = 0.000).

The average fat percentage for male subjects was 19.4%, which yields 16 kg fat and 66.7 kg fat-free weight. The average fat percentage for female subjects was significantly larger (25.6%) compared to male subjects (p = 0.002). Of the average female weight 57.2 kg, 15.1 kg was fat and 42.1 kg was fat-free weight. Fat-free weight or lean body mass (LBM) of male subjects was statistically heavier than female subjects (p = 0.000). However, fat weight was not statistically different between genders (p = 0.589).

Male subjects had statistically larger sitting height, shoulder width, head width, head circumference, head depth, chest breadth, and chest depth than female subjects (p = 0.000 for all) . Descriptive statistics about these anthropometrics are presented in Table 5.2.

Descriptive statistics about subjects anthropometrics taken from both sides of the upper and lower limbs are presented in Table 5.3. These anthropometrics include arm, elbow, wrist, hand, knee, and ankle width and circumferences as well as hand and arm length. These measurements were taken an upright standing posture. All these measurements were significantly larger for male subjects compared to female subjects at $\alpha = 0.05$ significancy level.

Pairwise T-tests were conducted to determine whether there was any statistical difference between the right and left side regarding limb anthropometrics. The results indicated that there was significant difference between the right and left wrist circumference (right was 0.111 cm larger, $p = 0.018$), the right and left hand length (left was 0.063 cm larger, $p = 0.008$), the right and left hand width (right was 0.066 cm larger, $p = 0.038$), the right and left knee width (right was 0.071 cm larger, $p = 0.034$), and the right and left ankle width (right was 0.049 cm larger, $p = 0.039$) (note that differences are in average of both genders). However, these differences were small and mostly not meaningful. Since the difference between the right and left sides is relatively small (approximately 1%), an average value for both sides was calculated. The average values for the limb anthropometrics are presented in Table 5.3. All average limb anthropometrics were also significantly larger for male subjects compared to female subjects at $\alpha = 0.05$ significancy level. The main reason for averaging both sides was that the number of variables exceeded the number of observations, which does not provide enough data for statistical tests.

### Cross sectional area (CSA) of the erector spinae muscle mass (ESMM)

Descriptive statistics for cross sectional areas (CSAs) of the right, left, and total erector spinae muscle masses (ESMMs) are given in Table 5.4. The average CSA of ESMM was the largest at the L3/L4 vertebral disc level; the average CSA for the ESMM at the L3/L4 level was 25.38 $cm^2$ for the right side, 26.09 $cm^2$ for the left side, and 51.46 $cm^2$ for the total of both sides. The average CSAs for the ESMM at the L4/L5 level were virtually identical to the L3/L4 level; 25.36 $cm^2$ for the right side, 26.06 $cm^2$ for the left side, and 51.42 $cm^2$ for the total of both sides. The total CSA of ESMM at the L5/S1 level (49.22 $cm^2$) was approximately 4% smaller than the L3/L4 and L4/L5 levels. Note that these interpretations were for the overall population, not for a specific gender. However, males had sharp reductions in muscle sizes with lower disc levels. The CSA of the total ESMM for male subjects at the L5/S1 level, for instance, was approximately 12% smaller than the

Table 5.2: Subject anthropometrics

| Variable | Gender | N | Mean | St.d. | Min | Max | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|
| Height | Female | 13 | 160.9 | 7.8 | 149.8 | 180.2 | -5.995 | 33 | *0.000** |
| | Male | 22 | 177.1 | 7.7 | 162.1 | 191.0 | | | |
| Weight | Female | 13 | 57.2 | 10.2 | 45.2 | 75.4 | -6.867 | 33 | *0.000** |
| | Male | 22 | 82.7 | 10.8 | 66.8 | 107.8 | | | |
| BMI | Female | 13 | 22.0 | 2.6 | 19.7 | 27.1 | -4.753 | 33 | *0.000** |
| | Male | 22 | 26.3 | 2.6 | 21.2 | 31.6 | | | |
| Fat (%) | Female | 13 | 25.6% | 6.7% | 16.8% | 34.9% | 3.413 | 33 | *0.002** |
| | Male | 22 | 19.4% | 4.2% | 8.9% | 24.6% | | | |
| Fat Weight | Female | 13 | 15.1 | 5.9 | 8.2 | 24.6 | -.546 | 33 | 0.589 |
| | Male | 22 | 16.0 | 4.1 | 7.8 | 26.5 | | | |
| Fat-free Weight | Female | 13 | 42.1 | 5.7 | 36.0 | 55.2 | -8.476 | 33 | *0.000** |
| | Male | 22 | 66.7 | 9.4 | 53.8 | 86.6 | | | |
| Sitting Height | Female | 13 | 125.4 | 4.6 | 120.6 | 136.9 | -4.311 | 33 | *0.000** |
| | Male | 22 | 131.7 | 4.0 | 125.4 | 140.7 | | | |
| Shoulder Width | Female | 13 | 39.0 | 3.2 | 35.3 | 45.2 | -7.534 | 33 | *0.000** |
| | Male | 22 | 46.3 | 2.5 | 42.8 | 51.1 | | | |
| Head Width | Female | 13 | 14.5 | 0.6 | 13.7 | 15.4 | -4.344 | 33 | *0.000** |
| | Male | 22 | 15.5 | 0.7 | 14.3 | 17.1 | | | |
| Head Circumference | Female | 13 | 55.0 | 2.1 | 52.2 | 58.5 | -3.890 | 33 | *0.000** |
| | Male | 22 | 57.5 | 1.6 | 53.6 | 60.6 | | | |
| Head Depth | Female | 13 | 20.2 | 0.9 | 17.9 | 21.1 | -6.187 | 33 | *0.000** |
| | Male | 22 | 22.8 | 1.3 | 20.1 | 24.8 | | | |
| Chest Breadth | Female | 13 | 28.1 | 2.0 | 25.8 | 32.3 | -4.948 | 33 | *0.000** |
| | Male | 22 | 33.2 | 3.4 | 29.2 | 45.4 | | | |
| Chest Depth | Female | 13 | 18.4 | 2.2 | 14.4 | 23.5 | -4.691 | 33 | *0.000** |
| | Male | 22 | 21.8 | 2.0 | 17.5 | 24.6 | | | |

Height: cm; Weight: kg; BMI: kg/$m^2$; Width, Circumference, Depth, and Breadth: cm

L3/L4 level and 9% smaller than the L4/L5 disc level. On the contrary, the total CSA of ESMM was the largest at the L5/S1 level for female subjects and was approximately 14%

Table 5.3: Right and left side measurements (cm) of limbs

| | | Side | Gender | N | Mean | St.d. | Min | Max | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Elbow** | **Width** | Right | Female | 13 | 7.6 | 0.7 | 6.2 | 9.0 | -5.839 | 33 | *0.000** |
| | | | Male | 22 | 9.1 | 0.8 | 7.2 | 10.8 | | | |
| | | Left | Female | 13 | 7.5 | 0.6 | 6.4 | 9.0 | -6.080 | 33 | *0.000** |
| | | | Male | 22 | 9.1 | 0.8 | 7.0 | 10.8 | | | |
| | | Average | Female | 13 | 7.5 | 0.7 | 6.3 | 9.0 | -5.997 | 33 | *0.000** |
| | | | Male | 22 | 9.1 | 0.8 | 7.1 | 10.8 | | | |
| | **Circumference** | Right | Female | 13 | 22.6 | 1.6 | 20.4 | 25.3 | -8.278 | 33 | *0.000** |
| | | | Male | 22 | 27.5 | 1.7 | 24.5 | 31.1 | | | |
| | | Left | Female | 13 | 22.6 | 1.6 | 20.5 | 25.3 | -8.004 | 33 | *0.000** |
| | | | Male | 22 | 27.3 | 1.7 | 23.8 | 31.5 | | | |
| | | Average | Female | 13 | 22.6 | 1.6 | 20.5 | 25.3 | -8.189 | 33 | *0.000** |
| | | | Male | 22 | 27.4 | 1.7 | 24.2 | 31.3 | | | |
| | | | | | | | | | | | |
| **Wrist** | **Width** | Right | Female | 13 | 5.0 | 0.3 | 4.5 | 5.5 | -7.856 | 33 | *0.000** |
| | | | Male | 22 | 5.8 | 0.3 | 5.2 | 6.4 | | | |
| | | Left | Female | 13 | 5.0 | 0.3 | 4.5 | 5.5 | -7.800 | 33 | *0.000** |
| | | | Male | 22 | 5.7 | 0.3 | 5.1 | 6.1 | | | |
| | | Average | Female | 13 | 5.0 | 0.2 | 4.5 | 5.5 | -8.040 | 33 | *0.000** |
| | | | Male | 22 | 5.8 | 0.3 | 5.2 | 6.3 | | | |
| | **Circumference** | Right | Female | 13 | 14.7 | 0.8 | 13.8 | 16.6 | -8.117 | 33 | *0.000** |
| | | | Male | 22 | 17.1 | 0.9 | 15.4 | 18.5 | | | |
| | | Left | Female | 13 | 14.6 | 0.7 | 13.8 | 15.9 | -9.070 | 33 | *0.000** |
| | | | Male | 22 | 17.0 | 0.8 | 15.4 | 18.0 | | | |
| | | Average | Female | 13 | 14.6 | 0.8 | 13.8 | 16.2 | -8.682 | 33 | *0.000** |
| | | | Male | 22 | 17.1 | 0.8 | 15.4 | 18.1 | | | |
| **Arm** | **Length** | Right | Female | 13 | 70.1 | 4.4 | 63.5 | 78.7 | -6.093 | 33 | *0.000** |
| | | | Male | 22 | 79.8 | 4.6 | 72.9 | 89.5 | | | |
| | | Left | Female | 13 | 70.0 | 4.5 | 63.6 | 78.9 | -6.107 | 33 | *0.000** |
| | | | Male | 22 | 79.9 | 4.7 | 72.9 | 88.8 | | | |
| | | Average | Female | 13 | 70.1 | 4.5 | 63.6 | 78.8 | -6.106 | 33 | *0.000** |
| | | | Male | 22 | 79.9 | 4.6 | 72.9 | 89.2 | | | |
| **Hand** | **Length** | Right | Female | 13 | 16.7 | 0.8 | 15.5 | 18.0 | -6.664 | 33 | *0.000** |
| | | | Male | 22 | 19.3 | 1.3 | 16.8 | 21.9 | | | |
| | | Left | Female | 13 | 16.7 | 0.8 | 15.3 | 18.0 | -6.959 | 33 | *0.000** |
| | | | Male | 22 | 19.4 | 1.2 | 17.0 | 21.9 | | | |
| | | Average | Female | 13 | 16.7 | 0.8 | 15.4 | 18.0 | -6.821 | 33 | *0.000** |
| | | | Male | 22 | 19.3 | 1.3 | 16.9 | 21.9 | | | |
| | **Width** | Right | Female | 13 | 7.3 | 0.3 | 6.9 | 8.0 | -10.608 | 33 | *0.000** |
| | | | Male | 22 | 8.6 | 0.4 | 8.0 | 9.3 | | | |
| | | Left | Female | 13 | 7.3 | 0.3 | 6.8 | 7.8 | -9.085 | 33 | *0.000** |
| | | | Male | 22 | 8.5 | 0.4 | 7.7 | 9.3 | | | |
| | | Average | Female | 13 | 7.3 | 0.3 | 6.9 | 7.8 | -10.069 | 33 | *0.000** |
| | | | Male | 22 | 8.6 | 0.4 | 7.9 | 9.3 | | | |
| | **Circumference** | Right | Female | 13 | 17.8 | 0.7 | 17.0 | 18.8 | -10.563 | 33 | *0.000** |
| | | | Male | 22 | 21.1 | 1.0 | 19.5 | 23.0 | | | |
| | | Left | Female | 13 | 17.8 | 0.7 | 16.5 | 18.8 | -10.168 | 33 | *0.000** |
| | | | Male | 22 | 21.0 | 1.0 | 18.9 | 22.8 | | | |
| | | Average | Female | 13 | 17.8 | 0.7 | 16.9 | 18.8 | -10.594 | 33 | *0.000** |
| | | | Male | 22 | 21.0 | 1.0 | 19.6 | 22.9 | | | |

Continue on the next page ⇒

Table 5.3 (Continued): Right and left side measurements (cm) of limbs

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Knee** | **Width** | Right | Female | 13 | 9.4 | 1.1 | 8.0 | 11.1 | -3.356 | 33 | *0.002** |
| | | | Male | 22 | 10.4 | 0.6 | 9.3 | 11.7 | | | |
| | | Left | Female | 13 | 9.4 | 1.1 | 7.5 | 11.2 | -3.158 | 33 | *0.003** |
| | | | Male | 22 | 10.3 | 0.6 | 9.4 | 11.5 | | | |
| | | Average | Female | 13 | 9.4 | 1.1 | 7.8 | 11.2 | -3.276 | 33 | *0.002** |
| | | | Male | 22 | 10.3 | 0.6 | 9.4 | 11.6 | | | |
| | **Circumference** | Right | Female | 13 | 34.7 | 3.3 | 30.5 | 40.8 | -3.317 | 33 | *0.002** |
| | | | Male | 22 | 37.6 | 2.1 | 33.6 | 42.0 | | | |
| | | Left | Female | 13 | 34.8 | 3.2 | 30.3 | 40.4 | -2.966 | 33 | *0.006** |
| | | | Male | 22 | 37.5 | 2.1 | 33.2 | 40.5 | | | |
| | | Average | Female | 13 | 34.7 | 3.2 | 30.4 | 40.6 | -3.194 | 33 | *0.003** |
| | | | Male | 22 | 37.5 | 2.0 | 33.4 | 41.3 | | | |
| **Ankle** | **Width** | Right | Female | 13 | 6.3 | 0.4 | 5.8 | 7.3 | -9.097 | 33 | *0.000** |
| | | | Male | 22 | 7.4 | 0.3 | 7.0 | 8.0 | | | |
| | | Left | Female | 13 | 6.3 | 0.4 | 5.8 | 7.3 | -8.184 | 33 | *0.000** |
| | | | Male | 22 | 7.4 | 0.3 | 6.8 | 7.9 | | | |
| | | Average | Female | 13 | 6.3 | 0.4 | 5.8 | 7.3 | -8.780 | 33 | *0.000** |
| | | | Male | 22 | 7.4 | 0.3 | 6.9 | 7.9 | | | |
| | **Circumference** | Right | Female | 13 | 22.4 | 1.6 | 20.4 | 25.1 | -7.277 | 33 | *0.000** |
| | | | Male | 22 | 26.1 | 1.3 | 23.3 | 29.0 | | | |
| | | Left | Female | 13 | 22.4 | 1.6 | 20.4 | 25.0 | -7.466 | 33 | *0.000** |
| | | | Male | 22 | 26.1 | 1.3 | 23.4 | 28.8 | | | |
| | | Average | Female | 13 | 22.4 | 1.6 | 20.5 | 25.1 | -7.466 | 33 | *0.000** |
| | | | Male | 22 | 26.1 | 1.3 | 23.4 | 28.9 | | | |

larger than the L3/L4 level and 5% larger than the L4/L5 level. Figure 5.5 graphically summarizes the descriptive statistics of the CSA of the right (a), left (b), and total (c) ESMMs at each IVD level. Note that bars represent the 95% confidence intervals (CI).

### Cross sectional area (CSA) of the inter-vertebral disc (IVD)

Descriptive statistics for cross sectional areas (CSAs) of the inter-vertebral discs (IVDs) are given in Table 5.5. The average CSA of the IVD was largest at the L4/L5 disc level, 15.93 $cm^2$. The average CSA of ESMMs and IVDs were the smallest at the lowest vertebral disc level (L5/S1). The CSA of IVD at the L5/S1 level (14.67 $cm^2$) was approximately 7% smaller than the L3/L4 (15.77 $cm^2$) and and 8% smaller than the L4/L5 level (15.93 $cm^2$). Figure 5.5 also shows the mean and confidence intervals at each IVD level (Figure 5.5.d).

Table 5.4: Cross-sectional areas (CSAs) of the erector spinae muscle masses (ESMMs)

| | | | **CSA of Right ESMM ($cm^2$)** | | | | **CSA of Left ESMM ($cm^2$)** | | | | **CSA of Total ESMM ($cm^2$)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **IVD Level** | **Gender** | **N** | **Mean** | **St.d.** | **Min** | **Max** | **Mean** | **St.d.** | **Min** | **Max** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 13 | 19.20 | 2.46 | 15.88 | 24.82 | 20.32 | 3.27 | 16.04 | 26.77 | 39.52 | 5.68 | 31.93 | 51.59 |
| | Male | 22 | 29.03 | 5.20 | 21.98 | 43.27 | 29.49 | 4.44 | 21.18 | 39.09 | 58.52 | 9.42 | 43.16 | 82.36 |
| | Total | 35 | 25.38 | 6.49 | 15.88 | 43.27 | 26.09 | 6.01 | 16.04 | 39.09 | 51.46 | 12.37 | 31.93 | 82.36 |
| **L4/L5** | Female | 13 | 21.34 | 3.29 | 17.66 | 28.59 | 21.45 | 3.34 | 18.00 | 29.97 | 42.79 | 6.52 | 36.86 | 58.57 |
| | Male | 22 | 27.74 | 5.27 | 21.60 | 44.99 | 28.78 | 4.71 | 21.92 | 40.67 | 56.52 | 9.79 | 43.52 | 85.65 |
| | Total | 35 | 25.36 | 5.55 | 17.66 | 44.99 | 26.06 | 5.53 | 18.00 | 40.67 | 51.42 | 10.93 | 36.86 | 85.65 |
| **L5/S1** | Female | 13 | 22.63 | 3.93 | 17.33 | 32.38 | 22.42 | 4.71 | 15.03 | 33.95 | 45.05 | 8.55 | 32.36 | 66.32 |
| | Male | 22 | 25.50 | 4.99 | 17.33 | 33.85 | 26.18 | 5.40 | 15.00 | 36.94 | 51.68 | 10.17 | 32.33 | 70.67 |
| | Total | 35 | 24.43 | 4.78 | 17.33 | 33.85 | 24.79 | 5.40 | 15.00 | 36.94 | 49.22 | 10.01 | 32.33 | 70.67 |

Table 5.5: Cross-sectional areas (CSAs) of the inter-vertebral discs (IVDs)

| | | | **CSA of IVD ($cm^2$)** | | | |
|---|---|---|---|---|---|---|
| **IVD Level** | **Gender** | **N** | **Mean** | **St.d.** | **Min** | **Max** |
| **L3/L4** | Female | 13 | 13.21 | 2.24 | 10.70 | 18.10 |
| | Male | 22 | 17.28 | 1.95 | 13.18 | 20.34 |
| | Total | 35 | 15.77 | 2.84 | 10.70 | 20.34 |
| **L4/L5** | Female | 13 | 12.84 | 1.55 | 10.29 | 17.02 |
| | Male | 22 | 17.75 | 1.99 | 12.82 | 20.74 |
| | Total | 35 | 15.93 | 3.02 | 10.29 | 20.74 |
| **L5/S1** | Female | 13 | 12.03 | 1.57 | 9.65 | 15.32 |
| | Male | 22 | 16.23 | 2.29 | 11.40 | 20.10 |
| | Total | 35 | 14.67 | 2.89 | 9.65 | 20.10 |

Paired-samples T-tests were performed to determine whether there was a significant difference between the right and left ESMM CSAs (Table 5.6). Statistical analyses showed that the left ESMM was larger than the right ESMM for female subjects at the L3/L4 level ($p = 0.004$) and for male subjects at the L4/L5 level. The difference between the right and left side was not significant for females at the L4/L5 and L5/S1 levels and for males at the L3/L4 and L5/S1 levels. It should be noted that the CSA of the ESMM was larger on the left side than the right side, except for females at the L5/S1 level. Statistical analyses revealed that the CSAs of the right and left ESMMs were highly correlated (correlation coefficients ranging from 0.912 to 0.959).

Table 5.6: Comparisons of the right and left ESMM CSAs

| | | | Right ($cm^2$) | | Left ($cm^2$) | | Correlations | | Paired T-tests | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Mean | St.d. | Coeff. | Sig. | t | df | Sig. |
| L3/L4 | Female | 13 | 19.20 | 2.46 | 20.32 | 3.27 | 0.959 | *0.000** | -3.538 | 12 | *0.004** |
| | Male | 22 | 29.03 | 5.20 | 29.49 | 4.44 | 0.912 | *0.000** | -1.008 | 21 | 0.325 |
| L4/L5 | Female | 13 | 21.34 | 3.29 | 21.45 | 3.34 | 0.935 | *0.000** | -0.327 | 12 | 0.749 |
| | Male | 22 | 27.74 | 5.27 | 28.78 | 4.71 | 0.924 | *0.000** | -2.418 | 21 | *0.025** |
| L5/S1 | Female | 13 | 22.63 | 3.93 | 22.42 | 4.71 | 0.956 | *0.000** | 0.490 | 12 | 0.633 |
| | Male | 22 | 25.50 | 4.99 | 26.18 | 5.40 | 0.919 | *0.000** | -1.496 | 21 | 0.149 |

Comparison of dominant side to non-dominant side may provide a better understanding of the training effect on muscle size. The contralateral side would be expected to be larger than the dominant hand side. There were 3 left-hand dominant male subjects and 1 ambidextrous male subject in the present study. The data set was modified for dominant and non-dominant hand sides. The CSA of these left-dominant subjects were replaced and the ambidextrous subject was removed from the data set for this analysis. The results of pairwise comparisons for the ESMM CSAs of the dominant- and non-dominant hand sides are presented in Table 5.7.

Since there were no left-hand dominant female subjects, pairwise comparison of the dominant and non-dominant hand sides gave the same results as the comparison of the

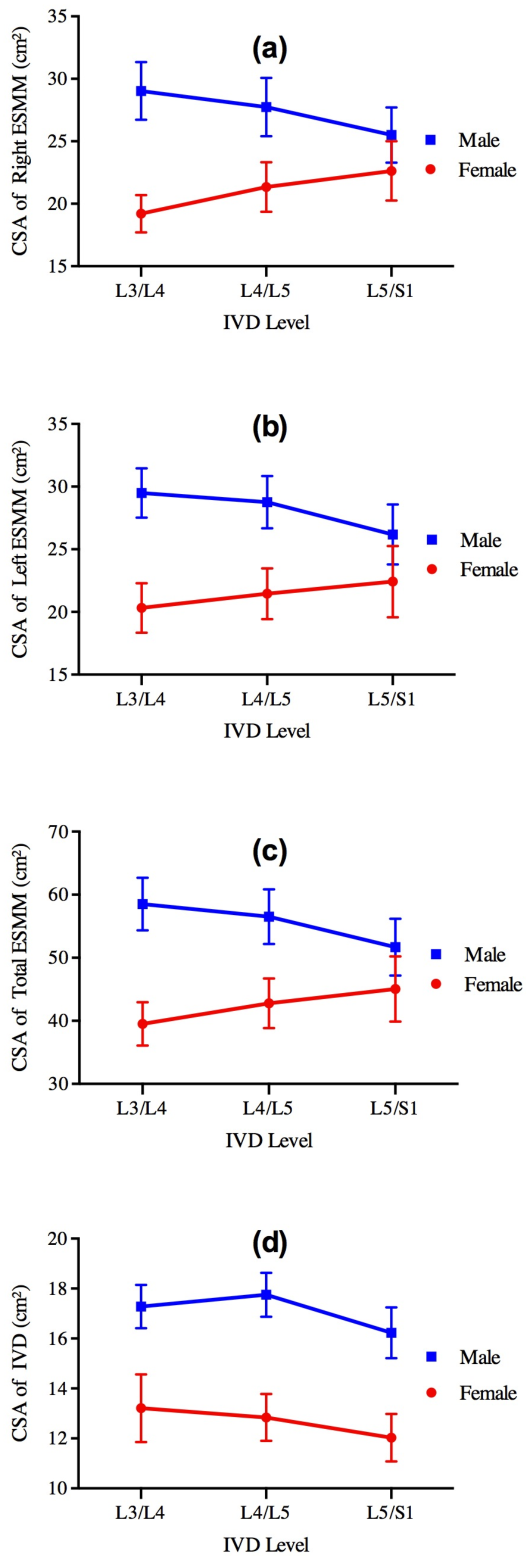



Figure 5.5: Gender comparisons on the CSAs of ESMMs (a: Right ESMM, b: Left ESMM, and c: Total ESMM) and IVDs (d)

Table 5.7: Comparisons of ESMM CSAs of the dominant- and non-dominant hand sides

| | | | Dom. | | Non-Dom. | | Correlations | | Paired T-tests | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | Mean | St.d. | Mean | St.d. | Coeff. | Sig. | t | df | Sig. |
| L3/L4 | Female | 13 | 19.20 | 2.46 | 20.32 | 3.27 | 0.959 | *0.000** | -3.538 | 12 | *0.004** |
| | Male | 21 | 29.1 | 4.97 | 28.80 | 4.48 | 0.893 | *0.000** | 0.624 | 20 | 0.539 |
| L4/L5 | Female | 13 | 21.34 | 3.29 | 21.45 | 3.34 | 0.935 | *0.000** | -0.327 | 12 | 0.749 |
| | Male | 21 | 27.92 | 5.18 | 28.41 | 5.07 | 0.901 | *0.000** | -0.979 | 20 | 0.339 |
| L5/S1 | Female | 13 | 22.63 | 3.93 | 22.42 | 4.71 | 0.956 | *0.000** | 0.490 | 12 | 0.633 |
| | Male | 21 | 25.71 | 4.74 | 26.12 | 5.83 | 0.933 | *0.000** | -0.850 | 20 | 0.406 |

CSA: $cm^2$; Dom: Dominant hand side; Non-Dom: Non-dominant hand side.

right and left sides. However, modifying the male subject data based on their dominant side results in non statistically significant differences at all IVD levels. The difference between the right and left sides was significant at the L4/L5 level, but it is not signifiant after modifying data with the dominant side. The significancy levels (p-values) are much higher now, meaning less difference between two comparison groups. It should be noted that all three male subjects had larger ESMM sizes at their non-dominant sides (an average of 1 $cm^2$ or 5% difference).

To test the effect of gender and IVD level and the interaction effect of gender and IVD level on the CSA of the total ESMM, a 2 X 3 split plot factorial design (SPF) was performed. Results of the SPF analysis are given in Table 5.8. The two factors splitplot design found a main effect of gender ($p = 0.000$). The main effect of the IVD level was not significant ($p = 0.081$). However, the interaction between the IVD level and gender was significant ($p = 0.000$). Figure 5.6 graphically represents the interaction effect on the CSA of the total ESMM.

Table 5.8: ANOVA summary table for main and interaction effects of gender and IVD level on the total ESMM CSA

| Source | SS | df | MS | F-stat | Sig. |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 4222.80 | 1 | 4222.80 | 21.88 | *0.000** |
| Subject(Gender) | 6369.71 | 33 | 193.02 | | |
| **Within Subjects** | | | | | |
| IVD Level | 115.09 | 2 | 57.55 | 2.61 | 0.081 |
| Gender*IVD Level | 629.83 | 2 | 314.92 | 14.28 | *0.000** |
| IVD Level * Subject(Gender) | 1455.06 | 66 | 22.05 | | |
| Total | 12792.49 | 104 | | | |

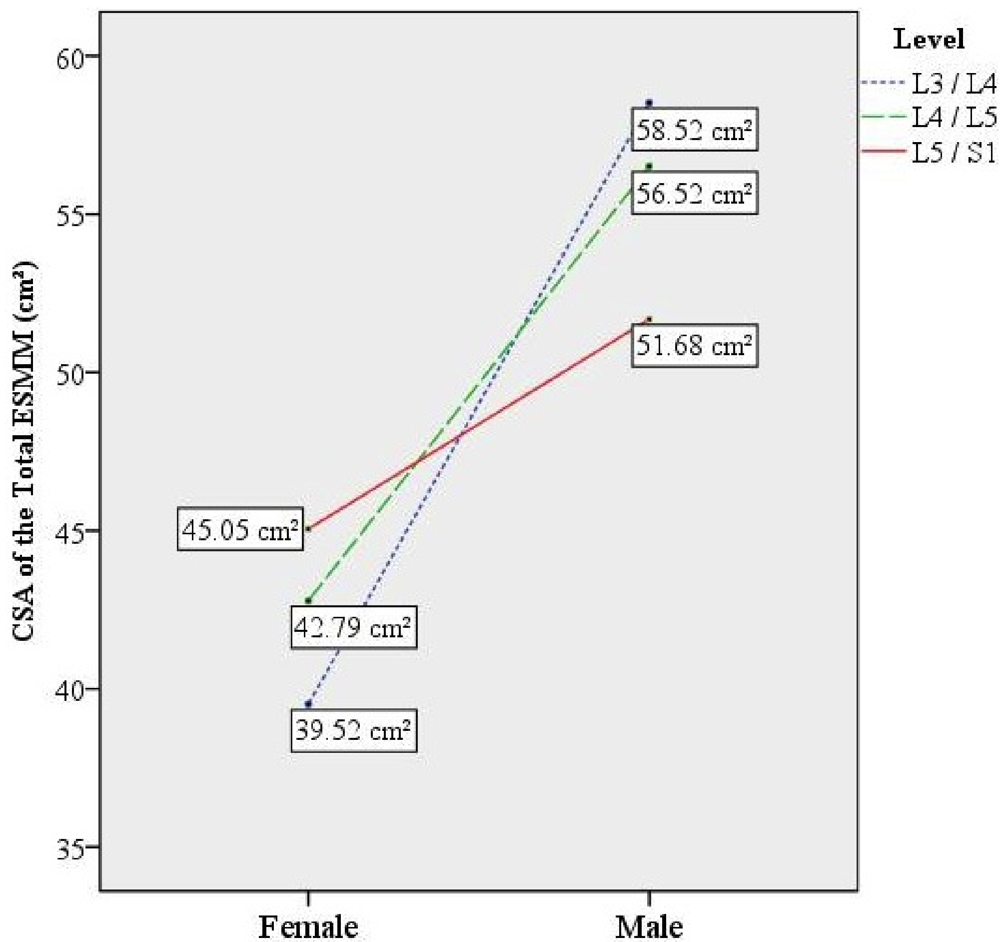



Figure 5.6: Interaction effect of gender and IVD level on the total ESMM CSAs

**The erector spinae muscle mass lever arm (ESMLA) distance**

Descriptive statistics for the erector spinae muscle mass lever arm (ESMLA) distance are presented in Table 5.9. The ESMLA distance was 5.41 cm for males and 4.77 cm for females at the L3/L4 IVD level. The lever arm distance slightly decreased at the L4/L5 IVD level; 5.32 cm for males and 4.75 cm for females, which were the smallest ESMLAs among the three lumbar IVD levels studied. The ESMLA distance was 5.55 cm for males and 4.83 cm for females at the L5/S1 IVD level. The average ESMLA distances for each gender and all subjects are given in Figure 5.7.a. The average ESMLA distance along with the 95% confidence intervals (CI) for each gender are given in Figure 5.7.b.

Table 5.9: Descriptives for the erector spinae muscle mass lever arm (ESMLA) distance

| | | | **ESMLA (cm)** | | | |
|---|---|---|---|---|---|---|
| **Level** | **Gender** | **N** | **Mean** | **St.d.** | **Min** | **Max** |
| L3/L4 | Female | 13 | 4.77 | 0.36 | 4.36 | 5.57 |
| | Male | 22 | 5.41 | 0.32 | 4.98 | 6.04 |
| | Total | 35 | 5.17 | 0.46 | 4.36 | 6.04 |
| L4/L5 | Female | 13 | 4.75 | 0.36 | 4.24 | 5.59 |
| | Male | 22 | 5.32 | 0.32 | 4.82 | 6.00 |
| | Total | 35 | 5.11 | 0.43 | 4.24 | 6.00 |
| L5/S1 | Female | 13 | 4.83 | 0.34 | 4.26 | 5.69 |
| | Male | 22 | 5.55 | 0.35 | 5.06 | 6.28 |
| | Total | 35 | 5.28 | 0.50 | 4.26 | 6.28 |

A split-plot factorial design test was performed to evaluate the effect of gender, IVD level, and the interaction between gender and IVD level on the ESMLA distance (Table 5.10). The SPF-2 X 3 found a main effect of gender ($p = 0.000$), main effect of IVD level ($p = 0.000$) on the ESMLA distances. Interaction effect between gender and IVD level was also significant ($p = 0.049$). Figure 5.7 demonstrates how average ESMLA distances change based on gender and IVD level.

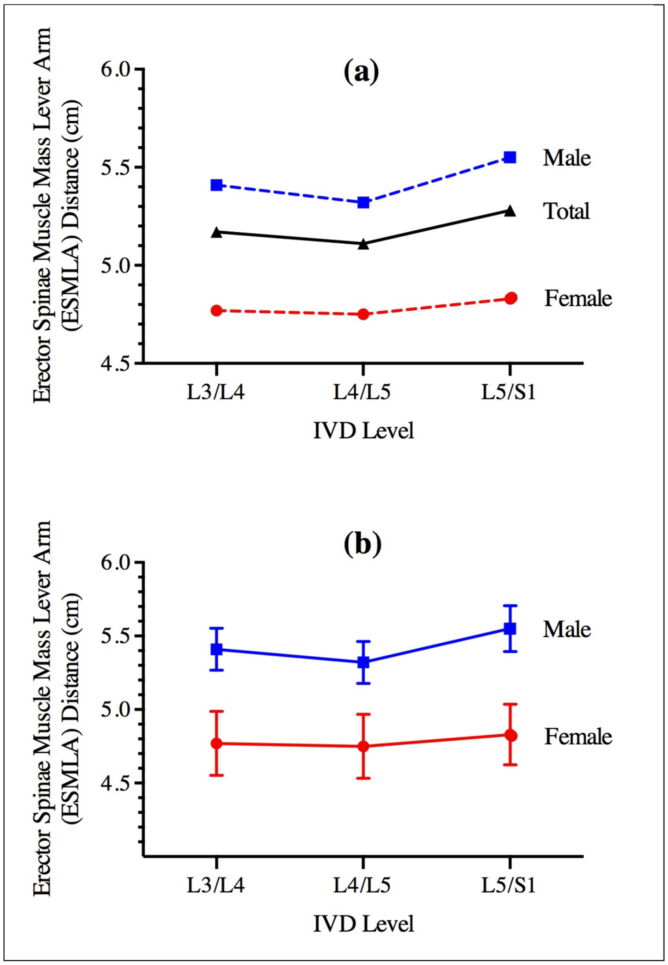



Figure 5.7: The average ESMLA distances and confidence intervals at each IVD level

Table 5.10: ANOVA summary table for main and interaction effects of gender and IVD level on the ESMLA distance

| Source | SS | df | MS | F-stat | Sig. |
|---|---|---|---|---|---|
| **Between Subjects** | | | | | |
| Gender | 10.29 | 1 | 10.29 | 32.55 | *0.000** |
| Subject(Gender) | 10.43 | 33 | 0.32 | 20.74 | |
| **Within Subjects** | | | | | |
| IVD Level | 0.55 | 2 | 0.28 | 18.14 | *0.000** |
| Gender*IVD Level | 0.10 | 2 | 0.05 | 3.17 | *0.049** |
| IVD Level * Subject(Gender) | 1.01 | 66 | 0.02 | | |
| Total | 22.38 | 104 | | | |

### 5.3.2 Correlation and Regression Analyses

***Correlations among subject variables and the ESMLA distance, the CSAs of the total, right, and left ESMMs***

Correlation analyses were performed to determine correlations between subject variables (characteristics and anthropometrics) and sizes of the ESMMs and ESMLAs. Results of correlation analyses are presented in Table 5.11. Results indicate no correlations between the subject age and the ESMM size and ESMLA distances. Performing lifting exercise did not correlate with ESMM size and ESMLA distances for all IVD levels. However, performing cardiovascular exercise had an effect on these dimensions at the L5/S1 level. Amount of fat in a subject's body was correlated at the L5/S1 level only. Gender was correlated with the ESMLA distance at the L5/S1 level. The left ESMM size was also correlated with gender at the same IVD level. Chest depth, only at the L5/S1 level, was not correlated with the ESMM sizes. However, it was correlated with the ESMLA distance at the same level. Hand length and knee width were also correlated with the ESMM size and not correlated with the ESMLA distance at this level (the L5/S1). Arm length was not correlated with the ESMLA distance at the L5/S1 level. Some variables were correlated with only the right or left ESMM CSA (but not both). For example, elbow width and wrist width were correlated with only the right ESMM and arm length was correlated with the left ESMM.

Correlation analyses among subject variables (subject anthropometrics and subject characteristics) were also performed (Table 5.12). Correlations among subject anthropometrics were mostly significant. Subject age, lifting exercise, and cardio exercise did not significantly correlate with other subject variables, except age was correlated with chest breadth and depth, and cardio exercise was correlated with lifting exercise frequency.

Table 5.11: Correlations among subjects variables and the ESMLA distance, the CSAs of the total, right, and left ESMMs

| | L3/L4 Level | | | | L4/L5 Level | | | | L5/S1 Level | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ESMLA | CSA of ESMM | | | ESMLA | CSA of ESMM | | | ESMLA | CSA of ESMM | | |
| **Variable** | | **Total** | **Right** | **Left** | | **Total** | **Right** | **Left** | | **Total** | **Right** | **Left** |
| **Gender** | *0.692** | *0.753** | *0.743** | *0.748** | *0.648** | *0.616** | *0.565** | *0.65** | 0.719 | *0.325** | *0.295** | 0.341 |
| **Age** | 0.223 | 0.219 | 0.170 | 0.267 | 0.130 | 0.139 | 0.108 | 0.166 | 0.288 | -0.062 | -0.117 | -0.012 |
| **Height** | *0.806** | *0.699** | *0.673** | *0.712** | *0.775** | *0.665** | *0.612** | *0.702** | *0.792** | *0.476** | *0.424** | *0.507** |
| **Weight** | *0.782** | *0.809** | *0.776** | *0.828** | *0.779** | *0.748** | *0.690** | *0.786** | *0.814** | *0.468** | *0.435** | *0.483** |
| **BMI** | *0.565** | *0.715** | *0.686** | *0.731** | *0.586** | *0.648** | *0.603** | *0.675** | *0.628** | *0.368** | *0.368** | *0.357** |
| **Fat (%)** | *-0.365** | *-0.460** | *-0.456** | *-0.454** | *-0.340** | *-0.384** | *-0.333** | *-0.425** | -0.312 | -0.249 | -0.197 | -0.288 |
| **Fat-free Weight** | *0.801** | *0.86** | *0.831** | *0.873** | *0.792** | *0.785** | *0.718** | *0.831** | *0.812** | *0.491** | *0.448** | *0.513** |
| **Fat Weight** | 0.226 | 0.141 | 0.116 | 0.164 | 0.243 | 0.159 | 0.165 | 0.149 | *0.301** | *0.103** | *0.121** | *0.084** |
| **Lifting exercise** | -0.005 | 0.031 | 0.043 | 0.018 | -0.100 | 0.048 | 0.113 | -0.018 | -0.216 | -0.047 | -0.022 | -0.067 |
| **Cardio Exercise** | 0.211 | 0.192 | 0.217 | 0.161 | 0.190 | 0.251 | 0.271 | 0.224 | *0.169** | *0.272** | *0.294** | *0.244** |
| **Sitting Height** | *0.727** | *0.544** | *0.534** | *0.542** | *0.721** | *0.495** | *0.458** | *0.518** | *0.693** | *0.470** | *0.433** | *0.488** |
| **Shoulder Width** | *0.816** | *0.807** | *0.772** | *0.828** | *0.764** | *0.745** | *0.682** | *0.789** | *0.783** | *0.520** | *0.480** | *0.540** |
| **Head Width** | *0.412** | *0.492** | *0.488** | *0.486** | *0.441** | *0.424** | *0.381** | *0.456** | *0.490** | *0.368** | *0.368** | *0.356** |
| **Head Circumference** | *0.593** | *0.660** | *0.621** | *0.688** | *0.583** | *0.667** | *0.590** | *0.726** | *0.608** | *0.609** | *0.571** | *0.624** |
| **Head Depth** | *0.657** | *0.594** | *0.604** | *0.571** | *0.651** | *0.529** | *0.479** | *0.566** | *0.620** | *0.454** | *0.419** | *0.471** |
| **Chest Breadth** | *0.681** | *0.648** | *0.604** | *0.682** | *0.652** | *0.572** | *0.519** | *0.609** | *0.703** | *0.404** | *0.340** | *0.448** |
| **Chest Depth** | *0.588** | *0.554** | *0.530** | *0.569** | *0.563** | *0.446** | *0.406** | *0.474** | *0.568** | 0.277 | 0.256 | 0.287 |
| **Elbow Width** | *0.624** | *0.697** | *0.665** | *0.716** | *0.593** | *0.611** | *0.535** | *0.672** | *0.627** | *0.348** | 0.295 | *0.384** |
| **Elbow Circumference** | *0.8** | *0.753** | *0.718** | *0.773** | *0.775** | *0.683** | *0.614** | *0.734** | *0.836** | *0.440** | *0.383** | *0.477** |
| **Wrist Width** | *0.794** | *0.714** | *0.687** | *0.728** | *0.756** | *0.631** | *0.558** | *0.688** | *0.828** | *0.358** | 0.299 | *0.399** |
| **Wrist Circumference** | *0.841** | *0.786** | *0.751** | *0.806** | *0.818** | *0.726** | *0.659** | *0.775** | *0.867** | *0.449** | *0.391** | *0.486** |
| **Arm Length** | *0.762** | *0.697** | *0.678** | *0.702** | *0.699** | *0.645** | *0.594** | *0.678** | 0.725 | 0.323 | *0.272** | 0.358 |
| **Hand Length** | *0.653** | *0.671** | *0.654** | *0.674** | *0.600** | *0.561** | *0.509** | *0.598** | *0.622** | 0.203 | 0.171 | 0.225 |
| **Hand Width** | *0.800** | *0.773** | *0.749** | *0.783** | *0.770** | *0.676** | *0.598** | *0.736** | *0.790** | *0.398** | *0.341** | *0.436** |
| **Hand Circumference** | *0.816** | *0.803** | *0.781** | *0.809** | *0.797** | *0.717** | *0.642** | *0.773** | *0.825** | *0.426** | *0.377** | *0.457** |
| **Knee Width** | *0.442** | *0.542** | *0.506** | *0.570** | *0.405** | *0.492** | *0.495** | *0.475** | *0.485** | 0.240 | 0.259 | 0.215 |
| **Knee Circumference** | *0.603** | *0.564** | *0.532** | *0.587** | *0.624** | *0.529** | *0.509** | *0.534** | *0.638** | *0.380** | *0.371** | *0.376** |
| **AnkleWidth** | *0.817** | *0.778** | *0.772** | *0.766** | *0.821** | *0.730** | *0.679** | *0.761** | *0.848** | *0.539** | *0.507** | *0.551** |
| **Ankle Circumference** | *0.851** | *0.812** | *0.804** | *0.803** | *0.837** | *0.790** | *0.745** | *0.815** | *0.850** | *0.538** | *0.516** | *0.542** |

* = significant at $\alpha \leq 0.05$

Table 5.12: Correlations among subjects variables (subject anthropometrics and subject characteristics)

| Variable | Age | Height | Weight | BMI | Fat (%) | Fat-free Weight | Fat Weight | Lifting Exercise | Cardio Exercise | Sitting Height | Shoulder Width | Head Width | Head Circumference | Head Depth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gender** | 0.304 | 0.722* | 0.767* | 0.637* | -0.511* | 0.828* | 0.095 | -0.022 | 0.144 | 0.600* | 0.795* | 0.603* | 0.561* | 0.733* |
| **Age** | | 0.231 | 0.325 | 0.300 | -0.043 | 0.286 | 0.234 | -0.089 | -0.066 | 0.055 | 0.305 | 0.152 | 0.205 | 0.129 |
| **Height** | | | 0.860* | 0.515* | -0.300 | 0.855* | 0.327 | -0.105 | 0.051 | 0.868* | 0.829* | 0.510* | 0.719* | 0.728* |
| **Weight** | | | | 0.874* | -0.228 | 0.958* | 0.491* | -0.132 | -0.007 | 0.713* | 0.858* | 0.598* | 0.710* | 0.742* |
| **BMI** | | | | | -0.075 | 0.800* | 0.540* | -0.126 | -0.080 | 0.405* | 0.685* | 0.554* | 0.543* | 0.571* |
| **Fat (%)** | | | | | | -0.495* | 0.721* | -0.148 | -0.335* | -0.105 | -0.454* | -0.348* | -0.312 | -0.251 |
| **Fat-free Weight** | | | | | | | 0.219 | -0.073 | 0.100 | 0.662* | 0.898* | 0.627* | 0.729* | 0.736* |
| **Fat Weight** | | | | | | | | -0.224 | -0.324 | 0.411* | 0.192 | 0.129 | 0.199 | 0.284 |
| **Lifting Exercise** | | | | | | | | | 0.511* | -0.131 | -0.139 | -0.279 | -0.163 | -0.115 |
| **Cardio Exercise** | | | | | | | | | | 0.014 | 0.033 | -0.147 | 0.118 | -0.021 |
| **Sitting Height** | | | | | | | | | | | 0.685* | 0.504* | 0.609* | 0.748* |
| **Shoulder Width** | | | | | | | | | | | | 0.620* | 0.762* | 0.697* |
| **Head Width** | | | | | | | | | | | | | 0.505* | 0.483* |
| **Head Circumference** | | | | | | | | | | | | | | 0.536* |
| **Head Depth** | | | | | | | | | | | | | | |
| **Chest Breadth** | | | | | | | | | | | | | | |
| **Chest Depth** | | | | | | | | | | | | | | |
| **Elbow Width** | | | | | | | | | | | | | | |
| **Elbow Circumference** | | | | | | | | | | | | | | |
| **Wrist Width** | | | | | | | | | | | | | | |
| **Wrist Circumference** | | | | | | | | | | | | | | |
| **Arm Length** | | | | | | | | | | | | | | |
| **Hand Length** | | | | | | | | | | | | | | |
| **Hand Width** | | | | | | | | | | | | | | |
| **Hand Circumference** | | | | | | | | | | | | | | |
| **Knee Width** | | | | | | | | | | | | | | |
| **Knee Circumference** | | | | | | | | | | | | | | |
| **AnkleWidth** | | | | | | | | | | | | | | |

* = significant at $\alpha \leq 0.05$

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Table 5.12 (Continued): Correlations among subjects variables (subject anthropometrics and subject characteristics)

| **Variable** | **Chest Breadth** | **Chest Depth** | **Elbow Width** | **Elbow Circumference** | **Wrist Width** | **Wrist Circumference** | **Arm Length** | **Hand Length** | **Hand Width** | **Hand Circumference** | **Knee Width** | **Knee Circumference** | **AnkleWidth** | **Ankle Circumference** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gender** | *0.653** | *0.633** | *0.722** | *0.819** | *0.814** | *0.834** | *0.728** | *0.765** | *0.869** | *0.879** | *0.495** | *0.486** | *0.837** | *0.793** |
| **Age** | *0.431** | *0.364** | 0.129 | 0.356 | 0.310 | 0.299 | 0.244 | 0.290 | 0.318 | 0.313 | 0.299 | 0.155 | 0.172 | 0.321 |
| **Height** | *0.752** | *0.493** | *0.706** | *0.892** | *0.838** | *0.877** | *0.932** | *0.796** | *0.834** | *0.833** | *0.529** | *0.727** | *0.797** | *0.773** |
| **Weight** | *0.888** | *0.724** | *0.791** | *0.935** | *0.809** | *0.888** | *0.761** | *0.690** | *0.834** | *0.859** | *0.695** | *0.751** | *0.800** | *0.852** |
| **BMI** | *0.766** | *0.766** | *0.681** | *0.741** | *0.584** | *0.680** | *0.407** | *0.423** | *0.628** | *0.673** | *0.717** | *0.607** | *0.636** | *0.737** |
| **Fat (%)** | -0.131 | -0.141 | -0.253 | -0.294 | *-0.389** | *-0.386** | *-0.406** | *-0.470** | *-0.489** | *-0.470** | 0.218 | 0.131 | *-0.356** | -0.258 |
| **Fat-free Weight** | *0.815** | *0.679** | *0.778** | *0.918** | *0.836** | *0.905** | *0.805** | *0.760** | *0.892** | *0.908** | *0.559** | *0.632** | *0.817** | *0.839** |
| **Fat Weight** | *0.542** | *0.400** | 0.326 | *0.390** | 0.210 | 0.272 | 0.143 | 0.040 | 0.129 | 0.165 | *0.666** | *0.632** | 0.240 | *0.349** |
| **Lifting Exercise** | -0.157 | -0.049 | -0.107 | -0.141 | -0.219 | -0.173 | -0.058 | -0.080 | -0.077 | -0.121 | -0.008 | -0.213 | -0.157 | -0.096 |
| **Cardio Exercise** | -0.066 | -0.103 | 0.011 | 0.032 | 0.006 | 0.035 | 0.066 | 0.006 | 0.136 | 0.128 | -0.208 | -0.232 | 0.027 | 0.083 |
| **Sitting Height** | *0.642** | *0.477** | *0.588** | *0.722** | *0.733** | *0.733** | *0.714** | *0.584** | *0.644** | *0.639** | *0.494** | *0.678** | *0.732** | *0.654** |
| **Shoulder Width** | *0.727** | *0.626** | *0.695** | *0.866** | *0.839** | *0.866** | *0.789** | *0.766** | *0.874** | *0.871** | *0.517** | *0.597** | *0.782** | *0.809** |
| **Head Width** | *0.525** | *0.555** | *0.370** | *0.522** | *0.501** | *0.541** | *0.391** | *0.434** | *0.483** | *0.525** | *0.412** | *0.409** | *0.590** | *0.547** |
| **Head Circumference** | *0.586** | *0.413** | *0.640** | *0.693** | *0.62** | *0.673** | *0.619** | *0.599** | *0.714** | *0.709** | *0.500** | *0.560** | *0.617** | *0.656** |
| **Head Depth** | *0.653** | *0.592** | *0.632** | *0.768** | *0.732** | *0.721** | *0.633** | *0.597** | *0.720** | *0.715** | *0.474** | *0.570** | *0.745** | *0.720** |
| **Chest Breadth** | | *0.695** | *0.709** | *0.844** | *0.645** | *0.736** | *0.612** | *0.504** | *0.682** | *0.691** | *0.553** | *0.612** | *0.622** | *0.659** |
| **Chest Depth** | | | *0.519** | *0.671** | *0.629** | *0.634** | *0.410** | *0.381** | *0.618** | *0.638** | *0.591** | *0.491** | *0.599** | *0.664** |
| **Elbow Width** | | | | *0.828** | *0.765** | *0.814** | *0.667** | *0.664** | *0.777** | *0.768** | *0.473** | *0.603** | *0.742** | *0.736** |
| **Elbow Circumference** | | | | | *0.899** | *0.939** | *0.829** | *0.758** | *0.917** | *0.918** | *0.589** | *0.723** | *0.854** | *0.873** |
| **Wrist Width** | | | | | | *0.961** | *0.834** | *0.807** | *0.914** | *0.919** | *0.506** | *0.625** | *0.889** | *0.867** |
| **Wrist Circumference** | | | | | | | *0.837** | *0.800** | *0.921** | *0.936** | *0.579** | *0.703** | *0.925** | *0.910** |
| **Arm Length** | | | | | | | | *0.901** | *0.858** | *0.846** | *0.434** | *0.609** | *0.740** | *0.738** |
| **Hand Length** | | | | | | | | | *0.873** | *0.856** | *0.445** | *0.593** | *0.714** | *0.759** |
| **Hand Width** | | | | | | | | | | *0.982** | *0.481** | *0.594** | *0.849** | *0.879** |
| **Hand Circumference** | | | | | | | | | | | *0.503** | *0.621** | *0.868** | *0.907** |
| **Knee Width** | | | | | | | | | | | | *0.786** | *0.569** | *0.652** |
| **Knee Circumference** | | | | | | | | | | | | | *0.656** | *0.721** |
| **AnkleWidth** | | | | | | | | | | | | | | *0.909** |

* = significant at $\alpha \leq 0.05$

Correlations among subject variables were very high, which may result in multicollinearity problems. The variance of the regression coefficients are inflated with higher multicollinearity, resulting in small t-values and unstable regression coefficients. To eliminate or minimize multicollinearity, it is suggested that only one variable (the best representer) be kept and other (highly correlated) variables from the independent variable list be removed from statistical analyses. On the other hand, preliminary regression models suggested that the best representer for one IVD level may not be the best representer for another level. Moreover, the best representer variable for the ESMM size may not be the best representer for the ESMLA distance, or vice versa. Independent variables were combined to address these complexities. An index value was created for each anthropometric location. For example, a wrist index was created by multiplying wrist width and wrist circumference. Table 5.13 represents how the anthropometric index variables are calculated. The index variables, rather than individual measurements, were used in regression models.

Table 5.13: Anthropometric index variables and their combining variables

| **Index** | | **Variable Combinations** | | | | |
|---|---|---|---|---|---|---|
| Head | = | Head Width | X | Head Circumference | X | Head Depth |
| Chest | = | Chest Breadth | X | Chest Depth | | |
| Elbow | = | Elbow Width | X | Elbow Circumference | | |
| Wrist | = | Wrist Width | X | Wrist Circumference | | |
| Hand | = | Hand Width | X | Hand Circumference | X | Hand Length |
| Knee | = | Knee Width | X | Knee Circumference | | |
| Ankle | = | AnkleWidth | X | Ankle Circumference | | |

Body fat percentage, fat-free weight or lean body mass (LBM), and fat weight were correlated with each other. This is not sup rising since LBM and fat weight are a function of body fat percentage and weight. To minimize multicollinearity problems, LBM was selected to describe a subject's body composition. BMI was not included in regression analyses because of its correlations with other variables and because it does not measure the underlying construct of muscle mass as well as LBM. BMI does address body composition directly, but rather estimates for a homogenous population that is neither significantly lean (fit) or significantly heavy (fat).

After removing some variables (age, frequency of lifting and cardio exercises, BMI, fat percentage, and fat weight) and combining anthropometric measurements in anthropometric indexes, the list of independent variables that were used to regress over the ESMM size and ESMLA distance are given in Table 5.14. Note that Table 5.14 also provides correlations between these variables and the ESMM size and ESMLA distance at each level. All fourteen independent predictors were significantly correlated with the ESMLA distance at all IVD levels. All of these independent variables were significantly correlated with the total CSA of the ESMM at the L3/L4 and L4/L5 levels. However, some correlations among the independent variables and the L5/S1 ESMM size were not significant correlated; gender ($p = 0.057$), arm length ($p = 0.058$), and knee ($p = 0.060$) were not significantly correlated with the ESMM size at the L5/S1 level. However, it should be noted that p-values were very close to the significance level ($p \leq 0.050$).

### Selection of regression models

There are some model selection procedures that try to estimate "the best" regression model. However, they may provide different "best models" based on their selection algorithm. It should be noted that no one procedure is universally accepted as better than the others. For example, forward selection methods add one independent variable to the model one at a time. At each step, the variable that yields the largest increment in $R^2$ is selected. It stops when any remaining variable does not increase the power. On the other hand, backward selection methods delete independent variables one at a time. Stepwise selection methods add or delete independent variables one at a time, as well. However, there is a possibility that a combination of some independent predictors may better explain the variation in prediction than an individual predictor itself. An all-possible-regressions

Table 5.14: Correlations among independent and dependent variables used for regression analyses

| | Total ESMM | | | ESMLA | | |
|---|---|---|---|---|---|---|
| **Variable** | **L3/L4** | **L4/L5** | **L5/S1** | **L3/L4** | **L4/L5** | **L5/S1** |
| **Gender** | *0.753** | *0.616** | 0.325 | *0.692** | *0.648** | *0.719** |
| **Height** | *0.699** | *0.665** | *0.476** | *0.806** | *0.775** | *0.792** |
| **Weight** | *0.809** | *0.748** | *0.468** | *0.782** | *0.779** | *0.814** |
| **Fat-free Weight** | *0.860** | *0.785** | *0.491** | *0.801** | *0.792** | *0.812** |
| **Sitting Height** | *0.544** | *0.495** | *0.470** | *0.727** | *0.721** | *0.693** |
| **Shoulder Width** | *0.807** | *0.745** | *0.520** | *0.816** | *0.764** | *0.783** |
| **Arm Length** | *0.697** | *0.645** | 0.323 | *0.762** | *0.699** | *0.725** |
| **Head** | *0.692** | *0.630** | *0.557** | *0.679** | *0.683** | *0.691** |
| **Chest** | *0.631** | *0.527** | *0.349** | *0.665** | *0.638** | *0.672** |
| **Elbow** | *0.746** | *0.663** | *0.396** | *0.729** | *0.697** | *0.745** |
| **Wrist** | *0.756** | *0.684** | *0.402** | *0.823** | *0.794** | *0.854** |
| **Hand** | *0.773** | *0.673** | *0.343** | *0.776** | *0.741** | *0.758** |
| **Knee** | *0.589** | *0.542** | 0.321 | *0.548** | *0.536** | *0.591** |
| **Ankle** | *0.820** | *0.787** | *0.555** | *0.859** | *0.853** | *0.874** |

procedure, on the other hand, minimizes the disadvantages of these procedures. Thanks to advances in computing power and procedures, it is feasible to investigate all-possible-regression models in a very short time. Researchers then may select "the best model" from all possible subsets by employing decision criteria for acceptance/rejection of potential model. Logistical considerations may also be factored in. For example, if two models have similar performance but one is much easier to employ, the simpler model might be chosen. The coefficient of determination ($R^2$), Adjusted-$R^2$, residual mean square (MSE), Mallows' prediction criterion ($C_P$), Akaike information criterion (AIC), and Schwarz Bayesian criterion (SBC) are the most common model selection criteria used to determine the "optimal" model.

In this dissertation, the five best subsets of each size (number of parameters) were identified by "best subset regression" methodology using Minitab statistical software (version 15.1). Minitab uses maximum $R^2$ to select these subsets from $2^n$-1 alternative regression models, where n is the number of regression parameters. There were 15 parameters (fourteen independent variables and one intercept) in the present study, which yields 32,767 different regression models for the ESMM size and 32,767 different regression models for the ESMLA distance at "each" IVD level. For example, only "the best five" regression models out of fourteen two-parameter models (one independent variable and one intercept model) were reported. A total of 66 different subsets were presented for the total ESMM size at each IVD level, yielding a total of 196 regression models for all three IVD levels. There were 196 different regression models for the ESMLA distance, as well. All these subset regression models are presented in Appendices (F.1, F.2, F.3, G.1, G.2, and G.3). The values of Adjusted-$R^2$, Mallows' $C_P$, and residual mean square are given for each set in these tables. Note that the subsets written in bold and italic fonts are the models selected as "the best models" for this dissertation.

After determining regression subsets, they were evaluated based on their statistics (i.e., $C_P$ criterion, Adjusted-$R^2$, and residual mean square) to determine the best model(s). The primary model selection criteria used in this dissertation was to select models with the largest Adjusted-$R^2$ since Adjusted-$R^2$ provides information on how well a model fits the data. Adjusted-$R^2$ is preferred over $R^2$ since it removes the impact of degrees of freedom and allows for better comparisons of models involving different numbers of parameters. $R^2$ typically increases with each variable added to a model even though these variables may not significantly improve model performance. Based on the maximum $R^2$, the subset with all independent variables will always be the best regression model. However, Adjusted-$R^2$ penalizes models with unnecessary variables. The simplest model with the largest Adjusted-$R^2$ or near the largest Adjusted-$R^2$ were chosen as "the best model" in this dissertation.

Adjusted-$R^2$ was not the only criterion to determine the best regression models in this dissertation. Mallows' $C_P$ was used to assess the goodness of the fit of a regression model and/or measure the prediction error (or bias). Based on the assumption that the full model (having all variables and intercept) has sufficient terms to eliminate important bias, the $C_P$ statistic is used to search for a simpler model that also has little bias. For a given number of parameters, smaller values of $C_P$ indicate a better fit. The $C_P$ theory suggests that the best fitting model is the one whose $C_P$ approximately equals the number of parameters. Models having values of $C_P$ considerably larger than the number of parameters do not fit well and are assumed to have substantial bias. Models having values of $C_P$ smaller than the number of parameters are assumed to have no bias but may still have sampling error. The biased component is called the model error component. Mallows' $C_P$ is the most favored criteria for subset size selection. Note that the $C_P$ statistic does poorly when the difference between the number of subjects and the number of parameters in the model is less than or equal to 10, but it is suggested that this difference should be larger than 40. In this dissertation, the minimum difference is 20 (35 subjects, 15 parameters including intercept), which is above the minimum criteria but below the suggested criteria.

The best methodology is to consider more than one criterion in evaluating possible subsets. The goal of this dissertation is to have regression models with the smallest number of predictors while still providing a "satisfactory" Adjusted $R^2$, smaller $C_P$ values (close to the number of parameters), and smaller residual mean squares.

From the various "best" regression models, models with the minimum $C_P$ or as near to the number of parameters were selected. Among these subsets, models with the largest Adjusted-$R^2$ and minimum residual mean square ($s = \sqrt{MSE}$) values were selected. Models that had the minimum number of variables were preferred over ones having more variables. In addition to these quantitative criteria, a subjective approach was employed. The subjective approach looks for the tendency of a variable to enter the model. Variables that were often in models were preferred even though the quantitive criteria may have suggested selection of other models without those variables. For example, the subject weight variable is not a very promising variable to predict the total ESMM size at the L3/L4 level. It enters regression models only few times. On the other hand, the fat-free weight (LBM) variable enters almost all regression subsets. Based on the subjective criteria, the model with subject LBM was preferred over the model with subject weight even though the model with subject weight has larger Adjusted-$R^2$ than the model with subject LBM. The model selection procedure was stopped when the marginal increase in Adjusted-$R^2$ value was not satisfactory. Instead of providing only one regression model for each IVD level, several alternative models (approximately three models for each IVD level) are provided in this dissertation.

After determining best subsets, independent variables were regressed over the ESMM size and the ESMLA distance to determine coefficients. The "Enter Method" of regression in IBM SPSS Statistics (version 19.0) was used to determine these coefficients and regression equations.

### Best subsets regression analyses for the cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM)

Best subsets regression analyses were performed to determine prediction equations for the cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM). After applying model section criteria explained in the model selection part, several regression models were selected for each IVD level. Enter Method regression analyses were performed to determine coefficients for each variables and test whether these prediction models were statistically significant. Independent variables that were statistically significant were highlighted with italic and bold fonts in regression equations. Intercepts were also highlighted if they were significant. These alternative regression models are presented in Table 5.15. ANOVA tests revealed that all regression models were significant ($p \leq 0.050$). This means that the dependent variable can be estimated by independent variables at $\alpha = 0.050$, and at least one predictor variable will be included in the model to explain the variability in the total ESMM size.

The most "important" predictive variables seem to be LBM and ankle, wrist, and head indexes in most regression subsets. Shoulder width was also included in most regression subsets at L4/L5 level, and arm length was included in most regression subsets at L5/S1 level.

At the L3/L4 level, the regression model having five independent variables and one intercept had the smallest $C_P$ value, 4.4 (see Appendix F.1). However, its $R^2$ and Adjusted-$R^2$ values (0.835 and 0.807, respectively) were not the largest among all subsets. For example, the first two models of seven-parameter subsets had larger $R^2$ and Adjusted-$R^2$ values (0.842 and 0.808, respectively) compared to the this model. The seven-parameter model was obtained by adding subject weight into the six-variable model. It should be noted that the purpose of this dissertation was to provide the simplest models possible to increase applicability and ease of use by practitioners. The improvement obtained from adding the new variable (weight) into the model was questionable. Therefore, the model selection was stopped with the six-parameter model, leaving weight out of the model.

LBM, ankle, wrist, head, and shoulder width were the main predictor variables at the L4/L5 level. A six-parameter model including these variables was selected as the smallest best subset. Subset models with fewer parameters ($p < 6$) did not satisfy the $C_P$ criterion. Two seven-parameter models were also selected for the same IVD level. One of these models included the gender variable, and the other alternative seven-parameter model included the chest index variable. The eight-parameter model that included the hand variable in addition to chest index variable was the largest best subset for L4/L5 level. One nine-parameter model and one ten-parameter model had the largest Adjusted-$R^2$ values (0.787). However, they were not selected as best subset models since the improvement from adding more variables to the eight-parameter model was not deemed high enough to accept the complexity of these larger models.

Subset models at the L5/S1 level had the smallest $R^2$ and Adjusted-$R^2$ values and largest standard error values compared to subset models at the L3/L4 and L4/L5 levels. It may be due to the complexity and variability of lumbosacral structure (L5/S1). Note that the required number of variables to explain the variability in the CSA of the total ESMM was larger than other IVD levels, as well. Two eight-parameter and one nine-parameter models were selected as the best subsets at this level.

Scatter plots were drawn to demonstrate how the regression models fit the data. Regression models with the largest Adjusted-$R^2$ values from each IVD level were selected for this purpose. It can be seen from scatter plots that the six-parameter model (Figure 5.8.a) at the L3/L4 level, the eight-parameter model (Figure 5.8.b) at the L4/L5 level, and the nine-parameter model (Figure 5.9.c) at the L5/S1 level fit well with the measured data.

Table 5.15: Regression models for the CSA of the total ESMM

| Level | P | Equations for the CSA of the total ESMM | ANOVA p-value | $R^2$ | Adj-$R^2$ | S.E. | $C_P$ |
|---|---|---|---|---|---|---|---|
| L3/L4 | 4 | = 4.651 + 0.647****LBM*** + 0.261****An*** - 0.404****Wr*** | *0.000** | 0.797 | 0.778 | 5.83 | 6.6 |
| | 5 | = 16.355 + 0.806****LBM*** + 0.308****An*** - 0.449****Wr*** - 0.001*He | *0.000** | 0.817 | 0.793 | 5.63 | 5.4 |
| | 6 | = - 3.076 + 0.669****LBM*** + 0.323****An*** - 0.543****Wr*** - 0.002****He*** + 0.929*SW | *0.000** | 0.835 | 0.807 | 5.44 | 4.4 |
| L4/L5 | 6 | = 3.906 + 0.522****LBM*** + 0.384****An*** - 0.658****Wr*** - 0.002****He*** + 0.982*SW | *0.000** | 0.780 | 0.742 | 5.55 | 7.4 |
| | 7 | = - 8.459+ 0.566****LBM*** + 0.412****An*** - 0.626****Wr*** - 0.002****He*** + 1.029*SW - 5.938*G | *0.000** | 0.797 | 0.754 | 5.42 | 7.0 |
| | 7 | = 6.533 + 0.644****LBM*** + 0.375****An*** - 0.649****Wr*** - 0.002****He*** + 0.926*SW - 0.016*C | *0.000** | 0.796 | 0.752 | 5.44 | 7.2 |
| | 8 | = - 1.916 + 0.817****LBM*** + 0.394****An*** - 0.458****Wr*** - 0.002****He*** + 1.169****SW*** - 0.024****C*** - 0.007****Ha*** | *0.000** | 0.826 | 0.781 | 5.12 | 5.0 |
| L5/S1 | 8 | = - ***76.468*** + 0.496****An*** - 0.747****Wr*** - 9.322****G*** - 1.204****AL*** + 0.994****H*** + 1.321****SW*** - 0.066****K*** | *0.000** | 0.670 | 0.584 | 6.45 | 6.3 |
| | 8 | = - ***65.557*** + 1.043****LBM*** + 0.463****An*** - 0.662****Wr*** - 9.677*G - 1.594****AL*** + 1.294****H*** - 0.830****W*** | *0.000** | 0.659 | 0.571 | 6.56 | 7.1 |
| | 9 | = - ***85.211*** + 0.830****LBM*** + 0.466****An*** - 0.726****Wr*** - 10.738****G*** - 1.562****AL*** + 1.202****H*** - 0.796****W*** + 1.109*SW | *0.000** | 0.700 | 0.608 | 6.27 | 6.0 |

LBM: Lean Body Mass (Fat-free weight); An: Ankle Index; Wr: Wrist Index; He: Head Index; SW: Shoulder Width; G: Gender; C: Chest Index; Ha: Hand Index; AL: Arm Length; H: Height; K: Knee; W: Weight
Italic and bold fonts are used to indicate statistically significant variables.

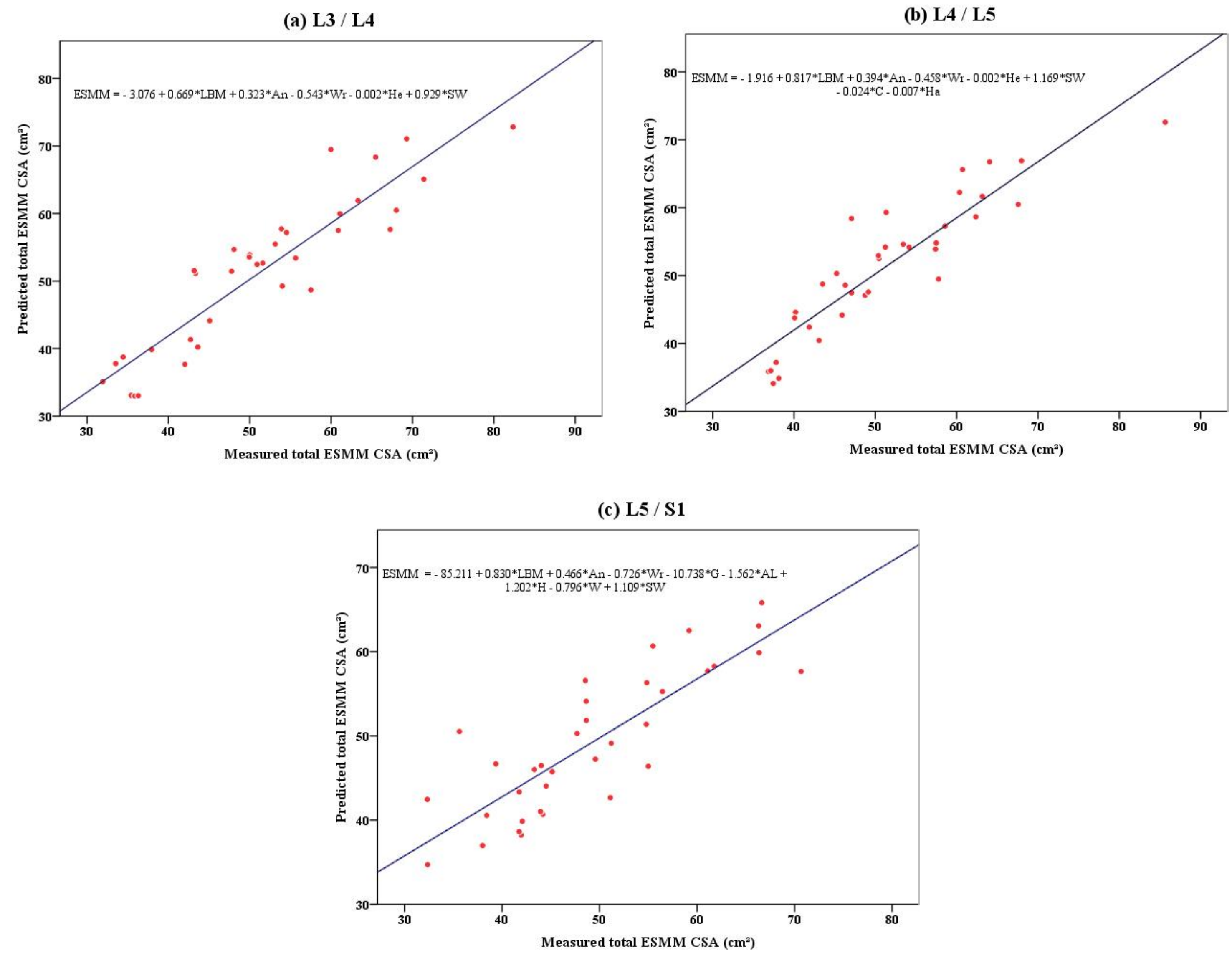


Figure 5.8: Scatter plots for the predicted and measured ESMM CSAs

**Best subsets regression analyses for the erector spinae muscle mass lever arm (ESMLA) distance**

Best subset regression analyses were performed to determine prediction equations for the ESMLA distance at each IVD level. Based on model selection criteria explained in the model selection methodology part, several regression models were selected as "the best regression subsets" at each level, and then coefficients of each variable in these models were determined by using enter method regression analyses. These regression models are presented in Table 5.16. Note that statistically significant variables and intercepts were highlighted with italic and bold fonts. ANOVA tests revealed that all regression models were significant at $\alpha = 0.050$. Ankle and head indexes and sitting height were "the most promising" variables to predict the ESMLA distance. In addition to these variables, the shoulder width and chest and wrist index variables were included in all regression subsets at the L3/L4 level. The knee index variable was included in all regression subsets at the L4/L5 level.

At the L3/L4 IVD level, three regression models (one eight-parameter, one nine-parameter, and one ten-parameter) subsets were preferred over other regression subsets since these models satisfied the minimum $C_P$ value and/or $C_P$ value that is near to the number of parameters in the model. These three regression models had the largest Adjusted-$R^2$ values within each parameter subsets, as well. The ten-parameter models had the largest Adjusted-$R^2$ values among all subset regressions.

Two seven-parameter and two eight-parameter models were selected for the prediction of the ESMLA distance at the L4/L5 level. It should be noted that there were several other models that were significant and can predict as well as these models. Appendices G.1, G.2, and G.3 present some of these regression models. Researchers who want to estimate the ESMLA distance using their own already measured anthropometrics (which may be limited to a few body parts) may be able to select a model that suits their needs.

The $C_P$ criteria were met for many models at the L5/S1 level, including many models with only a few independent variables. The purpose of this dissertation was to propose regression models having as few variables as possible. There was a two-parameter subset, which was the simplest model at the L5/S1 level. This two-parameter model has just the ankle index variable and intercept in the model (Adjusted-$R^2 = 0.756$). Two three-parameter models were also selected as best subsets. The first model has the height variable and the second model has the weight variable in addition to the ankle index. Both models had approximately the same Adjusted-$R^2$ values (0.774 and 0.771). Providing different regression models may allow other researchers to select models for which they have available anthropometric measurements. Two four-parameter and one five-parameter models are also provided. These models had the head index variable in addition to the ankle index and the height and/or weight variable. However, these models do not show further improvements in Adjusted-$R^2$ values. They are provided here to emphasize the importance of the head index variable which is included in most subsets at this IVD level.

Scatter plots demonstrate how well these regression models fit the data. Regression models with the largest Adjusted-$R^2$ values were selected for this purpose. Scatter plots show that the predicted ESMLA distances fit very well to the measured ESMLA distances. $R^2$ values were 0.905, 0.861, and 0.803 for the L3/L4 (Figure 5.9.a), L4/L5 (Figure 5.9.b), and L5/S1 (5.9.c) levels, respectively.

Table 5.16: Regression models for the ESMLA distance

| Level | P | Equations for ESMLA distance | ANOVA p-value | $R^2$ | Adj-$R^2$ | S.E. | $C_P$ |
|---|---|---|---|---|---|---|---|
| L3/L4 | 8 | = - 1.494 + 0.015****An*** + 0.0001****He*** + 0.038****SH*** + 0.057****SW*** + 0.001****C*** - 0.013****Wr*** - 0.002****K*** | *0.000** | 0.878 | 0.847 | 0.18 | 8.7 |
| | 9 | = - 2.078 + 0.014****An*** + 0.0001****He*** + 0.047****SH*** + 0.047****SW*** + 0.001****C*** - 0.017****Wr*** - 0.023****W*** + 0.027****LBM*** | *0.000** | 0.889 | 0.855 | 0.17 | 8.2 |
| | 10 | = - ***2.487*** + 0.016****An*** + 0.0001****He*** + 0.046****SH*** + 0.049****SW*** + 0.001****C*** - 0.016****Wr*** - 0.029****W*** + 0.033****LBM*** - 0.255*G | *0.000** | 0.905 | 0.870 | 0.16 | 6.6 |
| L4/L5 | 7 | = 0.435 + 0.012****An*** + 0.0001****He*** + 0.032****SH*** - 0.004****E*** - 0.003****K*** + 0.021****W*** | *0.000** | 0.844 | 0.810 | 0.19 | 7.2 |
| | 7 | = - 0.478 + 0.015****An*** + 0.0001****He*** + 0.043****SH*** - 0.002****K*** + 0.020****LBM*** - 0.016****Wr*** | *0.000** | 0.840 | 0.806 | 0.19 | 7.8 |
| | 8 | = - 0.641 + 0.016****An*** + 0.0001****He*** + 0.040****SH*** - 0.002****K*** + 0.022****LBM*** - 0.014****Wr*** - 0.264*G | *0.000** | 0.861 | 0.825 | 0.18 | 6.1 |
| | 8 | = - 0.318 + 0.013****An*** + 0.0001****He*** + 0.034****SH*** - 0.002*K + 0.022****LBM*** - 0.268*G - 0.003*E | *0.000** | 0.858 | 0.822 | 0.18 | 6.6 |
| L5/S1 | 2 | = ***2.773*** + 0.014****An*** | *0.000** | 0.763 | 0.756 | 0.24 | 1.7 |
| | 3 | = 1.382 + 0.011****An*** + 0.012*H | *0.000** | 0.787 | 0.774 | 0.24 | 0.5 |
| | 3 | = ***2.824*** + 0.011****An*** + 0.008*W | *0.000** | 0.784 | 0.771 | 0.24 | 0.9 |
| | 4 | = 1.245 + 0.012****An*** + 0.0001*He + 0.014****H*** | *0.000** | 0.793 | 0.773 | 0.24 | 1.6 |
| | 4 | = ***3.063*** + 0.012****An*** + 0.0001*He + 0.011****W*** | *0.000** | 0.792 | 0.772 | 0.24 | 1.8 |
| | 5 | = 1.894 + 0.011****An*** + 0.0001*He + 0.010*H + 0.007*W | *0.000** | 0.803 | 0.777 | 0.23 | 2.2 |

An: Ankle Index; He: Head Index; SH: Sitting Height; SW: Shoulder Width; C: Chest Index; Wr: Wrist Index; K: Knee Index;
W: Weight; LBM: Lean Body Mass (Fat-free weight); G: Gender; E: Elbow Index; H: Height
Italic and bold fonts are used to indicate statistically significant variables.

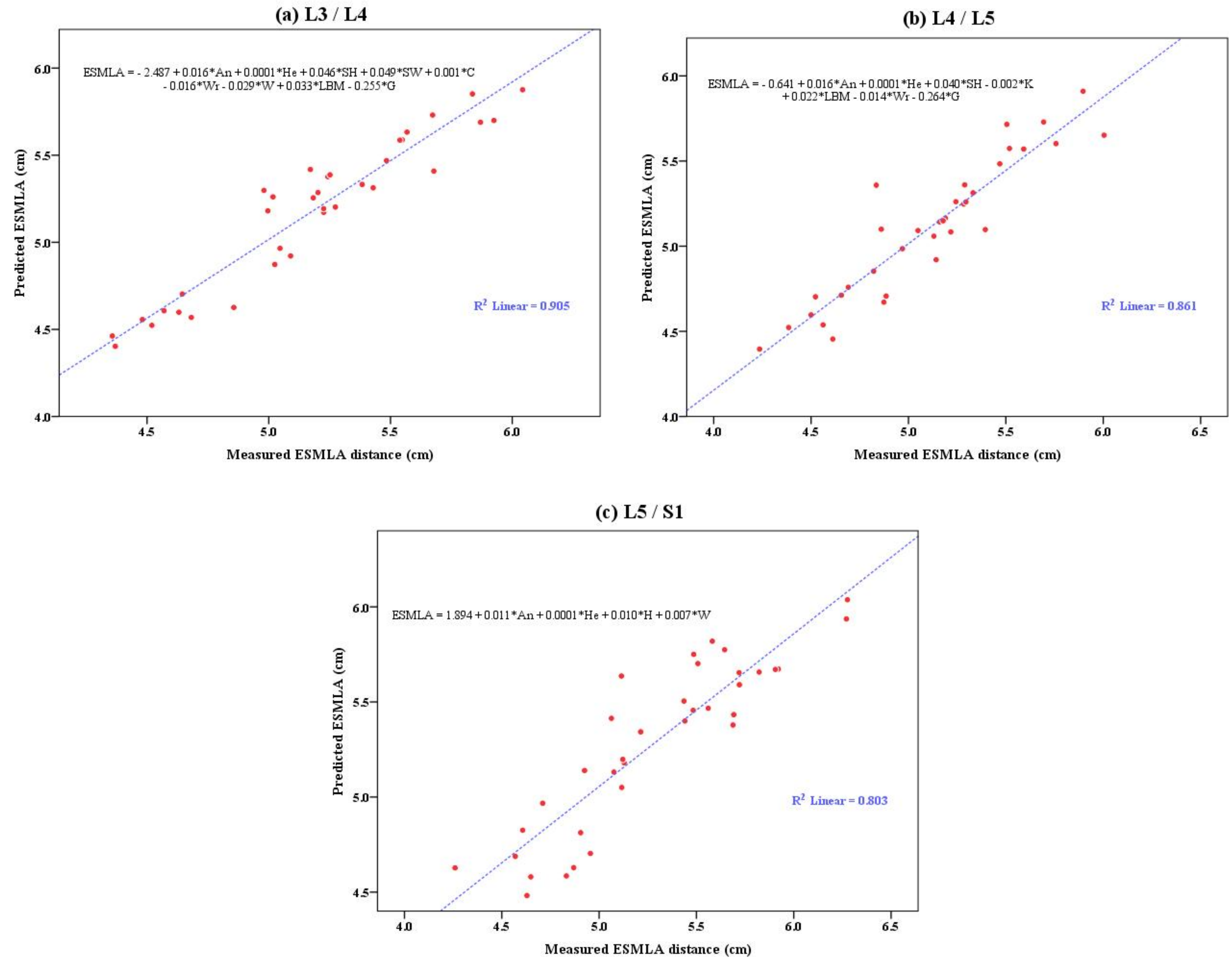


Figure 5.9: Scatter plots for the predicted and measured ESMLA distances

### 5.3.3 Further Statistical Analyses

**Regression analyses for the ESMM size and ESMLA distance with easy-to-measure subject variable**

Regression analyses were performed to determine the CSA of the total ESMM and the ESMLA distance using easy-to-measure subject variables (gender, age, height, and weight). The purpose of these analyses is to provide alternative regression models that use some easy-to-measure subject variables rather than relatively difficult-to-measure anthropometrics such as LBM and limb width and circumferences. Regression models with easy-to-measure subject variables are generally preferred in practice. However, limiting regression models with few variables may result in a loss of prediction power. To test whether there is any loss of power, the total ESMM sizes and ESMLA distances were regressed over subject gender, age, height, and weight. Backward regression selection methodology as discussed in Chapter 4 was employed. Results of regression analyses to estimate the CSA of the total ESMM and the ESMLA distances at each level are presented in Table 5.17 and Table 5.18, respectively. Note that the results of regression analyses presented in Chapter 4 are also provided in Table 5.17 and 5.18 to compare two studies.

Table 5.17: The CSA of the total ESMM prediction equations with easy-to-measure variables

| Level | Study | Equations for the CSA of the total ESMM | $R^2$ | Adj-$R^2$ | S.E. | p-value |
|---|---|---|---|---|---|---|
| **L3/L4** | 1 | = - 9.262 + 7.146*G + 0.244*H + 0.209*W | 0.537 | 0.524 | 7.61 | *0.000** |
| | 2 | = 15.081 + 8.121*G + 0.427*W | 0.698 | 0.679 | 7.01 | *0.000** |
| **L4/L5** | 1 | = - 20.378 + 0.358*H + 0.138*W | 0.398 | 0.385 | 7.04 | *0.000** |
| | 2 | = 14.660 + 0.502*W | 0.559 | 0.546 | 7.37 | *0.000** |
| **L5/S1** | 1 | = - 20.300 - 6.811*G + 0.356*H + 0.135*W | 0.209 | 0.176 | 9.22 | *0.000** |
| | 2 | = 28.134 + 0.288*W | 0.219 | 0.196 | 8.98 | *0.005** |

Study 1: Chapter 4; Study 2: Chapter 5; CSA ($cm^2$); G: Gender (0 for female, 1 for male); H: Height (cm); W: Weight (kg)

Table 5.18: The ESMLA distance prediction equations with easy-to-measure variables

| Level | Study | Equations for the ESMLA | $R^2$ | Adj-$R^2$ | S.E. | p-value |
|---|---|---|---|---|---|---|
| **L3/L4** | 1 | = 0.016 + 0.031*H | 0.437 | 0.432 | 0.39 | *0.000** |
| | 2 | = - 0.535 + 0.033*H | 0.650 | 0.640 | 0.27 | *0.000** |
| **L4/L5** | 1 | = 0.515 + 0.027*H | 0.415 | 0.409 | 0.37 | *0.000** |
| | 2 | = 3.585 + 0.021*W | 0.607 | 0.595 | 0.28 | *0.000** |
| **L5/S1** | 1 | = 1.063 + 0.025*H | 0.356 | 0.347 | 0.37 | *0.000** |
| | 2 | = 3.469 + 0.025*W | 0.662 | 0.652 | 0.29 | *0.000** |

Study 1: Chapter 4; Study 2: Chapter 5; ESMLA (cm); G: Gender (0 for female, 1 for male); H: Height (cm); W: Weight (kg)

**Comparison of subject weight and fat-free-weight (LBM) as a predictor variable to estimate the total ESMM size and ESMLA distance**

Subject weight is easier to measure than LBM. However, the size of the ESMM may not be correlated with subject weight as well as subject LBM because the size of the ESMM depends more on the physical requirements placed on the muscle during normal manual activities and not on simple gross body weight (Chaffin *et al.*, 1990). To compare weight and LBM in terms of their correlations with the total ESMM size, Enter Method regression analyses were performed. Table 5.19 shows regression equations for the ESMM CSA at each IVD level. Results showed that regression models with LBM had larger $R^2$ and Adjusted-$R^2$ and smaller standard errors at all IVD levels. This can be interpreted that LBM is better predictive variable than weight for predicting the total ESMM size.

Table 5.19: Regression equations for comparison of weight and LBM to estimate the total ESMM size

| Level | Model | Equations for ESMM | $R^2$ | Adj.$R^2$ | S.E. | p-value |
|---|---|---|---|---|---|---|
| **L3/L4** | 1 | = 6.458 + 0.615*W | 0.655 | 0.644 | 7.38 | *0.000** |
| | 2 | = 9.349 + 0.732*LBM | 0.739 | 0.732 | 6.41 | *0.000** |
| **L4/L5** | 1 | = 14.660 + 0.502*W | 0.559 | 0.546 | 7.37 | *0.000** |
| | 2 | = 17.441 + 0.590*LBM | 0.616 | 0.604 | 6.88 | *0.000** |
| **L5/S1** | 1 | = 28.134 + 0.288*W | 0.219 | 0.196 | 8.98 | *0.005** |
| | 2 | = 29.775 + 0.338*LBM | 0.241 | 0.218 | 8.86 | *0.003** |

Model 1: Model with subject weight; Model 2: Model with subject LBM;
CSA ($cm^2$); LBM: Lean Body Mass (kg); W: Weight (kg)

Enter Method regression analyses were performed to compare weight and LBM in terms of their prediction powers to predict the ESMLA distance. The results of regression analyses are presented in Table 5.20. Regression models with LBM had larger $R^2$ and Adjusted-$R^2$ and smaller standard errors at the L3/L4 and L4/L5 IVD levels. These statistics were also better at the L5/S1 level for LBM than weight, however, the difference was relatively small. Otherwise, subject LBM was better predictor than subject weight in all cases.

Table 5.20: Regression equations for comparison of weight and LBM to estimate the ESMLA distance

| **Level** | **Model** | **Equations for ESMLA** | **$R^2$** | **Adj.$R^2$** | **S.E.** | **p-value** |
|---|---|---|---|---|---|---|
| **L3/L4** | 1 | = 3.571 + 0.022*W | 0.611 | 0.600 | 0.29 | *0.000** |
| | 2 | = 3.728 + 0.025*LBM | 0.642 | 0.631 | 0.28 | *0.000** |
| **L4/L5** | 1 | = 3.585 + 0.021*W | 0.607 | 0.595 | 0.28 | *0.000** |
| | 2 | = 3.744 + 0.024*LBM | 0.627 | 0.616 | 0.27 | *0.000** |
| **L5/S1** | 1 | = 3.469 + 0.025*W | 0.662 | 0.652 | 0.29 | *0.005** |
| | 2 | = 3.689 + 0.028*LBM | 0.659 | 0.649 | 0.29 | *0.000** |

Model 1: Model with subject weight; Model 2: Model with subject LBM;
ESMLA ($cm^2$); LBM: Lean Body Mass (kg); W: Weight (kg)

### The effect of performing physical exercise on the ESMM size and ESMLA distance

The CSA of the ESMM and the ESMLA distance could be a function of performing physical exercise such as weight lifting (resistance exercise) and/or cardiovascular exercise (i.e., running). Earlier correlation analyses in the present study suggested that the frequency of physical exercises did not have any effect on the ESMM size. The frequency of cardiovascular exercise was correlated with the ESMLA distance at only the L5/S1 level. However, further investigation of physical exercises on the ESMM size and ESMLA distance may provide better understanding. Independent samples T-tests were performed to examine there was any difference between the subjects who perform physical exercises and the subjects who do not perform physical exercises. The results of T-tests are given in

Table 5.21: The effect of physical exercise on the ESMLA distance and the CSA of the total ESMM

| | | | | N | Mean | St.d. | t | df | Sig. | | | N | Mean | St.d. | t | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ESMM ($cm^2$)** | **L3/L4** | **Cardio Exercise** | No | 7 | 51.66 | 9.96 | 0.045 | 33 | 0.964 | **Lifting Exercise** | No | 19 | 51.11 | 11.92 | -0.183 | 33 | 0.856 |
| | | | Yes | 28 | 51.41 | 13.06 | | | | | Yes | 16 | 51.89 | 13.26 | | | |
| | **L4/L5** | | No | 7 | 50.29 | 6.72 | -0.300 | 33 | 0.766 | | No | 19 | 51.27 | 9.76 | -0.086 | 33 | 0.932 |
| | | | Yes | 28 | 51.70 | 11.84 | | | | | Yes | 16 | 51.59 | 12.51 | | | |
| | **L5/S1** | | No | 7 | 47.06 | 9.12 | -0.632 | 33 | 0.532 | | No | 19 | 49.82 | 10.68 | 0.384 | 33 | 0.703 |
| | | | Yes | 28 | 49.76 | 10.31 | | | | | Yes | 16 | 48.50 | 9.46 | | | |
| **ESMLA (cm)** | **L3/L4** | | No | 7 | 5.18 | 0.43 | 0.043 | 33 | 0.966 | | No | 19 | 5.18 | 0.49 | 0.132 | 33 | 0.896 |
| | | | Yes | 28 | 5.17 | 0.47 | | | | | Yes | 16 | 5.16 | 0.42 | | | |
| | **L4/L5** | | No | 7 | 5.13 | 0.44 | 0.165 | 33 | 0.870 | | No | 19 | 5.17 | 0.44 | 0.866 | 33 | 0.393 |
| | | | Yes | 28 | 5.10 | 0.44 | | | | | Yes | 16 | 5.04 | 0.44 | | | |
| | **L5/S1** | | No | 7 | 5.36 | 0.50 | 0.455 | 33 | 0.652 | | No | 19 | 5.39 | 0.50 | 1.398 | 33 | 0.171 |
| | | | Yes | 28 | 5.26 | 0.50 | | | | | Yes | 16 | 5.16 | 0.48 | | | |

Table 5.21. The results found that there was not any significant difference between exercise performing and not-performing groups in terms of their ESMM sizes and ESMLA distances.

**Comparison of the present study with the study presented in Chapter 3**

The values of the CSA of the total ESMM and ESMLA distance in the present study can be compared with the study presented in Chapter 3 (Study 1). Note that the methodology was the same in both studies. Subject variables from both studies were compared and are presented in Table 5.22. Subjects in Study 1 were older, taller, heavier, and more obese than the present study (Study 2); but only female subjects were "statistically" older, heavier, and more obese. Independent samples T-tests were performed to compare the CSA of the total ESMM and ESMLA distance in the Study 2 to the Study 1. The results of these comparisons are presented in Table 5.23. Subjects in the Study 1 generally had larger ESMMs and ESMLAs than the present study. However, these differences were significant for only female subjects. Female subjects in the present study also had significantly smaller ESMMs at the L4/L5 level and ESMLAs at the L5/S1 level than female subjects in the Study 1. Male subjects in the Study 2 had larger ESMM sizes at the L4/L5 and L5/S1 levels and ESMLA distance at the L5/S1 level.

Table 5.22: Comparison of the present study to the earlier study (Chapter 3) regarding subject variables

| | | | | Age | | | | | Height | | | | | Weight | | | | | BMI | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Level** | **Gender** | **S** | **N** | **Mean** | **St.d.** | **t** | **df** | **Sig.** | **Mean** | **St.d.** | **t** | **df** | **Sig.** | **Mean** | **St.d.** | **t** | **df** | **Sig.** | **Mean** | **St.d.** | **t** | **df** | **Sig.** |
| **L3/L4** | **Female** | 1 | 54 | 29.2 | 5.4 | 2.363 | 65 | ***0.021**** | 165.3 | 9.0 | 1.620 | 65 | 0.110 | 76.7 | 21.6 | 3.156 | 65 | ***0.002**** | 28.1 | 8.2 | 2.684 | 65 | ***0.009**** |
| | | 2 | 13 | 25.5 | 3.6 | | | | 160.9 | 7.8 | | | | 57.2 | 10.2 | | | | 22.0 | 2.6 | | | |
| | **Male** | 1 | 53 | 30.1 | 5.7 | 1.717 | 73 | 0.090 | 178.6 | 8.9 | 0.679 | 73 | 0.499 | 84.5 | 19.5 | 0.423 | 73 | 0.673 | 26.4 | 5.2 | 0.077 | 73 | 0.939 |
| | | 2 | 22 | 27.8 | 3.7 | | | | 177.1 | 7.7 | | | | 82.7 | 10.8 | | | | 26.3 | 2.6 | | | |
| **L4/L5** | **Female** | 1 | 50 | 29.2 | 5.4 | 2.349 | 61 | ***0.022**** | 164.9 | 8.9 | 1.476 | 61 | 0.145 | 77.2 | 22.0 | 3.182 | 61 | ***0.002**** | 28.5 | 8.4 | 2.761 | 61 | ***0.008**** |
| | | 2 | 13 | 25.5 | 3.6 | | | | 160.9 | 7.8 | | | | 57.2 | 10.2 | | | | 22.0 | 2.6 | | | |
| | **Male** | 1 | 44 | 29.7 | 5.5 | 1.421 | 64 | 0.160 | 178.4 | 9.1 | 0.591 | 64 | 0.556 | 85.1 | 19.2 | 0.555 | 64 | 0.581 | 26.7 | 5.2 | 0.304 | 64 | 0.762 |
| | | 2 | 22 | 27.8 | 3.7 | | | | 177.1 | 7.7 | | | | 82.7 | 10.8 | | | | 26.3 | 2.6 | | | |
| **L5/S1** | **Female** | 1 | 41 | 30.1 | 5.3 | 2.950 | 52 | ***0.005**** | 166.1 | 9.3 | 1.821 | 52 | 0.074 | 74.4 | 19.3 | 3.070 | 52 | ***0.003**** | 27.2 | 7.7 | 2.365 | 52 | ***0.022**** |
| | | 2 | 13 | 25.5 | 3.6 | | | | 160.9 | 7.8 | | | | 57.2 | 10.2 | | | | 22.0 | 2.6 | | | |
| | **Male** | 1 | 35 | 30.0 | 5.7 | 1.578 | 55 | 0.120 | 178.1 | 9.4 | 0.416 | 55 | 0.679 | 84.7 | 19.6 | 0.455 | 55 | 0.651 | 26.7 | 5.6 | 0.311 | 55 | 0.757 |
| | | 2 | 22 | 27.8 | 3.7 | | | | 177.1 | 7.7 | | | | 82.7 | 10.8 | | | | 26.3 | 2.6 | | | |

S: Study; Study 1: Previous study (Chapter 3); Study 2: Present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: kg/m$^2$

Table 5.23: Comparison of the present study to the earlier study (Chapter 3) regarding the ESMM size and ESMLA distance

| | | | | CSA of Total ESMM | | | | | ESMLA distance | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Level** | **Gender** | **S** | **N** | **Mean** | **St.d.** | **t** | **df** | **Sig.** | **Mean** | **St.d.** | **t** | **df** | **Sig.** |
| **L3/L4** | **Female** | 1 | 54 | 47.1 | 8.2 | 3.168 | 65 | ***0.002**** | 5.1 | 0.4 | 2.419 | 65 | ***0.018**** |
| | | 2 | 13 | 39.5 | 5.7 | | | | 4.8 | 0.4 | | | |
| | **Male** | 1 | 53 | 59.2 | 10.3 | 0.247 | 73 | 0.806 | 5.6 | 0.5 | 1.473 | 73 | 0.145 |
| | | 2 | 22 | 58.5 | 9.4 | | | | 5.4 | 0.3 | | | |
| **L4/L5** | **Female** | 1 | 50 | 49.0 | 8.3 | 2.508 | 61 | ***0.015**** | 5.0 | 0.4 | 1.947 | 61 | 0.056 |
| | | 2 | 13 | 42.8 | 6.5 | | | | 4.7 | 0.4 | | | |
| | **Male** | 1 | 44 | 55.5 | 8.5 | -0.424 | 64 | 0.673 | 5.5 | 0.4 | 1.464 | 64 | 0.148 |
| | | 2 | 22 | 56.5 | 9.8 | | | | 5.3 | 0.3 | | | |
| **L5/S1** | **Female** | 1 | 41 | 48.9 | 10.0 | 1.257 | 52 | 0.214 | 5.1 | 0.4 | 2.111 | 52 | ***0.040**** |
| | | 2 | 13 | 45.0 | 8.5 | | | | 4.8 | 0.3 | | | |
| | **Male** | 1 | 35 | 47.8 | 10.4 | -1.386 | 55 | 0.171 | 5.5 | 0.4 | -0.375 | 55 | 0.709 |
| | | 2 | 22 | 51.7 | 10.2 | | | | 5.6 | 0.4 | | | |

S: Study; Study 1: Previous study (Chapter 3); Study 2: Present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: kg/m$^2$

## 5.4 Discussion

***Cross-sectional area (CSA) of the erector spinae muscle mass (ESMM)***

The purpose of this MRI study was to provide prediction models for the cross-sectional area (CSA) of the total erector spinae muscle mass (total ESMM) and the erector spinae muscle mass lever arm (ESMLA) derived from an asymptomatic population. A total of 35 subjects (22 males and 13 females) were included in this study. Subjects were relatively young (males, 27.8 years old and females, 25.5 years old).

Direct comparisons were possible with the studies that measured the CSA of the total ESMM at an inter-vertebral disc level. Comparison of the findings of the present study and previous studies are provided in Table 5.24. The CSA of the ESMM in the present study are mostly larger than previous studies. McGill *et al.* (1988), Tracy *et al.* (1989), Chaffin *et al.* (1990), Han *et al.* (1992), Tveit *et al.* (1994), Lin *et al.* (2001), Seo *et al.* (2003), Jorgensen *et al.* (2003a), Kamaz *et al.* (2007), and Neimelainen *et al.* (2011) reported smaller ESMM sizes. On the other hand, Parkkola *et al.* (1992), Wood *et al.* (1996), and Lee *et al.* (2006) reported smaller ESMM sizes. These differences may be due to the subject variables and muscle group definition. For example, Wood *et al.* (1996) reported larger ESMM size than the present study at the L4/L5 level. Their subjects were older and heavier than the subjects in the present study. Han *et al.* (1992) did not include the multifidus muscles in their measurements, which may explain why they reported smaller total CSAs than the present study. Tracy *et al.* (1989) did not report subject anthropometrics. Chaffin *et al.* (1990), Kang *et al.* (2007), and Neimelainen *et al.* (2011) had older subjects in their studies. Age related muscle atrophy may explain some of the differences between these studies and the present study. McGill *et al.* (1988), Han *et al.* (1992), Parkkola *et al.* (1992), Tsuang *et al.* (1993), Tveit *et al.* (1994), and Lin *et al.* (2001) had relatively smaller sample sizes in their studies (13 subjects or less). These small sample sizes are unlikely to accurately represent the entire population. Previous studies also studied different ethnicities such as Japanese (Han *et al.*, 1992; Seo *et al.*, 1993), Taiwanese (Lin *et al.*, 2001), Korean (Lee *et al.*, 2006; Kang *et al.*, 2007), Turkish (Kamaz *et al.*, 2007), and Finish (Neimelainen *et al.*, 2011). Ethnicity may also partially explain some of the variation among studies. Future studies can address whether there is any ethnicity effect on the ESMM size. Besides, McGill *et al.* (1988), Tracy *et al.* (1989), Han *et al.* (1992), Lee *et al.* (2006), and Kang *et al.* (2007) had LBP patients in their studies. Kamaz *et al.* (2007) reported that LBP patients had smaller ESMM sizes than asymptomatic subjects. Subjects in the present study were healthy and did not have any LBP symptoms, which may explain differences in ESMM sizes among studies.

The ESMMs of the present study (Study 2) was smaller than those of Study 1 presented in Chapter 3. The methodology was the same in both studies. Subjects in Gungor (2013)[1], on the other hand, were older, taller, heavier, and more obese than the present study, but only female subjects were "statistically" younger, heavier, and more obese than female subjects in the present study. Differences in subject variables may explain the difference between Study 2 and Study 1. It should also be noted that subjects in the Study 1 had undertaken an MRI scan to help medical doctors explore whether they had medical abnormalities in their lumbar spinal region. No medical history was provided with these historical MRI data. All that is known is that subjects received MRI scans of their low backs as part of their medical treatment. Subjects in the Study 2 were asymptomatic subjects. It may also explain the differences in the ESMM morphometry.

Study 2 found that there was significant difference between the right and left CSAs of the ESMM for females at the L3/L4 level and for males at the L4/L5 level. However, significant differences were not consistent with both genders and at all IVD levels. This may be the result of a relatively small sample size. Comparison of the right and left ESMM sizes were performed in Study 1 and it was found that there were no difference between the two sides. Note that Study 1 had 163 subjects in total compared to 35 subjects in Study 2. Reid and Costigan (1985), Kumar (1988), Millerchip *et al.* (1988), Chaffin *et al.* (1990), Moga *et al.* (1993), McGill *et al.* (1993), Guzik *et al.* (1996), and Jorgensen *et al.* (2001)

were in agreement with Study 1 that there was not any significant difference between the right and left ESMM sizes.

Since it was expected that the ESMM on the contralateral side might be larger than the dominant hand side, statistical analyses to compare the dominant side to non-dominant side were performed. Note that there were no female left-hand dominant subjects. Pairwise comparisons revealed that there were no statistically significant differences between the dominant and non-dominant hand sides in terms of their ESMM sizes except female subjects at the L3/L4 level. Having relatively few left-hand dominant subjects may be the reason for not determining any dominant side effect on the ESMM size. There were only 3 male subjects who were left-hand dominant. This is a limitation of Study 2. Future studies should include quite large sample sizes for both left- and right-hand dominant to address whether there is any dominant side effect (or training effect) on the ESMM size.

Chaffin *et al.* (1990) indicated that the size of the ESMM depends more on the physical requirements placed on the muscle during normal manual activities and not on simple gross body weight. Comparisons of regression models with subject weight and LBM agreed with Chaffin *et al.*'s (1990) claims. Results showed that regression models with LBM had larger power ($R^2$ and Adjusted-$R^2$) and smaller bias (S.E.) at all IVD level. This can be interpreted that LBM is better than weight for predicting the total ESMM size. The increase in $R^2$ and Adjusted-$R^2$ was approximately 10%. There is also a trade-off between the accuracy of the model and the simplicity of data collection. A biomechanic practitioner may prefer using subject weight over LBM since weight measurements are easier than body composition (skinfold) measurements.

Study 2 also recorded subjects' physical activity levels. Correlation analyses found that the level of physical exercise was not correlated except the level of cardio exercise and the size of ESMM and ESMLA distance. Independent samples T-test compared exercise performing and not-performing groups in terms of their ESMM sizes and ESMLA distances. There was not a significant ESMM size difference between the two groups. This

Table 5.24: Comparison of CSAs of ESMM reported by various authors by IVD level

| | Subjects | Age | Height | Weight | BMI | | L1/L2 | L2/L3 | L3/L4 | L4/5 | L5/S1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | L+R | | | | 45.1 | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 26.2(3.4) | 26(3.3) | 19.6(5.9) | 8.3(2.7) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 17.9(3.1) | 18.5(3.0) | 17.3(3.0) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 18.2(2.7) | 18.5(3.0) | 17.4(3.0) | |
| Han *et al.* (1992) | 6M+4F | 40.1 | 163 | 58.4 | | Left | 18.31 | 19.60 | 18.82 | 16.58 | 11.33 |
| *(CT, Supine, LBP, Japan)* | | | | | | Right | 18.23 | 19.33 | 18.47 | 16.48 | 11.44 |
| Parkkola *et al.* (1992) | 1M+11F | 23.3 | | 59.1 | | L+R | | | | 48(8) | |
| *(MRI, Healthy)* | | | | | | | | | | | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 18.1 | 19.3 | 20.0 | 8.8 |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 17.7 | 18.1 | 20.3 | 9.4 |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis(L+R) | 68(11.8) | 67(9.8) | 58.6(6.8 ) | 42.6(9.8) | 17.8(4.6) |
| *(MRI)* | | | | | | Kyphosis(L+R) | 45.1(9.2) | 55.4(9.9) | 53.1(8.3) | 49.8(6.2) | 27.2(6.7) |
| | 5 Female | 31 | 173 | 64 | | Lordosis(L+R) | 40.6(9.1) | 41.3(8.2) | 40.8(3.1) | 38.4(7.1) | 12.2(3.9) |
| | | | | | | Kyphosis(L+R) | 33.1(8.8) | 36.2(7.8) | 37.3(5.8) | 37.4(4.9) | 20.8(6.5) |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 30.6(8.4) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | Left | | | | | 21.78(6.47) |
| *(MRI, Supine, Healthy Asian)* | | | | | | Right | | | | | 21.47(6.80) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 23.9(4.5) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 17.1(3.1) | | |
| Jorgensen *et al.* (2003a) | 12 Male | 23.1 | 177.1 | 74.5 | | Right | 20.2(3.3) | 22.1(3.1) | 22.3(3.9) | 22.7(3.4) | 17.4(4.8) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 10.7(1.3) | 12.1(1.3) | 13.7(1.8) | 14.5(2.2) | 10.6(1.9) |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK (L+R) | | | | 33.77(9.15) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control (L+R) | | | | 52.41(8.9) | |
| Kamaz *et al.* (2007) | 36 Female | 43.2 | | | 28.6 | LBP | | | 17.7(2.6) | 17.9(2.7) | |
| *(CT, Prone, Turkish)* | 34 Female | 44.4 | | | 28.5 | Control | | | 18.6(2.6) | 19.6(2.7) | |
| Kang *et al.* (2007) | 54 Female | 60 | 154 | 62 | 26.9 | LBP | | | | 39.5(5.0) | |
| *(MRI, Korean)* | 54 Female | 60 | 153 | 57 | 24.19 | LDK | | | | 29.2(4.5) | |
| Niemelainen *et al.* (2011) | 126 Male | 49.8 | 175.4 | | 25.9 | Left | | | 26.6 | 24.8 | 21.2 |
| *(MRI, Currently Healthy, Finnish)* | | | | | | Right | | | 26.9 | 24.4 | 20.5 |
| Gungor (Study 1) | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | Left | | | 29.9(5.4) | 28.4(5.4) | 25.1(6.2) |
| *(MRI, Supine, LBP)* | | | | | | Right | | | 30.0(5.4) | 28.2(4.9) | 24.6(5.9) |
| | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | Left | | | 23.4(3.7) | 24.4(3.9) | 25.0(5.9) |
| | | | | | | Right | | | 23.5(3.9) | 24.2(4.0) | 24.3(5.2) |
| Gungor (Study 2) | 22 Males | 27.8 | 177.1 | 82.7 | 26.3 | Left | | | 29.5(4.4) | 28.8(4.7) | 26.2(5.4) |
| *(MRI, Supine, Healthy)* | | | | | | Right | | | 29.0(5.2) | 27.7(5.3) | 25.5(5.0) |
| | 13 Female | 25.5 | 160.9 | 57.2 | 22.0 | Left | | | 22.3(3.3) | 21.5(3.3) | 22.4(4.7) |
| | | | | | | Right | | | 19.2(2.5) | 21.3(3.3) | 22.6(3.9) |

Gungor (Study 1): Study presented in Chapter 3; Gungor (Study 2): The present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; CSA: $cm^2$

result was contradictory to expectations. This may be caused by a methodological error. In the present study, the data for the level of physical activity was collected by subjects' self-reporting. Moreover, they were asked the frequency of their activities, but not the intensity, nor the duration of their exercise. Future studies should address the effect of physical activity on the ESMM by controlling and/or more accurately measuring subjects' physical activities in intensity, duration, and frequency levels.

***The erector spinae muscle mass lever arm (ESMLA) distance***

Reid and Costigan (1987), Kumar (1988), McGill *et al.* (1993), Gilsanz *et al.* (1995), Jorgensen *et al.* (2001), and Anderson *et al.* (2012) measured the ESMLA distances at vertebral body levels rather than at the IVD as in the present study. Despite this, the results of the present study generally agree with Reid and Costigan's (1987) and Jorgensen *et al.*'s (2001) studies. Kumar (1988) and Anderson *et al.* (2012) separated the erector spinae and transverse spinalis muscle groups in their studies. Their ESMLA distance measurements were larger than the present study. Note that subjects in both of these studies were older than subjects in the present study. Gilsanz *et al.* (1995) also had older subjects (elderly women with osteoporosis). McGill *et al.* (1993) also reported larger ESMLA measurements than the present study. They positioned subjects in a supine posture with knees extended while subjects in the present study were positioned in a supine posture with knees slightly flexed by positioning a cushion under the legs.

However, direct comparisons were possible with the studies that measured the ESMLA distance at an IVD level. Comparison of the ESMLA distances of the present study to previous studies are presented in Table 5.25. The ESMLA distances in the present study were mostly smaller than previous studies. Nemeth and Ohlsen (1986), McGill *et al.* (1988), Tracy *et al.* (1989), Chaffin *et al.* (1990), Dumas *et al.* (1991), Moga *et al.* (1993), Tveit *et al.* (1994), Guzik *et al.* (1996), Jorgensen *et al.* (2003b), and Lee *et al.* (2006) reported larger ESMLA distances than the present study. On the other hand, the present study reported larger ESMLA distances than Tsuang *et al.*'s (1993) and Lin *et al.*'s (2001) studies. Wood *et al.*'s (1996) study with 26 males and Seo *et al.*'s (2003) study with 152 males and 98 females reported very similar ESMLA distances. The results of the present study was also in the range of Bogduk *et al.*'s (1992) findings. As discussed in the ESMM section, differences between the present study and previous studies may be explained by subjects variables, measurement techniques, and muscle group definitions. Nemeth and Ohlsen (1986), McGill *et al.* (1988), Tracy *et al.* (1989), Moga *et al.* (1993), Tveit *et al.* (1994), and Lee *et al.* (2006) studied with medical (mostly LBP) patients. Subjects in Nemeth and Ohlsen (1986), McGill *et al.* (1988), Chaffin *et al.* (1990), and Lee *et al.* (2006) were older, as well. Tracy *et al.* (1989) and Moga *et al.* (1993) did not report their subjects' ages. Dumas *et al.* (1991) had 7 male cadavers in their study. On the other hand, Guzik *et al.* (1996) studied healthy athletes.

Subject position for scans may also have an effect on the variation in these studies. For example, Bogduk *et al.*'s (1992) subjects were in upright standing posture, Kamaz *et al.*'s (2007) subjects were lying face down, and Jorgensen *et al.*'s (2003b) subjects were lying on their sides. Tracy *et al.*'s (1989) subjects were positioned in a spine with knees extended. The activation of and placement of the muscles alters as a function of posture (McGill *et al.*, 1996).

Definition of the ESMM and ESMLA distance measurement techniques also varied among studies. Lee *et al.* (2006) did not include the multifidus muscles in their measurements. Tracy *et al.* (1989) measured the ESMLA distances on lumbar transverse images, which results in larger values than oblique images may provide. Jorgensen *et al.* (2003b) took transverse plane scans and then corrected their direct ESMLA measurements to oblique measurements. Tracy *et al.* (1989), Moga *et al.* (1993), Seo *et al.* (2003), and Lee *et al.* (2006) determined the centroids of the ESMM and IVD by simple visual determination or drawing axes visually with the assumption that the ESMM and IVD have ellipsoid shapes. The definition of the ESMLA may also affect the size of the ESMLA distance. Lee *et al.* (2006) measured the ESMLA distance from the centroid of the IVD to the centroid of each ESMM rather than the anterior-posterior distance, which resulted in larger ESMLA measurements.

The ESMLA distances in the present study were approximately 5% smaller than Study 1. Differences in subject variables may explain the difference in ESMLA distances. Regression analysis in Chapter 4 in this dissertation showed that the CSA of the ESMM is dependent on subject's height and weight. Tang (2013) also indicated that the CSA of the IVD is a function of subject height, weight, and age. Subjects in the present study are younger, shorter, lighter, and less obese than Study 1, with corresponding smaller ESMM and IVD sizes. Moreover, the ESMLA distance is a function of the ESMM and IVD sizes. Smaller ESMM and IVD sizes, therefore, yield smaller ESMLA distances. This may explain why the subjects in the present study (Study 2) have smaller ESMLA distances than the subjects presented in Study 1.

Male subjects had larger ESMLA distances than female subjects at all IVD levels. However, there is a possibility that these ESMLA distance differences might be better explained by different subject variables rather than gender. For example, male and female subjects did not match in terms of their anthropometrics in the present study. Male subjects were taller, heavier, and more obese than female subjects. Future studies that match male and female subject variables (age, height, and weight) may address whether gender has a main effect on the ESMM size or if gender differences are due primarily to differences in heights and weights between the genders.

Recall that comparison of regression models with subject weight and LBM were performed for the ESMM size, and results indicated that LBM was more predictive than weight. Both variables were separately regressed over the ESMLA distance, as well. LBM was also a better predictor for the ESMLA distance at the L3/L4 and L4/L5 levels, but not for the L5/S1 level. It should be noted that the difference between model powers and biases were not very high. For example, Adjusted-$R^2$ increases from 0.600 to 0.631 at the

Table 5.25: Comparison of anterior-posterior ESMLA distances reported by various authors by IVD level

| | **Subjects** | **Age** | **Height** | **Weight** | **BMI** | | **L1/L2** | **L2/L3** | **L3/L4** | **L4/L5** | **L5/S1** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nemeth and Ohlsen (1986) | 11 Male | 70 | 176 | 75.02 | | | | | | | 7.1(0.2) |
| *(CT, Supine, Carcinomas)* | 10 Female | 63 | 166 | 60.06 | | | | | | | 6.5(0.2) |
| McGill *et al.* (1988) | 13 Male | 40.5 | 173.8 | 89.1 | | | | | | 5.9(0.52) | |
| *(CT, Supine, Suspicious for LBP)* | | | | | | | | | | | |
| Tracy *et al.* (1989) | 26 Male | | | | | Right | | 5.78(0.44) | 5.76(0.46) | 6.00(0.53) | 6.17(0.59) |
| *(MRI, Supine, LBP)* | | | | | | | | | | | |
| Chaffin *et al.* (1990) | 96 Female | 49.6 | 163.1 | 67.6 | | Left | | 5.4(0.4) | 5.3(0.2) | 5.4(0.4) | |
| *(CT, Supine, Healthy)* | | | | | | Right | | 5.4(0.4) | 5.2(0.4) | 5.2(0.3) | |
| Dumas *et al.* (1991) *(Cadavers)* | 7 Male | 55.6 | 163.6 | | (Range of avarages) | | | | | 6.0 - 6.4 | |
| Bogduk *et al.* (1992) | 9 Male | 29 | | | | (Min-Max) | 3.26-3.48 | 3.55-4.96 | 3.52-6.2 | 3.19-6.1 | 2.82-5.69 |
| *(Radiographs, Upright, Healthy)* | | | | | | | | | | | |
| Moga *et al.* (1993) | 11 Male | | | | | | 5.1 | 5.3 | 5.5 | 5.9 | |
| *(CT, Patients undertaken CT)* | 8 Female | | | | | | 4.9 | 4.7 | 5.1 | 4.9 | |
| Tsuang *et al.* (1993) | 5 Male | 25.4 | 171.8 | 64.6 | | Left | | 5.2 | 4.9 | 4.9 | |
| *(MRI, Supine, Healthy)* | | | | | | Right | | 5.1 | 4.9 | 4.8 | |
| Tveit *et al.* (1994) | 6 Male | 37 | 185 | 82 | | Lordosis | 6.4(0.3) | 6.3(0.3) | 6.2(0.1) | 6.4(0.2) | |
| *(MRI)* | 5 Female | 31 | 173 | 64 | | | 5.6(0.5) | 5.7(0.5) | 5.9(0.3) | 6.2(0.4) | |
| | 6 Male | 37 | 185 | 82 | | Kyphosis | 5.2(0.4) | 5.3(0.4) | 5.6(0.4) | 5.5(0.1) | 5.7(0.3) |
| | 5 Female | 31 | 173 | 64 | | | 4.5(0.5) | 5.2(0.3) | 5.5(0.3) | 5.6(0.5) | 5.7(0.2) |
| Guzik *et al.* (1996) | 16 Male | 24.9 | 179.8 | 75.2 | Average | Left | 5.67(0.32) | | | | |
| *(MRI, Healthy Athlete)* | | | | | Average | Right | 6.06(0.41) | | | | |
| Wood *et al.* (1996) *(MRI)* | 26 Male | 40.5 | 174.5 | 87.3 | 28.6 | | | | | 5.4(0.6) | |
| Lin *et al.* (2001) | 8 Male | 25.9 | 172.9 | 64 | | | | | | | 4.89(0.67) |
| *(MRI, Supine, Healthy Asian)* | | | | | | | | | | | |
| Jorgensen *et al.* (2003b) | 12 Male | 23.1 | 177.1 | 74.5 | | | 5.26(0.44) | 5.46(0.42) | 5.74(0.34) | 5.9(0.44) | 6.4(0.43) |
| *(MRI, Lying on side)* | 12 Female | 23.8 | 162.3 | 56.5 | | | 4.8(0.34) | 4.98(0.41) | 5.18(0.35) | 5.18(0.35) | 5.64(0.34) |
| Seo *et al.* (2003) | 152 Male | 36.2 | 168.5 | 65.5 | 23.1 | | | | 5.43(0.47) | | |
| *(MRI, Supine, Healthy, Japan)* | 98 Female | 39.7 | 155.5 | 54.4 | 22.5 | | | | 4.94(0.47) | | |
| Lee *et al.* (2006) | 17 Female | 62.5 | 157 | 55.6 | 22.6 | LDK | | | | 6.24(0.46) | |
| *(MRI, Supine, Korean)* | 17 Female | 63.6 | 156 | 59.7 | 24.4 | Control | | | | 6.86(0.40) | |
| Gungor (Study 1) | 82 Males | 30.1 | 178.8 | 85.7 | 26.2 | | | | 5.60(0.44) | 5.52(0.40) | 5.71(0.53) |
| *(MRI, Supine, LBP)* | 81 Female | 29.6 | 165.4 | 76.5 | 28.1 | | | | 5.09(0.42) | 5.00(0.40) | 5.06(0.42) |
| Gungor (Study 2) | 22 Males | 27.8 | 177.1 | 82.7 | 26.3 | | | | 5.41(0.32) | 5.32(0.32) | 5.55(0.35) |
| *(MRI, Supine, Healthy)* | 13 Female | 25.5 | 160.9 | 57.2 | 22.0 | | | | 4.77(0.36) | 4.75(0.36) | 4.83(0.34) |

Gungor (Study 1): Study presented in Chapter 3; Gungor (Study 2): This present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: $kg/m^2$; ESMLA distance: cm

L3/L4 level and 0.595 to 0.616 at the L4/L5 level, which questions the benefit of using LBM which requires additional body composition measurements. At the L5/S1 level, Adjusted-$R^2$ value decreased from 0.652 to 0.649 when LBM was preferred over weight in the model. However, this difference was not significant.

Based on personal observations of physically active subjects (weight lifters), it was observed that the ESMM increases more in an anterior-posterior direction than laterally, which results in larger ESMLA distances than might be expected from a more uniform circular shape. However, statistical analyses did not find any significant difference between the exercise performing and not-performing groups in terms of their ESMLA distances. A limitation of the present study is that it only asked subjects for their physical activity frequencies rather than the **frequency, duration, and intensity** of the physical activity. Data collection methodology for the physical activity frequency was also based on self-reporting. Future studies that control and/or better measure the intensity, duration, and frequency of physical activities may address these limitations.

***Regression models for the CSA of the total ESMM***

The all-possible-regressions procedure was used in the present study to minimize the disadvantages of stepwise regression procedures. Regression models with larger Adjusted-$R^2$, minimum number of variables, and smallest residual mean squares were selected as "the best models." Mallows' prediction criterion ($C_P$) was also an important model selection criterion in this study. Models with smaller values of ($C_P$) and/or $C_P$ value near the number of parameters were selected as "the best models."

The most important predictive variables seem to be fat-free weight (LBM), and the ankle, wrist, and head indexes for most regression subsets. Shoulder width and arm length were also included in most regression subsets. The six-parameter model at the L3/L4 level, eight-parameter model at the L4/L5 level, and nine-parameter model at the L5/S1 level had the largest Adjusted-$R^2$ values, 0.807, 0.781, and 0.608, respectively. Multiple correlation coefficients ($R^2$) of these models were 0.835, 0.826, and 0.700, respectively. These values are higher than some previous studies (Chaffin *et al.*,1990; Marras *et al.*, 2001; Seo *et al.*, 2003, and Anderson *et al.*, 2012). However, Reid and Costigan (1987) and Jorgensen *et al.* (2003a) reported approximately 3% higher $R^2$ values than the present study.

Trunk depth (Schultz *et al.*, 1982; Tracy *et al.*, 1989; Marras and Sommerich, 1991; Jorgensen *et al.*, 2003a), trunk width (Schultz *et al.*, 1982; Tracy *et al.*, 1989; Marras and Sommerich, 1991; Jorgensen *et al.*, 2003a), trunk circumference (Reid and Costigan, 1987), and trunk area (Chaffin *et al.*, 1990) have been studied to predict the CSA of the ESMM. The present study did not include any torso measurements as predictor variables. The reason for exclusion of these was related to concerns that trunk measurements may mislead results since body fat tissue is included in these measurements. Anthropometric measurements in the present study were taken mostly from body joints because joint locations include minimum body fat and may, therefore, be better indicator of overall skeletal frames size. Subjects' body compositions were addressed with skinfold measurements in the present study. Moreover, trunk measurements may inherently include gender bias in measurements. For example, Reid and Costigan (1987) measured trunk circumference at the ilium. Trunk circumferences at the ilium may differ for males and females due to their fat tissue storage modes.

Correlation analyses showed that most of the independent variables were correlated with the ESMM size. This means that the ESMM size can be estimated with almost all independent variables evaluated in the present study. However, some of the independent variables are better predictors. Better estimation means higher $R^2$ and smaller standard error. Selection a model among several other alternative models is a trade-off between model accuracy and model complexity. Complex models may require having more and more complicated anthropometric measurements. The CSA of the total ESMM was regressed over easy-to-measure subject variables (gender, age, height, and weight), as well.

Comparisons of model power and/or errors between the regression models with easy-to-measure predictors and the regression models with more predictor variables are presented in Table 5.26. Limiting predictor variables to gender, age, height, weight (only gender and weight were significant) results in smaller $R^2$ and Adjusted-$R^2$. Adding more predictor variables into regression analyses resulted in an increase in Adjusted-$R^2$ from 0.679 to 0.807 at the L3/L4 level, 0.546 to 0.781 at the L4/L5 level, and 0.196 to 0.608 at the L5/S1 level. Absolute errors were calculated for each of the regression models. Absolute error (residual) terms represent how far the fitted value is from the predicted value. On average, regression models with more predictors had smaller error percentages than regression models with only easy-to-measure predictors. For example, the model with five predictor variables at the L3/L4 level had 8.26% error in average while the model with only gender and height predictor variables at the same IVD level had 9.91% error in average. It is questionable whether adding more variables is justified by that amount of error reduction. It should be noted that these values are averages and do not represent the overall prediction ability of a model. At the L3/L4 level, maximum error terms for the five-variable models was 19.41% while the error term for this subject was 31.05% for the model with only gender and height predictors. It was 24.05% versus 40.00% at the L4/L5 level and 41.81% versus 49.31% at the L5/S1 level. To explain the estimation superiority/quality of the model with more variables (Model 1) over the model with easy-to-measure predictors (Model 2), a scatter plot was plotted (Figure 5.10) for the L5/S1 level. Red dots in the figure are error percentages for Model 1 and blue dots are error percentages for Model 2. Two curved lines are the fitted lines for these error percentages (continuous red line is for Model 1 and dotted blue line is for Model 2). Fitted lines indicate that Model 1 (model with more variables) performs better than Model 2 (model with only easy-to-measure variables), particularly for extremes. For example, for a subject who has a 30 $cm^2$ total ESMM CSA, the prediction error percentage for Model 1 is expected less than 35% while Model 2 is expected more than 50%. Note that residuals were calculated by subtracting the fitted value from the observed value, therefore, a positive value indicates that the regression model underestimates the ESMM size while a negative value indicates that regression model overestimates the ESMM size.

It should be noted that errors are greatest for population extremes (e.g., very large or very small CSAs). Errors for the majority of the samples are modest.

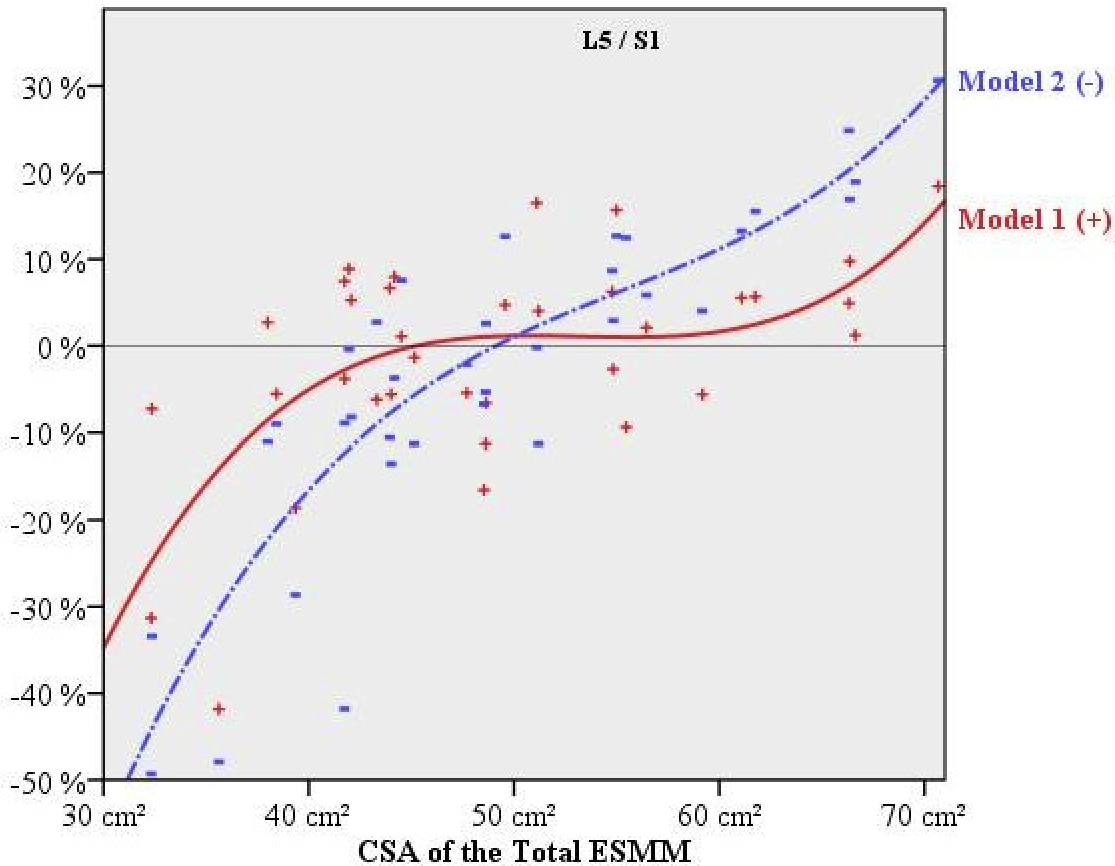


Figure 5.10: Comparison of absolute error percentages of regression models

Table 5.26: Comparisons of total ESMM size regression models in terms of absolute error percentages

| Level | M | Equations for the CSA of the total ESMM ($cm^2$) | $R^2$ | Adj-$R^2$ | S.E. | Absolute Residuals (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Mean | St.d. | Min | Max |
| L3/L4 | 1 | = - 3.076 + 0.669*LBM + 0.323*An − 0.543*Wr - 0.002*He + 0.929*SW | 0.835 | 0.807 | 5.44 | 8.26 | 4.79 | 1.84 | 19.41 |
| | 2 | = 15.081 + 8.121*G + 0.427*W | 0.698 | 0.679 | 7.01 | 9.91 | 7.62 | 0.11 | 31.05 |
| L4/L5 | 1 | = - 1.916 + 0.817*LBM + 0.394*An - 0.458*Wr - 0.002*He + 1.169*SW - 0.024*C - 0.007*Ha | 0.826 | 0.781 | 5.12 | 6.48 | 5.22 | 0.04 | 24.05 |
| | 2 | = 14.660 + 0.502*W | 0.559 | 0.546 | 7.37 | 9.98 | 7.83 | 0.40 | 40.00 |
| L5/S1 | 1 | = - 85.211 + 0.466*An - 0.726*Wr - 10.738*G - 1.562*AL + 1.202*H + 1.109*SW - 0.796*W + 0.830*LBM | 0.700 | 0.608 | 6.27 | 8.97 | 8.46 | 1.08 | 41.81 |
| | 2 | = 28.134 + 0.288*W | 0.219 | 0.196 | 8.98 | 14.16 | 12.93 | 0.19 | 49.31 |

M: Model; Model 1: Regression model regressed over all measured variables;
Model 2: Regression model regressed over only easy-to-measure variables (gender, age, height, and weight)

Table 5.27: Comparisons of ESMLA distance regression models in terms of absolute error percentages

| Level | M | Equations for the ESMLA distance (cm) | $R^2$ | Adj-$R^2$ | S.E. | Absolute Residuals (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Mean | St.d. | Min | Max |
| L3/L4 | 1 | Min2.487 + 0.046*SH - 0.049*SW + 0.0001*He + 0.001*C - 0.016*Wr + 0.016*An - 0.029*W + 0.033*LBM -0.255*G | 0.905 | 0.870 | 0.16 | 2.15 | 1.59 | 0.08 | 6.39 |
| | 2 | min 0.535 +0.033*H | 0.650 | 0.640 | 0.27 | 4.27 | 2.97 | 0.20 | 9.45 |
| | A | Average for 5.41 cm for males 4.77 for females | | | | 5.30 | 3.19 | 0.35 | 14.33 |
| | F | Fixed value of 5 cm | | | | 7.53 | 4.97 | 0.08 | 17.25 |
| L4/L5 | 1 | Min0.318 + 0.034*SH + 0.0001*He - 0.002*K + 0.013*An + 0.022*LBM - 0.268*G - 0.003*E | 0.858 | 0.822 | 0.18 | 2.39 | 2.17 | 0.19 | 10.57 |
| | 2 | 3.595 + 0.021*W | 0.607 | 0.595 | 0.28 | 4.33 | 3.12 | 0.05 | 11.13 |
| | A | Average for 5.32 cm for males 4.75 for females | | | | 5.02 | 3.84 | 0.22 | 15.05 |
| | F | Fixed value of 5 cm | | | | 7.19 | 4.60 | 0.62 | 18.05 |
| L5/S1 | 1 | 1.382 + 0.012*H + 0.011*An | 0.787 | 0.774 | 0.24 | 3.67 | 2.34 | 0.16 | 10.37 |
| | 2 | 3.469 + 0.025*W | 0.662 | 0.652 | 0.29 | 4.30 | 3.19 | 0.06 | 11.26 |
| | A | Average for 5.55 cm for males 4.83 for females | | | | 4.89 | 4.02 | 0.04 | 15.14 |
| | F | Fixed value of 5 cm | | | | 8.39 | 5.55 | 0.91 | 20.33 |

M: Model; Model 1: Regression model regressed over all measured variables;
Model 2: Regression model regressed over only easy-to-measure variables (gender, age, height, and weight);
Model A: Average value used for each gender; Model F: Fixed value of 5 cm (2 in) used for all subjects.

***Regression models for the ESMLA distance***

Several alternative best subset regression models to estimate the ESMLA distance are suggested in the present study. The most predictive variables seem to be the ankle and head indexes and sitting height at the L3/L4 and L4/L5 IVD levels. The knee and wrist indexes and LBM were also included in most regression subsets. The ankle index and height and/or weight were the most frequently included predictors at the L5/S1 level. The ten-parameter model at the L3/L4 level, eight-parameter model at the L4/L5 level, and three-parameter model at the L5/S1 level were selected as the best regression models since they had relatively larger Adjusted-$R^2$ values for the number of variables included, 0.870, 0.822, and 0.774, respectively. $R^2$ of these models were 0.905, 0.858, and 0.787, respectively. These values were higher than some previous studies (Wood *et al.*, 1996, Jorgensen *et al.*, 2001 and 2003b; Seo *et al.*, 2003; Anderson *et al.*, 2012). Reid and Costigan (1987) reported higher $R^2$ value at the L5/S1 level. They had 20 young male subjects and measured trunk width at the greater trochanter which may differ between genders. Moga *et al.* (1993) reported $R^2$ values ranging 0.230 to 0.260 for regressions derived from 11 males and 0.870 to 0.910 for regressions derived from 8 females (IVD level was not reported). $R^2$ for their female regressions are higher than the present study. However, their relatively small sample size and large difference between genders (very predictive for females and poor prediction for males) leave doubts about methodology and applicability to other populations.

As discussed earlier, model selection is a trade-off between model accuracy and model complexity. Complex models may require measuring more anthropometrics. The ESMLA distance was regressed over easy-to-measure subject variables. Comparisons of model power and/or errors between the regression models with easy-to-measure predictors and the regression models with more predictor variables are presented in Table 5.27. Limiting predictor variables to gender, age, height, weight (only height at the L3/L4 and only weight at L4/L5 and L5/S1 levels were significant) results in smaller $R^2$ and Adjusted-$R^2$. Adding more predictors into regression analyses resulted in an increase in Adjusted-$R^2$

from 0.640 to 0.870 at the L3/L4 level, 0.595 to 0.822 at the L4/L5 level, and 0.652 to 0.774 at the L5/S1 level. Standard errors were also smaller in the regression models with more predictors. Absolute residual percentages were calculated for these regression models. Regression models with more predictor variables had smaller absolute residual percentages than regression models limited to easy-to-measure predictor variables; 2.15% versus 4.27% at the L3/L4, 2.39% versus 4.33% at the L4/L5, and 3.67% versus 4.30% at the L5/S1 level.

The ESMLA distance has been generally assumed to be 5 cm in biomechanical calculations to estimate compression forces at IVDs (Bradford and Spurling, 1945; Morris *et al.*, 1961; Munchinger, 1962; Nachemson, 1968; Ayoub and El-Bassoussi, 1976; Poulsen, 1981; McGill and Norman, 1985). Absolute error percentages were calculated for a fixed value of 5 cm. This was calculated by subtracting the fixed 5 cm value from the observed value, and then dividing the absolute difference by the observed value. Regression models suggested in the present study yield much smaller absolute residual percentages than a fixed 5 cm lever arm can provide; 2.15% versus 7.53% at the L3/L4 level, 2.39% versus 7.19% at the L4/L5 level, and 3.67% versus 8.39% at the L5/S1 level (Table 5.27).

Some researchers have suggested using some empirically derived average values (Eie, 1966 (6.5 cm); Schultz and Anderson, 1981 (4.4 cm); Hutton and Adams, 1982 (6.1 cm); McGill and Norman, 1987a (7.5 cm); Bean *et al.*, 1988 (7.4 cm); Tracy and Munro, 1991 (5.8 cm); Tveit *et al.*, 1994 (a range of 5 to 8 cm); Chaffin, 1995 (a range of 5 to 7 cm); Merryweather *et al.*, 2009 (6.9 cm for males, 6.6 cm for females), Waters and Garg, 2010 (6.0 cm for males, 5.6 cm for females); 3D SSPP (6.0.6) (5.9 cm for males, 5.4 cm for the right side and 5.2 cm for the left side for females). In this present study, the average ESMLA was 5.41 cm for males and 4.77 cm for females at the L3/L4 level, 5.32 cm for males and 4.75 cm for females at the L4/L5 level, and 5.55 cm for males and 4.83 cm for females at the L5/S1 level. Absolute error percentages were also calculated for the average values. These were calculated by subtracting the average value (based on each gender and each IVD) from the observed value, and then dividing the absolute difference by the observed value. Absolute errors resulting from regression models in the present study had smaller absolute residual percentages than absolute error percentages resulting from using an average value for each gender and each IVD level; 2.15% versus 5.30% at the L3/L4 level, 2.39% versus 5.02% at the L4/L5 level, and 3.67% versus 4.89% at the L5/S1 level.

Figure 5.11 graphically represents absolute residual percentages in ESMLA distance comparisons between (1) Regression model regressed over more measured variables (Model 1), (2) Regression model regressed over only easy-to-measure variables such as gender, age, height, and weight (Model 2), (3) Average value used for each gender (Model A), and (4) Fixed value of 5 cm used for the entire population (Model F). Figure 5.11 summarizes that the regression models having more anthropometric predictors have the smallest error percentages at all IVD levels. Using the fixed value results in the largest error percentages. Note that confidence intervals are smallest for Model 1 and largest for Model F, as well. Regression models with limited to easy-to-measure predictors have larger error percentages than regression models with more predictors, however, they have still smaller error percentages than either an average or a fixed value provides.

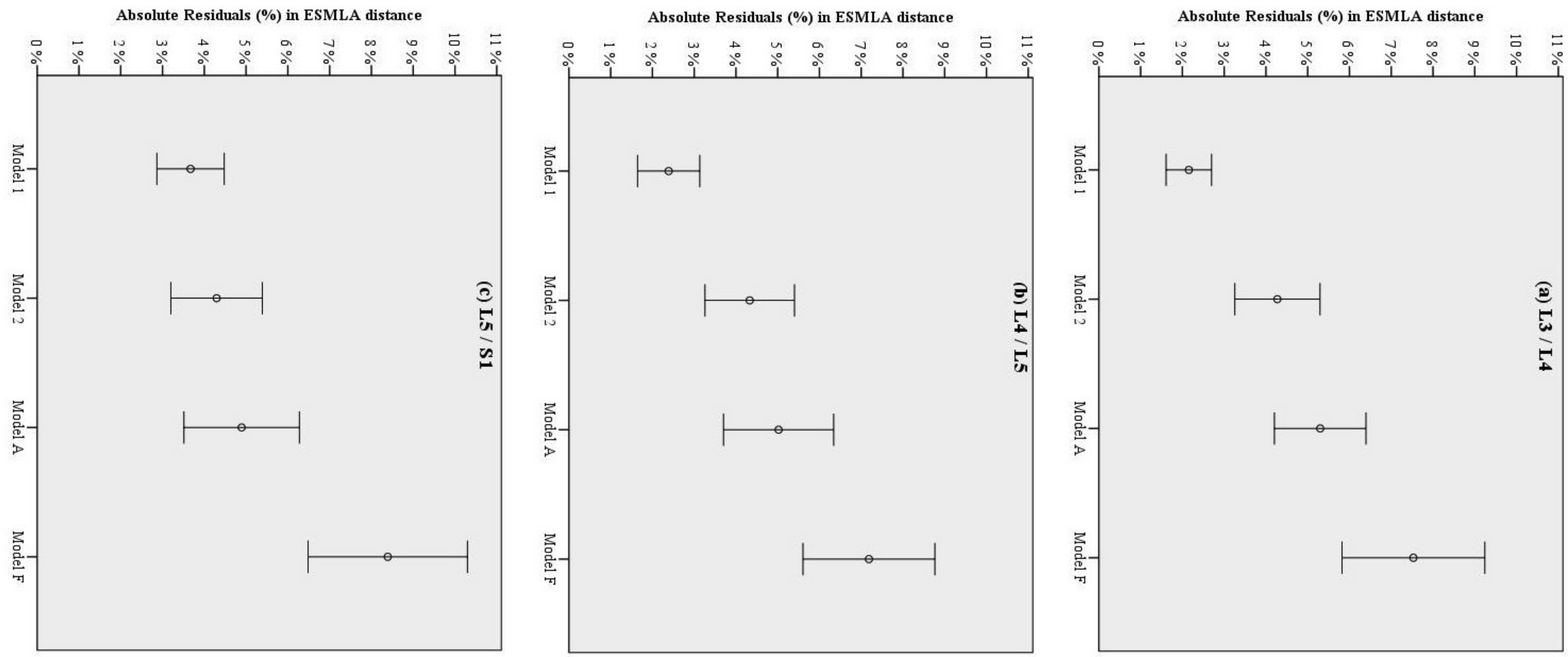


Figure 5.11: Comparison of ESMLA distance regression models in terms of absolute error percentages:
**Model 1**: Regression model regressed over more measured variables
**Model 2**: Regression model regressed over only easy-to-measure variables
**Model A**: Average value used for each gender
**Model F**: Fixed value of 5 cm 2 in used for all subjects

## 5.5 Conclusion

The objective of the present study was to provide regression models for low back biomechanical model inputs (the erector spine muscle mass (ESMM) cross-sectional area (CSA) and the erector spine muscle mass lever arm (ESMLA) distance). These model inputs should be accurate because the force generating capacity of an individual is dependent upon the muscle size, and the magnitude of spinal loading of an individual for a given task is dependent upon the ESMLA size. However, these model inputs are limited by assumptions. For example, some biomechanical low back models assume the ESMLA to be 5 cm for the entire population or use empirically derived average ESMLA values for a gender. Using a fixed or average (based on gender and IVD level) length may result in larger errors in spinal loading calculations.

The CSA of the ESMM in the present study are mostly larger than found in previous studies (McGill *et al.*, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990; Han *et al.*, 1992; Tveit *et al.*, 1994; Lin *et al.*, 2001; Seo *et al.*, 2003; Jorgensen *et al.*, 2003a; Kamaz *et al.*, 2007; and Neimelainen *et al.*, 2011) and smaller than some other studies (Parkkola *et al.*,1992; Wood *et al.*, 1996; and Lee *et al.*, 2006). The ESMLA distances in the present study are, on the other hand, mostly smaller than pervious studies (Nemeth and Ohlsen, 1986; McGill *et al.*, 1988; Tracy *et al.*, 1989; Chaffin *et al.*, 1990; Dumas *et al.*, 1991; Moga *et al.*, 1993; Tveit *et al.*, 1994; Guzik *et al.*, 1996; Jorgensen *et al.*, 2003b; and Lee *et al.*, 2006) and larger than some other studies (Tsuang *et al.*, 1993; Lin *et al.*, 2001). The results of the present study agree with some ESMM studies (Parkkola *et al.*, 1992; Wood *et al.*, 1996; Lee *et al.*, 2006) and ESMLA distance studies (Reid and Costigan, 1987; Bogduk *et al.*, 1992; Wood *et al.*, 1996; Seo *et al.*, 2003; Jorgensen *et al.*, 2001).

These differences are most likely due to subject variables and muscle group definition. For example, Tsuang *et al.* (1993) reported smaller male ESMM sizes than the presents study. Their subjects were similar in age (25.4 versus 25.5 years old); however, their subjects were lighter than the present study (64.6 versus 82.7 kg). This may explain why they reported smaller ESMMs. Age related muscle atrophy may explain some of the differences between the present study and studies with relatively older subjects (ESMM studies: Chaffin *et al.*, 1990; Neimelainen *et al.*, 2011 and ESMLA distance studies: Kumar, 1988; Chaffin *et al.*, 1990; Gilsanz *et al.*, 1995; Lee *et al.*, 2006; Anderson *et al.*, 2012). It is reported that LBP patients had smaller ESMM sizes than asymptomatic subjects (Kamaz *et al.*, 2007). The present study included asymptomatic subjects, which may also explain why the present study reports larger ESMMs than some previous studies that used LBP patients as subjects (McGill *et al.*, 1988; Tracy *et al.*, 1989; Han *et al.*, 1992). Han *et al.* (1992) did not include the multifidus muscles in their measurements, which may explain why they measured smaller ESMMs. Ethnicity may also partially explain some of the variation among studies. Future studies should address whether there is any ethnicity effect on the ESMMs and ESMLAs. In addition to subject variables and muscle group definition, the methodologies employed also have an affect on the variation among studies. Lee *et al.* (2006) measured the ESMLA distance from the centroid of the IVD to the centroid of each ESMM rather than the anterior-posterior distance, which yields larger ESMLA measurements (e.g., "diagonal" distance). Different scanning postures such as upright standing posture (Bogduk *et al.*, 1992), lying face down (prone) (Kamaz *et al.*, 2007), lying on a side (Jorgensen *et al.*, 2003b), and supine with extended knees (Tracy *et al.*, 1989) may result in variation on the muscle morphometry. Determination of the ESMM and IVD centroids by visual estimation (Tracy *et al.*, 1989; Moga *et al.*, 1993; Seo *et al.*, 2003; Lee *et al.*, 2006) may result in both reliability and accuracy problems.

The ESMM size and ESMLA distance in the present study were smaller than Study 1 (Chapter 3). Subjects in this study were younger, shorter, lighter, and less obese than Study 1, which may explain why the current study measured smaller ESMMs and ESMLAs.

The findings of the present study suggest that some future studies are required to address whether gender has a main effect on the ESMM size and ESMLA distance or if gender differences are due primarily to differences in heights and weights between the genders. Studies that match male and female subject variables (age, height, and weight) may address this issues and should be pursued.

Even though there were significant differences between the right and left ESMMs at some level for different genders in the present study, there was not a consistent trend for all IVD levels and both genders. Comparisons of the dominant- and non-dominant side CSAs of the ESMM did not show a consistent trend. However, it was a limitation of the present study that there were only three male subjects who were left-handed. To address the effect of the dominant hand side, future studies should include larger sample sizes from both groups (e.g., representative numbers of left-handed subjects). The present study asked only the frequency of physical activities. Results suggested that relationships between the ESMM size and physical activity frequencies were not strong. Future studies should measure not only the frequency but also duration and intensity of physical exercise.

The all-possible-regressions procedure provided several alternative regression models that include different predictor variables. However, some variables (LBM, and the ankle, wrist, and head indexes for the ESMM size and the knee and wrist indexes and LBM for the ESMLA distance) were more predictive and, therefore included in most regression subsets. Multiple correlation coefficients ranged from 0.659 to 0.835 for the ESMM and from 0.763 to 0.905 for the ESMLA regression models, which are larger than most previous studies (ESMM studies: Chaffin *et al.*,1990; Marras *et al.*, 2001; Seo *et al.*, 2003, and Anderson *et al.*, 2012 and ESMLA distance studies: Wood *et al.*, 1996, Jorgensen *et al.*, 2001 and 2003b; Seo *et al.*, 2003; Anderson *et al.*, 2012).

Since most subjects variables were highly correlated with the ESMM size and ESMLA distance, it is possible to estimate them with different subject variables. For example, a practitioner may prefer using a regression model that requires simple anthropometric measurements such as height and weight. However, comparisons of regression models showed that using models with only easy-to-measure variables results in a loss of predictive power and an increase in estimation error. The trade-off between model accuracy and complexity should be evaluated by practitioners. Practitioners can choose models that best meet their needs for predictive power and speed/ease of application. Comparisons of regression models with subject weight and LBM indicated that regression models with LBM had larger predictive power and smaller bias than the models with subject weight (approximately 10%). Therefore, a biomechanics practitioner can make their own decision about the trade-off between the model accuracy and the data collection simplicity.

Using a fixed (5 cm) or average length resulted in higher errors in spinal loading calculations. For example, it has been reported in the literature that the simplification assumption about the ESMLA distance could cause errors as great as 40% in predictions of spinal forces (Chaffin *et al.*, 1985; McGill and Norman, 1987a; and Chaffin *et al.*, 1990). The results of this study found that absolute residual percentage could be as great as 20% in prediction of the ESMLA distance when a 5 cm ESMLA is used. The absolute residual percent value for the fixed ESMLA was approximately 8% on average. Using an empirically derived average ESMLA value for a IVD level and gender could cause approximately 5% error in ESMLA distances. Regression equations provide much smaller prediction errors. The average absolute residual percentage for the ESMLA distance was approximately 4.3% for regression models that had easy-to-measure anthropometric variables (height and weight). Regression models that had more predictive variables (i.e., ankle, wrist, knee indexes), however, can provide much smaller prediction errors. The average absolute residual percentage was 2.15% for the L3/L4 level, 2.39% for the L4/L5 level, and 3.67% for the L5/S1 level. Smaller prediction errors in ESMLA distances result in smaller error in spinal loading calculations. Note that these numbers are the average error percentages. However, the error percentages are much higher in "extreme" subjects (e.g., very tall, short, heavy, light, or "muscular"). For example, using a 5 cm ESMLA distance at the L5/S1 for one of the taller subjects resulted in a 20% prediction error. Using a regression model with ankle index and height variables, the estimate for ESMLA distance at the same level results in a 10% prediction error for the same subject.

# Chapter 6

# CONCLUSION

The objective of this dissertation was to perform morphological analyses of the low back musculoskeletal structure and provide regression models that accurately estimate the size of the low back musculature and the mechanical lever arms associated with this musculature. Understanding low back structural morphology is critical to understanding spinal loading and the underlying injury mechanisms, which helps to characterizing risk and, therefore, minimize low back pain (LBP) injuries. The cross-sectional areas (CSA) of the erector spinae muscle mass (ESMM) and inter-vertebral disc (IVD) and the erector spinae muscle mass lever arm (ESMLA) distance were studied using magnetic resonance imaging (MRI) scans.

A comprehensive literature review indicated that previous studies regarding low back musculature had some limitations. For example, some previous studies had limited sample sizes, single gender, different age groups (either younger or older populations), different medical conditions, over-simplified measurement techniques (e.g., ellipsoid muscle shape assumption, visual center determination, etc.), and focused on a single vertebral body or IVD. This dissertation proposed to address these limitations by using larger sample sizes, collecting data using high resolution MRI scans, using computerized and reliable measurement techniques, and analyzing data for three IVD levels for both genders.

This dissertation studied both genders using relatively large sample sizes. The historical data study included 163 subjects (82 male and 81 female) for morphological analyses in Chapter 3. Out of 163, 112 subjects (54 males and 58 females) were used for regression analyses in Chapter 4. Note that subjects in these studies were medical patients and they had undertaken an MRI scan to help medical doctors to explore whether they had any medical abnormalities in their lumbar spinal region. To observe whether there was any structural difference between these medical patients and asymptomatic subjects, a new study was conducted. A total of 35 asymptomatic subjects (22 males and 13 females) was included in a second study. The historical data study is called Study 1. Study 2 refers to a study with asymptomatic subject population.

Measurement technology affects the outcomes. Measuring the anthropometric dimensions with computed tomography (CT), ultrasonography (US), and MRI is superior to manual tape measurements on cadavers since they are more repeatable and more applicable to live subjects. Problems regarding postmortem shape/volume distortions of soft tissues caused by the embalming process are eliminated with live subjects. Among these technologies, MRI is superior to CT and US due to its higher soft tissue resolution for muscles and IVDs. MRI is also the preferred technique for detailed morphometric studies of living subjects since the MRI does not produce ionizing radiation. Engstorm *et al.*'s (1991) study also indicated that MR measurements provide valid (high agreement) measures of the anatomical dissection of most individual muscles while CT scans tend to systematically overestimate (approximately 10-20%) anatomical the CSAs of most muscles. On the other hand, higher cost of MRI scanning may be considered as a downside when it is compared to other scanning technologies. T2-weighted standard soft-tissue MRI scans were taken using a 1.5 Tesla MRI scanner in Study 1 and a 3 Tesla MRI scanner was used in Study 2.

Some studies did not use axial oblique scans (Tracy *et al.*, 1989; Tveit *et al.*, 1994; Jorgensen *et al.*, 2001; Marras *et al.*, 2001; and possibly Reid and Costigan, 1985; Nemeth and Ohlsen, 1986; Reid and Costigan, 1987; McGill *et al.*, 1988). The ESMLA acts on an axial oblique plane. The results of these studies should be converted from transverse planes to oblique planes by using the muscle line-of-action or muscle fascicle orientation data. However, this data is mostly limited to male lumbar erector spinae muscles in the literature. The axial oblique scans were taken from subjects in the present study, which allows directly measurement of ESMLAs from MRI scans and eliminates the limitations associated with planer conversion of measurements. It should be noted that the method of centroids used to identify the line-of-action of the ESMM is based on a simplification assumption of muscle force. Jensen and Davy (1975) assumed that the muscle force acts at the centroid of the muscle CSA as a single point and all muscle fiber forces are parallel and uniformly distributed over the muscle's transverse CSA. The ESMM was assumed as a single muscle whose fibers are parallel to each other and the spine. However, in reality, there are several individual muscles (i.e., longissimus thoracis, iliocostalis lumborum) and several muscle fascicles inside these individual muscles. Muscle fascicles have different muscle fiber types, sizes, and orientations along with different points of insertion (attachment points), which results in different mechanical properties. The purpose of this dissertation was to produce morphometric data for simple sagittal plane low back biomechanical models. Future complex low back biomechanical models may consider these differences in the fascicle level.

CSAs of the IVD and ESMM and centroids of these CSAs were determined using software in the present study. Some previous studies employed simple measurement techniques such as visual determination of the centroids or drawing axes to determine the centroid in the intersection (Nemeth and Ohlsen, 1986; Kumar, 1988; Tracy *et al.*, 1989; Lin *et al.*, 2001; Seo *et al.*, 2003; Lee *et al.*, 2006). Simple measurement techniques inherently induce higher error into the measurements. The computerized measurement technique in the present study minimizes measurement error. Measurements were also highly reproducible in the present study. Intra-rater and inter-rater reliability tests indicated that the measurement technique was highly repeatable (good inter-rater reliability ranging from 0.811 to 0.997 and excellent intra-rater reliability ranging from 0.968 to 0.998).

Some previous researchers studied only at one IVD level (Seo *et al.*, 2003; McGill *et al.*, 1988; Wood *et al.*, 1996; Lee *et al.*, 2006, Tracy *et al.*, 1989) or one vertebral body level (Cooper *et al.*, 1992; Reid *et al.*, 1987). The present study includes the lowest three IVD levels (the L3/L4, L4/L5, and L5/S1) to comprehensively understand the low back musculoskeletal structure. These three levels were selected as the research interest since they are highly susceptible to low back pain. The IVD level was preferred over the vertebral body level in this study because most low back injuries occur at the IVDs rather than the vertebral bodies.

The average CSA of the ESMM for female subjects varies from 23.4 to 25 $cm^2$ in Study 1 (Chapter 3) and from 19.2 to 22.6 $cm^2$ in Study 2. For male subjects, the average CSA of the ESMM varies from 24.6 to 30.0 $cm^2$ in Study 1 and from 25.5 to 29.5 $cm^2$ in Study 2. These values tended towards the upper end of the spectrum when compared with previous studies. Differences were possibly due to differences in sampling, measurement techniques, and muscle definitions. For example, Han *et al.* (1992) and Lee *et al.* (2006) did not include the multifidus muscles in their measurements, which results in smaller ESMM sizes. Male subjects in Study 2 were slightly younger ($\approx$ 2 years), shorter ($\approx$ 2 cm) and lighter ($\approx$ 3 kg) than male subjects in Study 1. The slight difference in male ESMM sizes are possibly due to these slight differences in anthropometrics. On the other hand, the difference in female anthropometrics between both studies were larger; female subjects were younger ($\approx$ 4 years), shorter ($\approx$ 5 cm), and lighter ($\approx$ 26 kg). In addition to the differences in anthropometrics, female subjects in Study 2 had smaller ESMM sizes than subjects in Study 1.

The average ESMLA distance varies from 5.5 to 5.7 cm for males and from 5.0 to 5.1 cm for females in Study 1. The ESMLA distances were smaller in Study 2. The average ESMLA distance varies from 5.3 to 5.6 cm for males and from 4.7 to 4.8 cm for females in Study 2. The average ESMLA values tended towards the lower end of the spectrum of previous studies. Differences in sampling, measurement techniques, and muscle definitions may possibly explain the differences in ESMLA sizes. For example, Lee *et al.* (2006) measured the ESMLA distance directly from the IVD centroid to the ESMM centroid while the true ESMLA distance is the anterior-posterior distance from the IVD centroid to the connection line between the ESMMs. They reported approximately 40% larger ESMLA distances than the present study. As discussed earlier, subjects in Study 2 were younger, shorter, and lighter than subjects in Study 1. That may explain why ESMLA distances in Study 1 are larger than Study 2. Ethnicity of subjects has not been well studied in the literature. Future studies may address whether there is any ethnicity effect on the muscle sizes and associated lever arms.

Different scanning postures such as upright standing posture (Bogduk *et al.*, 1992), lying face down (prone) (Kamaz *et al.*, 2007), lying on a side (Jorgensen *et al.*, 2003b), and supine with extended knees (Tracy *et al.*, 1989) could be another reason for variation in the muscle morphometry among studies.

The ESMM sizes and ESMLA distances were larger for male subjects than female subjects. Male subjects were also taller, heavier, and more obese in both studies. Therefore, the present study might not address whether gender had a main effect on the ESMM size and ESMLA distance or if gender differences were due primarily to differences in heights and weights between the genders. Future studies should select matching male and female subjects in terms of their anthropometrics to better address the gender effect on the ESMMs and ESMLAs.

Since there were only few left-hand dominant subjects (3 males) in Study 2, a comparison of the dominant- and non-dominant side CSAs of the ESMM did not provide much information. Future studies should include larger samples of the left- and right-hand dominant subjects to address whether there is any effect of dominant hand side on the ESMMs and ESMLAs.

The results of Study 2 suggest that there is not a very strong relationship between the ESMM size and physical exercise frequencies. The present study asked only the frequency of physical exercise (i.e., weight lifting, cardio exercise). The intensity and duration of physical exercises were not collected in the present study. Future studies should address the effect of physical activity on the ESMMs and ESMLAs by controlling and/or more accurately measuring subjects' physical activities in intensity, duration, and frequency levels.

The objective of this study is to provide reliable regression equations that accurately estimate the ESMLA distance and the CSA of the ESMM at the low back region based on subject characteristics and anthropometrics. In Study 1 (Chapter 4), easily measured anthropometric variables (subject height and weight) and subject characteristics (gender and age) were utilized to estimate the ESMLA distance and the CSA of the total ESMM. In study 2, more subject characteristics (i.e., dominant hand side, exercise frequency) and anthropometrics (i.e., LBM, shoulder width, and widths and circumferences of limbs) were added to the predictor variables used in Study 1 to determine whether they may better estimate the ESMMs and ESMLAs than the easy-to-measure subject variables alone.

Gender, age, height, and weight were regressed over the CSA of the ESMM and ESMLA distance. Since age related muscle atrophy was reported in the literature (Lexell *et al.*, 1988; Brooks and Faulkner, 1994; and Faulkner *et al.*, 2007), it was anticipated that age would be a predictor variable for the ESMMs and ESMLAs. However, the finding of the present study indicated that the subject's age does not have any effect of the ESMM size and ESMLA distance. It should be noted that subject age was limited in range (21 - 39 years in Study 1 and 21 - 35 years in Study 2). This small range of subject age is a limitation of the present study. To derive a conclusion about the predictive ability of age on the ESMMs and ESMLAs, a great range of subject ages will be needed. Future studies should include subjects with different ages and larger age ranges to be able investigate whether there is an age effect on the ESMMs and ESMLAs. Gender was a predictor variable for the ESMM size at some IVD levels. However, the findings of the present study suggest that some future studies are required to address whether gender has a main effect on the ESMM size and ESMLA distance or if gender differences are due primarily to differences in heights and weights between the genders. Male subjects were heavier and taller in the present study. Future studies should include female and male subjects whose anthropometrics (height and weight) are matched to better address potential gender effects on the ESMM size and ESMLA distance. Regression models to estimate the ESMM size in

Study 1 included subject height and weight at all IVD levels. However, the ESMM size was more sensitive to the subject's height. This means that the coefficient of height was larger than the coefficient of weight. For example, the CSA of the ESMM at the L5/S1 level increases 1 $cm^2$ per 2.8 cm increase in height while 7.4 kg increase in weight is required for the same amount (1 $cm^2$) of increase in the ESMM size. The subject height was the only predictor parameter in ESMLA prediction models. The ESMLA distance increases approximately 1 cm in length per every 33 cm increase in height. Regression models were used to estimate the ESMM sizes and ESMLA distances for a sample of 20 subjects. Absolute errors were approximately 11 - 15% on average for the ESMM size and approximately 4% on average for the ESMLA distance. Using a fixed (5 cm) ESMLA value resulted in approximately 9% error on average. Therefore, a simple regression model that requires only subject height may decrease this error term more than 50%. It should be noted that the magnitude of the average error was higher for "extreme" subjects (e.g., very tall, short, heavy, light, or "muscular").

Study 1 had some limitations. For example, subjects in Study 1 were symptomatic enough to seek an MRI. Specific symptoms, however, are unknown. Study 2 included asymptomatic subjects so that it may provide the opportunity to compare the results of the asymptomatic study with the results of symptomatic subject studies including Study 1. Subject variables in Study 1 were limited to gender, age, height, and weight. However, some previous studies found some other relationships between muscle sizes and lever arm distances and subject characteristics such as sitting height (Wood *et al.*, 1996). Several anthropometric measurements such as head, elbow, wrist, hand, knee, and ankle width and circumferences, sitting height, shoulder width, chest breath and depth, head depth, and hand and arm lengths were measured in Study 2 to determine whether they may better estimate the ESMM size and ESMLA distance compared to easy-to-measure subject variables (i.e., gender, age, height, and weight). In Study 2, metric units (cm and kg) were used while integer British units (inches and pounds) were used in Study 1. Having metric units in one decimal resulted in higher resolution when constructing prediction models. Study 2 also used the all-possible-regressions procedure, which minimizes the disadvantages of stepwise regression procedures. Subset regression analyses allowed selection of regression models that had larger prediction powers and smaller bias/errors.

The results of the best subset regression analyses indicated that the most frequently included predictive variables seem to be LBM, and the ankle, wrist, and head indexes for most ESMM size regression subsets and the knee and wrist indexes and LBM for most ESMLA distance regression subsets. It should be noted that most of other subject variables were correlated with the ESMMs and ESMLAs. This means that a regression model with other subject variables may provide results that are "good enough." For example, a practitioner may prefer using a regression model that requires simple anthropometric measurements such as height and weight. However, comparisons of regression models showed that using models with only easy-to-measure variables results in a loss of predictive power and increases in estimation errors. The trade-off between model accuracy and complexity should be evaluated by practitioners. Practitioners can choose models that best meet their needs for predictive power and speed/ease of application. Comparisons of regression models with subject weight and LBM indicated that regression models with LBM had larger predictive power and smaller bias than the models with subject weight (approximately 10%). Therefore, a biomechanics practitioner can make a decision about the trade-off between the model accuracy and data collection simplicity that best meets their specific needs. Multiple correlation coefficients ($R^2$) for the regression models in Study 2 ranged from 0.659 to 0.835 for the ESMM and from 0.763 to 0.905 for the ESMLA. These $R^2$ values are higher than most previous studies (ESMM studies: Chaffin *et al.*,1990; Marras *et al.*, 2001; Seo *et al.*, 2003, and Anderson *et al.*, 2012 and ESMLA distance studies: Wood *et al.*, 1996, Jorgensen *et al.*, 2001 and 2003b; Seo *et al.*, 2003; Anderson *et al.*, 2012) and Study 1 (historical MRI patient data base).

The results of Study 2 indicate that absolute residual percentage could be as great as 20% in prediction of the ESMLA distance when a fixed (5 cm) ESMLA is used. The absolute residual percent value for the fixed ESMLA was approximately 8% on average. Using an empirically derived average ESMLA value for a specific gender at a specific IVD level could result in approximately 5% absolute error in ESMLA distances. However, regression equations can provide much smaller prediction errors. The average absolute residual percentage for the ESMLA distance was approximately 4.3% for regression models that had easy-to-measure anthropometric variables (height and weight). Regression models that had more predictive variables (i.e., ankle, wrist, knee indexes), however, can provide much smaller prediction errors. The average absolute residual percentage was 2.15% for the L3/L4 level, 2.39% for the L4/L5 level, and 3.67% for the L5/S1 level. Smaller prediction errors in ESMLA distances result in smaller errors in spinal loading calculations. Note that these numbers are the average error percentages. The error percentages can be much higher in "extreme" subjects (e.g., very tall, short, heavy, light, or "muscular"). For example, using a 5 cm ESMLA distance at the L5/S1 for one of the taller subjects resulted in a 20% prediction error. Using a regression model with ankle index and height variables, the estimate for ESMLA distance at the same level results in a 10% prediction error for the same subject. It should be noted that errors are greatest for population extremes (e.g., very large or very small ESMLAs). Errors for the majority of the samples are modest.

To conclude, the findings of this dissertation suggest that the ESMM size and ESMLA distance can accurately and reliably be estimated using regression models. Subject specific regression models allow biomechanics practitioners to estimate the ESMMs and ESMLAs for individuals and calculate their subsequent spinal loadings for a given task. Calculating spinal loading with smaller error will result in more accurate evaluations of the occupational risk for the low back region. Lastly, Annis's and McConville's (1990) paper demonstrated that there is no "average person." That is, individuals with "average" dimensions among multiple anthropometric categories (e.g., have average height, weight, limb size, etc.).

There is a great variation in anthropometrics not only among subjects but also within subjects. Race/ethnicity, occupation, genetics, medical history, life style, geographic region, climate, and several other confounding factors affect body dimensions and proportions, which results in a great variation in anthropometrics. Because of the variation in anthropometrics, multiple regression models will always have some amount of error in predicting the ESMM size and ESMLA distance. Regression models in this dissertation (Study 2) had approximately 3% error in predicting the ESMLA distance. Finally, the anthropometrics of a given subject sample should be considered before using the regression equations presented here. The regression equations provided in the present study may not be applicable for adolescent or older subjects, obese subjects, or highly trained athletes.

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# Appendix A

## The University of Utah, Institutional Review Board (IRB) approval letter

INSTITUTIONAL REVIEW BOARD
THE UNIVERSITY OF UTAH
75 South 2000 East Salt Lake City, UT 84112 | 801.581.3655 | IRB@utah.edu

**IRB_00046148**

**Principal Investigator: K. Bo Foreman**

**Title: Modifying Risk Estimates for Low Back Pain Based on Disc Pressure: An investigation of the relationship between general anthropometry and low back spine characteristics using radiographic image data (MRI)**

This Amendment Application (Auburn Univ IRB approval ) qualifies for an expedited review by a designated University of Utah IRB member according to University IRB policy. The designated IRB member has reviewed and approved your amendment request for this study on 3/15/2011. The approval of this amendment request does NOT change the expiration date of this research study as noted below.

Your study will expire on 1/4/2013 12:00 AM.
Any future changes to this study must be submitted to the IRB prior to initiation via an amendment form.

**APPROVED DOCUMENTS**

**Other Documents**
Auburn Univ IRB approval

Click AM_00009701 to view the application and access the approved documents.

Please take a moment to complete our customer service survey. We appreciate your opinions and feedback.

Appendix B

Auburn Univeristy, Institutional Review Board (IRB) approval letter

AUBURN UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

**(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)**

INFORMED CONSENT
**for a Research Study entitled**
**"Morphological Analysis of the Musculoskeletal Structures of the Lumbar Spine"**

**You are invited to participate in a research study** to develop a better estimation model of lumbar musculoskeletal structure. The study is being conducted under the direction of Richard F. Sesek, Assistant Professor in the Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because 1) you are age 21 or older, 2) have no current low back pain or injury, and 3) have no history of low back pain, injury or surgery.

You are qualified for this study because you are NOT experiencing any of the following exclusion conditions.

| |
|---|
| You have ever been treated by a doctor or health care provider for low back pain or injury. |
| You currently have significant low back pain or discomfort. |
| You have been told by a doctor or medical provider that you have a spinal defect or herniated (bulging) disc. |
| You are experiencing chronic leg pains. |
| You are experiencing chronic foot pains. |
| You have a cardiac pacemaker or implanted cardioverter defibrillator (ICD). |
| There is a possibility of metal in your head (for example aneurysm clips, do not include dental work). |
| You had an injury to the eye involving a metallic object or fragment (for example, metallic slivers, shavings, foreign body), or you have ever needed an eyewash having worked with metals. |
| You have an implanted medical device that is electrically, magnetically, or mechanically controlled or activated. |
| **Females Only**: You are pregnant or there is possibility that you may be pregnant. |
| You have body-piercing jewelry that cannot be removed. |
| You have inner ear disorders or experience vertigo or dizziness. |
| You are claustrophobic. |
| You have a breathing problem or motion disorder. |
| You have tattoos or permanent makeup that contains metal. |

The Auburn University Institutional Review Board has approved this document for use from 11/30/11 to 11/29/12
Protocol # 11-292 MR 1111



Participant's initials____

**What will be involved if you participate?**

If you decide to participate in this research study, you will be asked to undergo magnetic resonance imaging (MRI) scans, anthropometric measurements (basic body dimensions), 3-site skinfold body composition test, and a balance test.

You will first be asked screening questions to make sure it is safe for you to undergo an MRI scan. You will then be asked to lie on a bed that slides into the long tube of the scanner. The scanner is a magnet with a small, enclosed space. Radio waves and strong, changing magnetic fields are used to make images of your body. You will be given earplugs and earphones to protect your ears since these changing magnetic fields cause loud knocking, thumping, or pinging noises. You will be asked to remain very still while being scanned. To help you keep your body perfectly still, we will support you with pillows.

6 scans will be performed in a single session with approximately one minute of rest between scans. Each scan lasts about 4 minutes and will never exceed 15 minutes. Your total time in the scanner will be approximately 30 minutes to 40 minutes.

Anthropometric data (basic body dimensions) will be measured after the MRI scans, including height, weight, diameter of wrist, elbow, knee, and ankle, and head circumference, width, and chest breadth and depth. Both male and female research assistants will be available to perform these tasks.

A simple balance test will also be performed immediately before and after the MRI scans in order to explore the possible effect of MR field on individual's postural stability. These tasks will require approximately 10 minutes to 20 minutes.

Then, 3-site skinfold test will be performed to measure the body composition. This will take approximately 5 minutes to 10 minutes

The following is the detailed procedures of this study. If you have any questions, please ask the investigator.

After reading and signing the Informed Consent, you will present your driver's license, Auburn University student ID card or other photo ID. Only those who are able to do so will complete the remaining steps.

The anthropometry measurements (basic body dimensions) will be collected in the MRI center preparation room. (1 male and 1 female graduate research assistant will be available to perform the data collection under the supervision of the PI/Co-PI).*

Body composition will be measured using established 3-site skinfold test procedures (Male: Chest, Abdomen, and Thigh; Female: Tricep, Suprailiac, and Thigh).

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Protocol # 11-292 MR 1111



Participant's initials____

Then you will change into surgical scrubs supplied by the AU MRI Research Center and is screened a second time using handheld ferromagnetic detector to make sure it's safe for you to get MRI scan.

A simple measure of balance will be recorded using established procedures on a NeuroCom® Balance Master® system (version 8.1.0, using Unilateral Stance Assessment).

You will be introduced to the MRI scan room, and be asked to get on the scanner table and lay down in supine position. You will be provided with head and leg cushion, and you can ask for additional cushion.

You will be weighed facing outward from the scales. The weight is entered into the screening form and scanner. This information is used by the scanner to monitor specific absorption rate (SAR) during the scan.

You will undergo the standard MRI back examination used by East Alabama Medical Center (EAMC) of the lumbar region from L1/L2 to L5/S1, which consists of the following six Food and Drug Administration (FDA) approved imaging sequences:
- Three-axis (axial, coronal, sagittal) localizer.
- T2-weighted sagittal.
- T1-weighted sagittal.
- T1-weighted 3D.
- T2-weighted sagittal with fat suppression.
- T2-weighted axial

After MRI is done, you will be removed from the scanner and get off the scanner table. Then, you will leave the MRI scan room.

The same measure of balance will be performed as described in previous step.

Then you will be escorted to the dressing room, allowed to change back into your original clothing.

You will then be escorted out of the MRI suite.

*Anthropometry measurements may be performed before or after the MRI scan depending on MRI scanner availability.

Your total time commitment will be approximately 1-2 hours.

NONE of the scans done during this study are appropriate for clinical interpretation. This means that they are not designed to assess any medical condition you may have. They are not designed to reveal any clinically relevant problems. Rather, they are intended solely for research purposes.



 Participant's initials____

The Auburn University Institutional Review Board has approved this document for use from 11/30/11 to 11/29/12 Protocol # 11-292 MR 1111

**Are there any risks or discomforts?**

The risks associated with participating in this study are:

1. **The most obvious personal risk from having an MRI is blunt trauma due to metallic objects being brought into the magnetic field. As such, all necessary steps will be taken to make sure neither you nor anyone else who enters the MRI scanner room is in possession of an unrestrained metal object and no unauthorized person will be allowed to enter the MRI scanner room.**

2. Participants who have iron or steel implants or clips from surgery within their body or metallic objects such as shrapnel or metal slivers in their body may be pulled by the magnet and cause injury.

3. The MRI machine produces an intermittent loud noise, which some people find annoying.

4. Some participants may feel uncomfortable being in an enclosed place (claustrophobia) and others find it difficult to remain still.

5. Some people experience dizziness or a metallic taste in their mouth if they move their head rapidly in the magnet.

6. Some people experience brief nausea when being put into or taken out of the scanner.

Although long-term risk of exposure to the magnet is not known, the possibility of any long-term risk is extremely low based on information accumulated over the past 30 years of MRI use.

To minimize these risks, we will:

1. Have you filled out a screening form to determine if you have iron or steel implants, clips from surgery, or other metallic objects in your body. If you have implants, clips, or objects in your body, you will not be able to undergo an MRI scan.
2. Ask you to change into surgical scrubs supplied by the center and remove any watches, rings, earrings, or other jewelry or metallic objects. You will be provided a private place to change and you may retain your undergarments. If you are female, you will be asked to remove your bra if it has an underwire or metal fasteners.
3. Scan you with a handheld metal detector to detect any unknown metallic objects.
4. Provide you with either earplugs or a set of headphones specifically designed to work in an MRI scanner.
5. Maintain visual and verbal contact with you during the scan and check with you frequently to determine if you are having any negative feelings or sensations.
6. If some unknown risk becomes a safety issue, the research team will immediately stop the scan and remove you from the scanner.
7. You can stop the scan at any time and be immediately removed from the scanner.

 **Participant's initials____**

**Are there any benefits to yourself or others?**

If you participate in this study, you can expect to receive $80 dollars compensation for your 2-hour participation. Your participation provides the investigator with a greater understanding of the musculoskeletal structure of lumbar spine, which may be useful in developing better models for estimation of lumbar spine injury risk.

**Will you receive compensation for participating?**

You will be paid $80 dollars for your full participation in this study.

**Are there any costs?**

If you decide to participate, you will not incur any costs. However, for any incidental findings that require clinical attention, the associated cost of medical care will be at your expense. If you prefer, you can provide your doctor's information at the end of this document.

**If you change your mind about participating,** you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, the Samuel Ginn College of Engineering, the Department of Industrial and Systems Engineering or the Auburn University MRI Research Center.

**Your privacy will be protected.** Any information obtained in connection with this study will remain confidential. At the end of the study all links to identifiable information will be destroyed. Information obtained through your participation may be published in a professional journal and/or presented at a professional meeting.

**Incidental findings.**

These procedures are carried out purely for experimental purposes. The MRI scans that are acquired in this study are not the same as those acquired during a clinical examination as requested by a Medical doctor. Therefore, they are not useful to investigate any abnormalities or medical conditions you may have. Furthermore, the investigators who will analyze these images are not medical doctors and are not trained to evaluate these scans for medical problems.

It is possible however that an abnormality may be noticed. If this happens, a brief diagnostic scan will be performed and referred to a radiologist for reading. If you choose to provide the name and contact information of your primary physician, the results of the scan will be provided to them. If you do not have primary physician or do not provide contact information for your primary care physician, the results will be provided to Dr. Fred Kam, M.D. at the Auburn University Medical Clinic, who will discuss the results of the scan with you at your expense.



**Participant's initials____**

**If you have questions about this study,** *please ask them now or* contact Assistant Professor Richard F. Sesek at (334) 844-1552 (sesek@auburn.edu). A copy of this document will be given to you to keep.

**If you have questions about your rights as a research participant,** you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

**HAVING READ THE INFORMATION PROVIDED, YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.**

| | | | |
|---|---|---|---|
| Participant's signature | Date | Investigator obtaining consent | Date |

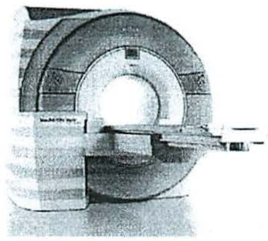
Printed Name | Printed Name

Doctor's Information

Name | Contact phone number



**Participant's initials____**



# RESEARCH STUDY: ADULT VOLUNTEERS 21 YEARS OR OLDER

TITLE: Morphological Analysis of the Musculoskeletal Structures of the Lumbar Spine

WHO: Adults, age 21 or older

WHAT: You will first be asked screening questions to make sure it is safe for you to undergo an MRI scan. A set of anthropometry measurements (basic body dimensions) will be taken. You will be asked to fill out a survey questionnaire. You will change into surgical scrubs. If you are female, you will be asked to remove your bra if it contains a metal underwire or metal fasteners. You will then be asked to lie on a bed that slides into the long tube of the MRI scanner. The scanner is a magnet with a small enclosed space. Radio waves and strong, changing magnetic fields are used to make images of your body. You will be given earplugs and earphones to protect your ears since these changing magnetic fields cause loud knocking, thumping, or pinging noises. You will be asked to remain very still while being scanned. To help you keep your body perfectly still, we will put support you with cushions around your body.

5 scans will be performed in a single session with approximately one minute of rest between scans. Each scan lasts about 4 minutes and will never exceed 15 minutes. Your total time in the scanner will be approximately 30 minutes to 40 minutes.

Anthropometric data will be measured after the MRI scans. Both male and female research assistants will be available to perform these tasks. A simple balance test will also be performed immediately before and after the MRI scans. These tasks will require 10 minutes to 20 minutes.

Then, 3-site skinfold test will be performed to measure the body composition. This will take approximately 5 minutes to 10 minutes

Your total time commitment will be approximately 1-2 hours.

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Protocol # 11-292 MR 1111

EXCLUSIONS
- Currently significant episode of low back pain
- Previous medical treatment for low back pain/injury
- Any metal in the body
- Breathing or motion disorder
- Tattoos that contain metal
- Body piercing jewelry that cannot be removed
- Pregnant or possibly pregnant
- Inner ear disorders
- Claustrophobia

RISKS:
- Having unrestrained metal objects brought near the scanner.
- The MRI scanner produces an intermittent loud noise, which some people find annoying.
- Some people experience claustrophobia, and are uncomfortable being in an enclosed place.
- Some people experience dizziness or a metallic taste in their mouth if they move their head rapidly in the magnet
- Brief nausea when being put into or taken out of the scanner

BENEFITS: $80 dollars for two hours participation. Your participation may benefit the research of low back pain with developing the estimation model of lumbar musculoskeletal structure.

WHERE: Auburn University MRI Research Center, 560 Devall Drive, Auburn, AL

CONTACT: Rio (Ruoliang) Tang, (334) 332-7390, rzt0002@tigermail.auburn.edu
Dr. Richard Sesek, (334) 844-1552, sesek@auburn.edu

Appendix C

Iterations for the total ESMM size regression models

## Appendix - C.1: Total ESMM size regression model summaries

| Model Summary | | | | |
|---|---|---|---|---|
| Level | Model | R Square | Adj-R Square | S.E. |
| L3/L4 | 1 | 0.537 | 0.519 | 7.650 |
| | ***2*** | ***0.537*** | ***0.524*** | ***7.614*** |
| L4/L5 | 1 | 0.400 | 0.373 | 7.110 |
| | 2 | 0.400 | 0.380 | 7.070 |
| | ***3*** | ***0.398*** | ***0.385*** | ***7.041*** |
| L5/S1 | 1 | 0.217 | 0.173 | 9.240 |
| | ***2*** | ***0.209*** | ***0.176*** | ***9.223*** |

## Appendix - C.2: Testing accuracy of the total ESMM size regression models

| ANOVA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Model** | | **SS** | **df** | **MS** | **F** | **Sig.** |
| L3/L4 | 1 | Regression | 6935.319 | 4 | 1733.830 | 29.627 | 0.000 |
| | | Residual | 5969.194 | 102 | 58.522 | | |
| | | Total | 12904.513 | 106 | | | |
| | ***2*** | ***Regression*** | ***6933.948*** | ***3*** | ***2311.316*** | ***39.873*** | ***0.000*** |
| | | ***Residual*** | ***5970.565*** | ***103*** | ***57.967*** | | |
| | | ***Total*** | ***12904.513*** | ***106*** | | | |
| L4/L5 | 1 | Regression | 2997.946 | 4 | 749.486 | 14.827 | 0.000 |
| | | Residual | 4498.893 | 89 | 50.549 | | |
| | | Total | 7496.839 | 93 | | | |
| | 2 | Regression | 2997.784 | 3 | 999.261 | 19.989 | 0.000 |
| | | Residual | 4499.055 | 90 | 49.990 | | |
| | | Total | 7496.839 | 93 | | | |
| | ***3*** | ***Regression*** | ***2985.459*** | ***2*** | ***1492.730*** | ***30.110*** | ***0.000*** |
| | | ***Residual*** | ***4511.380*** | ***91*** | ***49.576*** | | |
| | | ***Total*** | ***7496.839*** | ***93*** | | | |
| L5/S1 | ***1*** | Regression | 1681.220 | 4 | 420.305 | 4.923 | 0.001 |
| | | Residual | 6061.396 | 71 | 85.372 | | |
| | | Total | 7742.617 | 75 | | | |
| | ***2*** | ***Regression*** | ***1618.599*** | ***3*** | ***539.533*** | ***6.343*** | ***0.001*** |
| | | ***Residual*** | ***6124.017*** | ***72*** | ***85.056*** | | |
| | | ***Total*** | ***7742.617*** | ***75*** | | | |

## Appendix - C.3: Regression iterations for the total ESMM size

| Coefficients | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Level** | **Model** | | **Uns. Coeff.** | | **St. Coeff.** | **t** | **Sig.** | **Collinearity** | |
| | | | **B** | **St. Err.** | **Beta** | | | **Tolerance** | **VIF** |
| L3/L4 | 1 | Constant | -8.410 | 15.018 | | -0.560 | 0.577 | | |
| | | Gender | 7.184 | 1.867 | 0.327 | 3.849 | 0.000 | 0.628 | 1.592 |
| | | Age | -0.021 | 0.135 | -0.010 | -0.153 | 0.879 | 0.978 | 1.022 |
| | | Height | 0.243 | 0.089 | 0.244 | 2.733 | 0.007 | 0.567 | 1.764 |
| | | Weight | 0.209 | 0.038 | 0.395 | 5.448 | 0.000 | 0.863 | 1.158 |
| | 2 | ***Constant*** | -9.262 | 13.882 | | -0.667 | ***0.506*** | | |
| | | ***Gender*** | 7.146 | 1.841 | 0.325 | 3.882 | ***0.000*** | 0.639 | 1.564 |
| | | ***Height*** | 0.244 | 0.088 | 0.246 | 2.785 | ***0.006*** | 0.575 | 1.738 |
| | | ***Weight*** | 0.209 | 0.038 | 0.394 | 5.474 | ***0.000*** | 0.866 | 1.155 |
| L4/L5 | 1 | Constant | -16.303 | 14.668 | | -1.111 | 0.269 | | |
| | | Gender | 0.920 | 1.851 | 0.051 | 0.497 | 0.620 | 0.630 | 1.587 |
| | | Age | -0.008 | 0.138 | -0.005 | -0.057 | 0.955 | 0.972 | 1.029 |
| | | Height | 0.333 | 0.086 | 0.417 | 3.874 | 0.000 | 0.582 | 1.719 |
| | | Weight | 0.138 | 0.037 | 0.323 | 3.696 | 0.000 | 0.881 | 1.135 |
| | 2 | Constant | -16.613 | 13.531 | | -1.228 | 0.223 | | |
| | | Gender | 0.910 | 1.832 | 0.051 | 0.497 | 0.621 | 0.636 | 1.572 |
| | | Height | 0.333 | 0.085 | 0.418 | 3.935 | 0.000 | 0.591 | 1.691 |
| | | Weight | 0.138 | 0.037 | 0.323 | 3.741 | 0.000 | 0.896 | 1.116 |
| | 3 | ***Constant*** | -20.378 | 11.160 | | -1.826 | ***0.071*** | | |
| | | ***Height*** | 0.358 | 0.069 | 0.449 | 5.224 | ***0.000*** | 0.896 | 1.115 |
| | | ***Weight*** | 0.138 | 0.037 | 0.322 | 3.753 | ***0.000*** | 0.896 | 1.115 |
| L5/S1 | 1 | Constant | -12.249 | 21.361 | | -0.573 | 0.568 | | |
| | | Gender | -6.630 | 2.561 | -0.327 | -2.589 | 0.012 | 0.689 | 1.451 |
| | | Age | -0.170 | 0.199 | -0.091 | -0.856 | 0.395 | 0.969 | 1.032 |
| | | Height | 0.339 | 0.119 | 0.368 | 2.836 | 0.006 | 0.653 | 1.531 |
| | | Weight | 0.135 | 0.056 | 0.265 | 2.387 | 0.020 | 0.893 | 1.120 |
| | 2 | ***Constant*** | -20.300 | 19.146 | | -1.060 | ***0.293*** | | |
| | | ***Gender*** | -6.811 | 2.548 | -0.336 | -2.674 | ***0.009*** | 0.694 | 1.441 |
| | | ***Height*** | 0.356 | 0.117 | 0.388 | 3.034 | ***0.003*** | 0.673 | 1.486 |
| | | ***Weight*** | 0.135 | 0.056 | 0.265 | 2.392 | ***0.019*** | 0.893 | 1.120 |

Appendix D

Iterations for the ESMLA distance regression models

## Appendix - D.1: ESMLA distance regression model summaries

| Model Summary | | | | |
|---|---|---|---|---|
| **Level** | **Model** | **R Square** | **Adj-R Square** | **S.E.** |
| L3/L4 | 1 | 0.458 | 0.437 | 0.390 |
| | 2 | 0.454 | 0.438 | 0.390 |
| | 3 | 0.447 | 0.437 | 0.390 |
| | ***4*** | ***0.437*** | ***0.432*** | ***0.392*** |
| L4/L5 | 1 | 0.447 | 0.422 | 0.365 |
| | 2 | 0.442 | 0.424 | 0.364 |
| | 3 | 0.433 | 0.420 | 0.365 |
| | ***4*** | ***0.415*** | ***0.409*** | ***0.369*** |
| L5/S1 | 1 | 0.398 | 0.364 | 0.364 |
| | 2 | 0.397 | 0.372 | 0.362 |
| | 3 | 0.381 | 0.364 | 0.364 |
| | ***4*** | ***0.356*** | ***0.347*** | ***0.369*** |

## Appendix - D.2: Testing accuracy of the ESMLA distance regression models

| ANOVA | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Level** | **Model** | | **SS** | **df** | **MS** | **F** | **Sig.** |
| L3/L4 | 1 | Regression | 13.106 | 4.000 | 3.276 | 21.545 | 0.000 |
| | | Residual | 15.512 | 102.000 | 0.152 | | |
| | | Total | 28.618 | 106.000 | | | |
| | *2* | Regression | 12.982 | 3.000 | 4.327 | 28.508 | 0.000 |
| | | Residual | 15.635 | 103.000 | 0.152 | | |
| | | Total | 28.618 | 106.000 | | | |
| | 3 | Regression | 12.802 | 2.000 | 6.401 | 42.091 | 0.000 |
| | | Residual | 15.816 | 104.000 | 0.152 | | |
| | | Total | 28.618 | 106.000 | | | |
| | *4* | ***Regression*** | ***12.509*** | ***1.000*** | ***12.509*** | ***81.539*** | ***0.000*** |
| | | ***Residual*** | ***16.108*** | ***105.000*** | ***0.153*** | | |
| | | ***Total*** | ***28.618*** | ***106.000*** | | | |
| L4/L5 | 1 | Regression | 9.548 | 4.000 | 2.387 | 17.956 | 0.000 |
| | | Residual | 11.832 | 89.000 | 0.133 | | |
| | | Total | 21.380 | 93.000 | | | |
| | *2* | Regression | 9.458 | 3.000 | 3.153 | 23.797 | 0.000 |
| | | Residual | 11.923 | 90.000 | 0.132 | | |
| | | Total | 21.380 | 93.000 | | | |
| | 3 | Regression | 9.257 | 2.000 | 4.628 | 34.741 | 0.000 |
| | | Residual | 12.124 | 91.000 | 0.133 | | |
| | | Total | 21.380 | 93.000 | | | |
| | *4* | ***Regression*** | ***8.882*** | ***1.000*** | ***8.882*** | ***65.376*** | ***0.000*** |
| | | ***Residual*** | ***12.499*** | ***92.000*** | ***0.136*** | | |
| | | ***Total*** | ***21.380*** | ***93.000*** | | | |
| L5/S1 | 1 | Regression | 6.211 | 4.000 | 1.553 | 11.719 | 0.000 |
| | | Residual | 9.407 | 71.000 | 0.132 | | |
| | | Total | 15.617 | 75.000 | | | |
| | *2* | Regression | 6.199 | 3.000 | 2.066 | 15.799 | 0.000 |
| | | Residual | 9.418 | 72.000 | 0.131 | | |
| | | Total | 15.617 | 75.000 | | | |
| | 3 | Regression | 5.944 | 2.000 | 2.972 | 22.427 | 0.000 |
| | | Residual | 9.674 | 73.000 | 0.133 | | |
| | | Total | 15.617 | 75.000 | | | |
| | *4* | ***Regression*** | ***5.554*** | ***1.000*** | ***5.554*** | ***40.841*** | ***0.000*** |
| | | ***Residual*** | ***10.063*** | ***74.000*** | ***0.136*** | | |
| | | ***Total*** | ***15.617*** | ***75.000*** | | | |

## Appendix - D.3: Regression iterations for the ESMLA distance

| Coefficients | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Level | Model | | Uns. Coeff. | | St. Coeff. | t | Sig. | Collinearity | |
| | | | B | St. Err. | Beta | | | Tolerance | VIF |
| L3/L4 | *1* | Constant | 0.399 | 0.766 | | 0.521 | 0.603 | | |
| | | Gender | 0.123 | 0.095 | 0.119 | 1.295 | 0.198 | 0.628 | 1.592 |
| | | Age | 0.006 | 0.007 | 0.066 | 0.902 | 0.369 | 0.978 | 1.022 |
| | | Height | 0.026 | 0.005 | 0.563 | 5.810 | 0.000 | 0.567 | 1.764 |
| | | Weight | 0.002 | 0.002 | 0.082 | 1.039 | 0.301 | 0.863 | 1.158 |
| | *2* | Constant | 0.655 | 0.710 | | 0.922 | 0.359 | | |
| | | Gender | 0.135 | 0.094 | 0.130 | 1.429 | 0.156 | 0.639 | 1.564 |
| | | Height | 0.026 | 0.004 | 0.552 | 5.748 | 0.000 | 0.575 | 1.738 |
| | | Weight | 0.002 | 0.002 | 0.085 | 1.090 | 0.278 | 0.866 | 1.155 |
| | *3* | Constant | 0.560 | 0.706 | | 0.794 | 0.429 | | |
| | | Gender | 0.131 | 0.094 | 0.126 | 1.387 | 0.168 | 0.640 | 1.562 |
| | | Height | 0.027 | 0.004 | 0.585 | 6.426 | 0.000 | 0.640 | 1.562 |
| | *4* | ***Constant*** | 0.016 | 0.589 | | 0.027 | ***0.978*** | | |
| | | ***Height*** | 0.031 | 0.003 | 0.661 | 9.030 | ***0.000*** | 1.000 | 1.000 |
| L4/L5 | *1* | Constant | 0.770 | 0.752 | | 1.024 | 0.309 | | |
| | | Gender | 0.146 | 0.095 | 0.153 | 1.541 | 0.127 | 0.630 | 1.587 |
| | | Age | 0.009 | 0.007 | 0.106 | 1.326 | 0.188 | 0.972 | 1.029 |
| | | Height | 0.025 | 0.004 | 0.580 | 5.608 | 0.000 | 0.582 | 1.719 |
| | | Weight | -0.002 | 0.002 | -0.069 | -0.826 | 0.411 | 0.881 | 1.135 |
| | *2* | Constant | 0.837 | 0.747 | | 1.120 | 0.266 | | |
| | | Gender | 0.148 | 0.095 | 0.155 | 1.560 | 0.122 | 0.631 | 1.586 |
| | | Height | 0.009 | 0.007 | 0.097 | 1.231 | 0.222 | 0.989 | 1.011 |
| | | Weight | 0.024 | 0.004 | 0.556 | 5.609 | 0.000 | 0.630 | 1.587 |
| | *3* | Constant | 1.172 | 0.697 | | 1.681 | 0.096 | | |
| | | Gender | 0.159 | 0.095 | 0.166 | 1.678 | 0.097 | 0.636 | 1.572 |
| | | Height | 0.023 | 0.004 | 0.544 | 5.500 | 0.000 | 0.636 | 1.572 |
| | *4* | ***Constant*** | 0.515 | 0.583 | | 0.884 | ***0.379*** | | |
| | | ***Height*** | 0.027 | 0.003 | 0.645 | 8.086 | ***0.000*** | 1.000 | 1.000 |
| L5/S1 | *1* | Constant | 1.596 | 0.841 | | 1.897 | 0.062 | | |
| | | Gender | 0.153 | 0.101 | 0.168 | 1.517 | 0.134 | 0.689 | 1.451 |
| | | Age | 0.002 | 0.008 | 0.027 | 0.291 | 0.772 | 0.969 | 1.032 |
| | | Height | 0.019 | 0.005 | 0.467 | 4.098 | 0.000 | 0.653 | 1.531 |
| | | Weight | 0.003 | 0.002 | 0.135 | 1.389 | 0.169 | 0.893 | 1.120 |
| | *2* | Constant | 1.704 | 0.751 | | 2.269 | 0.026 | | |
| | | Gender | 0.155 | 0.100 | 0.171 | 1.556 | 0.124 | 0.694 | 1.441 |
| | | Height | 0.019 | 0.005 | 0.461 | 4.136 | 0.000 | 0.673 | 1.486 |
| | | Weight | 0.003 | 0.002 | 0.135 | 1.398 | 0.166 | 0.893 | 1.120 |
| | *3* | Constant | 1.712 | 0.756 | | 2.265 | 0.026 | | |
| | | Gender | 0.171 | 0.100 | 0.188 | 1.715 | 0.091 | 0.703 | 1.422 |
| | | Height | 0.020 | 0.005 | 0.494 | 4.495 | 0.000 | 0.703 | 1.422 |
| | *4* | ***Constant*** | 1.063 | 0.663 | | 1.604 | ***0.113*** | | |
| | | ***Height*** | 0.025 | 0.004 | 0.596 | 6.391 | ***0.000*** | 1.000 | 1.000 |

# Appendix E

## Data collection form

# Low Back MRI Study Data Collection Form

| | | | | | |
|---|---|---|---|---|---|
| Subject # | | Date | | Researcher | |
| | | | | | |
| Age | | Gender | ☐ Male | ☐ Female | |
| Physical Activity (check the corresponding box) | | | | | |
| ☐Yes ☐No | Do you regularly perform weight lifting or any resistance exercise? | | | | |
| | If yes, how often | | | | |
| | ☐ Everyday | | ☐ Every 2 to 3 days | | ☐ Every week |
| Notes --> | | | | | |
| ☐Yes ☐No | Do you regularly perform cardiovascular exercise? | | | | |
| | If yes, how often | | | | |
| | ☐ Everyday | | ☐ Every 2 to 3 days | | ☐ Every week |
| Notes --> | | | | | |
| Anthropometry Data | | | | | |
| Dominant Side | ☐ Right | | ☐ Left | | ☐ Ambidexterous |
| | | | | | |
| Standing Height | | | Weight | | |
| | | | | | |
| Sitting HT | | | Shoulder Width | | |
| | | | | | |
| Head Width | | | Chest Breadth | | |
| Head Circumference | | | Chest Depth | | |
| Head Depth | | | Notes --> | | |
| | | | | | |
| | **Right** | **Left** | | **Right** | **Left** |
| Elbow Width | | | Knee Width | | |
| Elbow Circumference | | | Knee Circumference | | |
| Notes --> | | | Notes --> | | |
| Wrist Width | | | Ankle Width | | |
| Wrist Circumference | | | Ankle Circumference | | |
| Notes --> | | | | | |
| Hand Length | | | Arm Length | | |
| Hand Width | | | Notes --> | | |
| Hand Circumference | | | | | |
| Notes --> | | | | | |
| 3-Site Skinfold Test | | | | | |
| **Male** | | | | | |
| Chest | | Abdominal | | Thigh | |
| **Female** | | | | | |
| Tricep | | Suprailiac | | Thigh | |
| Notes --> | | | | | |

# Appendix F

## Best subset regression models for the CSA of the total ESMM

## Appendix - F.1: Best subset regression models for the CSA of the total ESMM at the L3/L4 level

| Variable | | | | | | | | | | | | | | | Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender | Height | Weight | Sitting Height | Shoulder Width | Fat-free Weight | Arm Length | Head | Chest | Elbow | Wrist | Knee | Ankle | Hand | Intercept | # of Parameters | Mallows' Cp | $R^2$ | Adj. $R^2$ | $s\ (=\sqrt{MSE})$ |
| | | | | | X | | | | | | | | | X | 2 | 12.3 | 0.739 | 0.732 | 6.409 |
| | | | | | | | | | | | | X | | X | 2 | 23.5 | 0.672 | 0.662 | 7.192 |
| | | X | | | | | | | | | | | | X | 2 | 26.3 | 0.655 | 0.644 | 7.376 |
| | | | | X | | | | | | | | | | X | 2 | 26.9 | 0.652 | 0.641 | 7.412 |
| | | | | | | | | | | | | | X | X | 2 | 35.9 | 0.597 | 0.585 | 7.971 |
| | | | | | X | | | | | | | X | | X | 3 | 9.4 | 0.768 | 0.754 | 6.136 |
| | | | | | X | | | X | | | | | | X | 3 | 12.8 | 0.748 | 0.733 | 6.397 |
| | | | | X | X | | | | | | | | | X | 3 | 13.2 | 0.746 | 0.730 | 6.428 |
| X | | | | | X | | | | | | | | | X | 3 | 13.4 | 0.745 | 0.729 | 6.440 |
| | X | | | | X | | | | | | | | | X | 3 | 13.4 | 0.744 | 0.729 | 6.446 |
| | | | | | ***X*** | | | | | ***X*** | | ***X*** | | ***X*** | ***4**** | ***6.6*** | ***0.797*** | ***0.778*** | ***5.832*** |
| | X | | | | X | | | | | | | X | | X | 4 | 9.0 | 0.783 | 0.762 | 6.029 |
| | | | | | X | | X | | | | | X | | X | 4 | 9.2 | 0.782 | 0.761 | 6.049 |
| | | | X | | X | | | | | | | X | | X | 4 | 9.8 | 0.778 | 0.757 | 6.099 |
| | | | | | X | | | X | | | | X | | X | 4 | 10.1 | 0.776 | 0.755 | 6.126 |
| | | | | | ***X*** | | ***X*** | | | ***X*** | | ***X*** | | ***X*** | ***5**** | ***5.4*** | ***0.817*** | ***0.793*** | ***5.634*** |
| | | X | | | X | | | | | X | | X | | X | 5 | 7.1 | 0.807 | 0.781 | 5.790 |
| | | | | | X | | | X | | X | | X | | X | 5 | 7.3 | 0.806 | 0.780 | 5.807 |
| | | | | X | X | | | | | X | | X | | X | 5 | 7.4 | 0.805 | 0.779 | 5.817 |
| | X | | | | X | | | | | X | | X | | X | 5 | 8.0 | 0.801 | 0.775 | 5.871 |
| | | | | ***X*** | ***X*** | | ***X*** | | | ***X*** | | ***X*** | | ***X*** | ***6**** | ***4.4*** | ***0.835*** | ***0.807*** | ***5.440*** |
| | | X | | | X | | X | | | X | | X | | X | 6 | 6.1 | 0.825 | 0.795 | 5.606 |
| | | | | | X | | X | X | | X | | X | | X | 6 | 6.6 | 0.822 | 0.791 | 5.655 |
| | X | | | | X | X | | | | X | | X | | X | 6 | 6.8 | 0.820 | 0.789 | 5.677 |
| X | | | | | X | | X | | | X | | X | | X | 6 | 7.0 | 0.819 | 0.788 | 5.696 |
| | | X | | X | X | | X | | | X | | X | | X | 7 | 5.3 | 0.842 | 0.808 | 5.426 |
| | | | | X | X | | X | X | | X | | X | | X | 7 | 5.8 | 0.839 | 0.804 | 5.476 |
| | X | | | X | X | | X | | | X | | X | | X | 7 | 6.1 | 0.837 | 0.802 | 5.509 |
| X | | | | X | X | | X | | | X | | X | | X | 7 | 6.1 | 0.837 | 0.802 | 5.511 |
| | | | | X | X | | X | | | X | | X | X | X | 7 | 6.3 | 0.835 | 0.800 | 5.530 |
| | | X | | X | X | | X | | | X | X | X | | X | 8 | 6.3 | 0.847 | 0.808 | 5.423 |
| | | X | X | X | X | | X | | | X | | X | | X | 8 | 6.8 | 0.844 | 0.804 | 5.477 |
| | | X | | X | X | | X | | | X | | X | X | X | 8 | 6.9 | 0.844 | 0.804 | 5.480 |
| | | X | | X | X | | X | | X | X | | X | | X | 8 | 7.1 | 0.843 | 0.802 | 5.505 |
| | X | | | X | X | X | X | | | X | | X | | X | 8 | 7.1 | 0.843 | 0.802 | 5.509 |
| | X | | X | X | X | X | X | | | X | | X | | X | 9 | 6.7 | 0.857 | 0.813 | 5.345 |
| | X | | | X | X | X | X | | | X | | X | X | X | 9 | 7.7 | 0.851 | 0.806 | 5.452 |
| | | X | | X | X | | X | | | X | X | X | X | X | 9 | 7.7 | 0.851 | 0.805 | 5.458 |
| | X | X | X | X | X | | X | | | X | | X | | X | 9 | 7.8 | 0.851 | 0.805 | 5.470 |
| | | X | | X | X | | X | | X | X | X | X | | X | 9 | 7.9 | 0.850 | 0.804 | 5.476 |
| | X | | X | X | X | X | X | | | X | | X | X | X | 10 | 7.7 | 0.863 | 0.814 | 5.334 |
| | X | | X | X | X | X | X | X | | X | | X | | X | 10 | 8.3 | 0.860 | 0.810 | 5.399 |
| | X | X | X | X | X | X | X | | | X | | X | | X | 10 | 8.4 | 0.859 | 0.809 | 5.413 |
| | X | | X | X | X | X | X | | | X | X | X | | X | 10 | 8.6 | 0.858 | 0.807 | 5.434 |
| | X | | X | X | X | X | X | | X | X | | X | | X | 10 | 8.6 | 0.858 | 0.807 | 5.440 |
| | X | | X | X | X | X | X | X | | X | | X | X | X | 11 | 9.1 | 0.867 | 0.812 | 5.370 |
| | X | X | X | X | X | X | X | | | X | | X | X | X | 11 | 9.2 | 0.866 | 0.810 | 5.387 |
| | X | X | X | X | X | X | X | | | X | X | X | | X | 11 | 9.4 | 0.865 | 0.809 | 5.406 |
| | X | | X | X | X | X | X | | X | X | | X | X | X | 11 | 9.5 | 0.864 | 0.808 | 5.423 |
| | X | | X | X | X | X | X | | | X | X | X | X | X | 11 | 9.6 | 0.864 | 0.807 | 5.430 |
| | X | X | X | X | X | X | X | | | X | X | X | X | X | 12 | 10.1 | 0.873 | 0.812 | 5.362 |
| | X | | X | X | X | X | X | X | X | X | | X | X | X | 12 | 10.7 | 0.870 | 0.807 | 5.432 |
| | X | X | X | X | X | X | X | | X | X | | X | X | X | 12 | 10.7 | 0.869 | 0.807 | 5.437 |
| | X | X | X | X | X | X | X | | X | X | X | X | | X | 12 | 10.8 | 0.869 | 0.806 | 5.445 |
| | X | | X | X | X | X | X | X | | X | X | X | X | X | 12 | 10.8 | 0.869 | 0.806 | 5.445 |
| | X | X | X | X | X | X | X | | X | X | X | X | X | X | 13 | 11.1 | 0.879 | 0.813 | 5.348 |
| | X | X | X | X | X | X | X | X | | X | X | X | X | X | 13 | 12.0 | 0.873 | 0.804 | 5.475 |
| X | X | X | X | X | X | X | X | | | X | X | X | X | X | 13 | 12.1 | 0.873 | 0.804 | 5.482 |
| | X | | X | X | X | X | X | X | X | X | X | X | X | X | 13 | 12.3 | 0.871 | 0.801 | 5.513 |
| | X | X | X | X | X | X | X | X | X | X | | X | X | X | 13 | 12.4 | 0.871 | 0.801 | 5.525 |
| | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.880 | 0.805 | 5.464 |
| X | X | X | X | X | X | X | X | | X | X | X | X | X | X | 14 | 13.1 | 0.879 | 0.804 | 5.471 |
| X | X | X | X | X | X | X | X | X | | X | X | X | X | X | 14 | 14.0 | 0.873 | 0.795 | 5.601 |
| X | X | | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 14.3 | 0.872 | 0.792 | 5.636 |
| X | X | X | X | X | X | X | X | X | X | X | | X | X | X | 14 | 14.4 | 0.871 | 0.791 | 5.655 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.880 | 0.795 | 5.598 |

## Appendix - F.2: Best subset regression models for the CSA of the total ESMM at the L4/L5 level

| Variable | | | | | | | | | | | | | | | Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender | Height | Weight | Sitting Height | Shoulder Width | Fat-free Weight | Arm Length | Head | Chest | Elbow | Wrist | Knee | Ankle | Hand | Intercept | # of Parameters | Mallows' Cp | $R^2$ | Adj. $R^2$ | s $(=\sqrt{MSE})$ |
| | | | | | | | | | | | | X | | X | 2 | 21.7 | 0.619 | 0.607 | 6.852 |
| | | | | | X | | | | | | | | | X | 2 | 22.1 | 0.616 | 0.604 | 6.877 |
| | | X | | | | | | | | | | | | X | 2 | 30.0 | 0.559 | 0.546 | 7.370 |
| | | | | X | | | | | | | | | | X | 2 | 30.4 | 0.556 | 0.542 | 7.399 |
| | | | | | | | | | | X | | | | X | 2 | 42.5 | 0.468 | 0.452 | 8.951 |
| | | | | | X | | | | | | | X | | X | 3 | 16.9 | 0.668 | 0.647 | 6.493 |
| | | | | X | | | | | | | | X | | X | 3 | 19.1 | 0.652 | 0.631 | 6.646 |
| | | | | | X | | | X | | | | | | X | 3 | 20.3 | 0.644 | 0.621 | 6.728 |
| | | X | | | | | | | | | | X | | X | 3 | 20.3 | 0.644 | 0.621 | 6.728 |
| | | | | | | | | | | X | | X | | X | 3 | 22.1 | 0.631 | 0.607 | 6.851 |
| | | | | | X | | | | | X | | X | | X | 4 | 10.7 | 0.727 | 0.701 | 5.981 |
| | | | | X | | | | | | X | | X | | X | 4 | 14.3 | 0.701 | 0.672 | 6.258 |
| X | | | | | X | | | | | | | X | | X | 4 | 14.6 | 0.699 | 0.670 | 6.282 |
| | | | | | X | | | X | | | | X | | X | 4 | 15.4 | 0.694 | 0.664 | 6.340 |
| | | | | | X | | | | | | | X | X | X | 4 | 15.5 | 0.693 | 0.663 | 6.347 |
| | | | | | X | | X | | | X | | X | | X | 5 | 9.0 | 0.754 | 0.722 | 5.769 |
| | | | | | X | | | X | | X | | X | | X | 5 | 9.1 | 0.753 | 0.721 | 5.780 |
| X | | | | | X | | | | | X | | X | | X | 5 | 9.5 | 0.750 | 0.717 | 5.817 |
| | | | | | X | | | X | | | | X | X | X | 5 | 10.4 | 0.744 | 0.710 | 5.887 |
| | | | | X | X | | | | | X | | X | | X | 5 | 11.2 | 0.738 | 0.703 | 5.956 |
| | | | | ***X*** | ***X*** | | ***X*** | | | ***X*** | | ***X*** | | ***X*** | ***6**** | ***7.4*** | ***0.780*** | ***0.742*** | ***5.550*** |
| X | | | | | X | | | X | | X | | X | | X | 6 | 8.3 | 0.774 | 0.735 | 5.634 |
| | | | | | X | | X | X | | X | | X | | X | 6 | 8.3 | 0.773 | 0.734 | 5.638 |
| | | | | | X | | | X | | X | | X | X | X | 6 | 8.9 | 0.770 | 0.730 | 5.684 |
| X | | | | | X | | X | | | X | | X | | X | 6 | 8.9 | 0.769 | 0.729 | 5.689 |
| ***X*** | | | | ***X*** | ***X*** | | ***X*** | | | ***X*** | | ***X*** | | ***X*** | ***7**** | ***7.0*** | ***0.797*** | ***0.754*** | ***5.423*** |
| | | | | ***X*** | ***X*** | | ***X*** | ***X*** | | ***X*** | | ***X*** | | ***X*** | ***7**** | ***7.2*** | ***0.796*** | ***0.752*** | ***5.441*** |
| | | | | X | X | | X | | | X | | X | X | X | 7 | 7.5 | 0.794 | 0.750 | 5.470 |
| | | | | | X | | X | X | | X | | X | X | X | 7 | 7.8 | 0.792 | 0.747 | 5.518 |
| X | | | | X | X | | | X | | X | | X | | X | 7 | 8.3 | 0.788 | 0.742 | 5.552 |
| | | | | ***X*** | ***X*** | | ***X*** | ***X*** | | ***X*** | | ***X*** | ***X*** | ***X*** | ***8**** | ***5.0*** | ***0.826*** | ***0.781*** | ***5.116*** |
| X | | | | X | X | | X | X | | X | | X | | X | 8 | 7.0 | 0.812 | 0.763 | 5.319 |
| | | | | X | X | X | X | | | X | | X | X | X | 8 | 7.0 | 0.812 | 0.763 | 5.320 |
| X | | X | | X | X | | X | | | X | | X | | X | 8 | 7.6 | 0.807 | 0.757 | 5.385 |
| | | X | | X | X | | X | | | X | | X | X | X | 8 | 7.9 | 0.805 | 0.755 | 5.414 |
| | | | | X | X | X | X | X | | X | | X | X | X | 9 | 5.5 | 0.837 | 0.787 | 5.441 |
| X | | | | X | X | | X | X | | X | | X | X | X | 9 | 6.3 | 0.831 | 0.779 | 5.137 |
| | | X | | X | X | X | X | | | X | | X | X | X | 9 | 6.7 | 0.829 | 0.776 | 5.174 |
| | X | | | X | X | | X | X | | X | | X | X | X | 9 | 6.7 | 0.829 | 0.776 | 5.177 |
| | | | | X | X | | X | X | X | X | | X | X | X | 9 | 6.9 | 0.827 | 0.774 | 5.238 |
| | X | | | X | X | X | X | X | | X | | X | X | X | 10 | 6.7 | 0.843 | 0.787 | 5.518 |
| X | | | | X | X | X | X | X | | X | | X | X | X | 10 | 7.0 | 0.841 | 0.784 | 5.869 |
| | | | X | X | X | X | X | X | | X | | X | X | X | 10 | 7.0 | 0.841 | 0.783 | 5.915 |
| X | | X | | X | X | X | X | | | X | | X | X | X | 10 | 7.1 | 0.840 | 0.783 | 5.938 |
| | | X | | X | X | X | X | X | | X | | X | X | X | 10 | 7.2 | 0.839 | 0.781 | 5.112 |
| X | X | | | X | X | X | X | X | | X | | X | X | X | 11 | 7.7 | 0.850 | 0.788 | 5.328 |
| X | | X | | X | X | X | X | X | | X | | X | X | X | 11 | 8.3 | 0.846 | 0.781 | 5.114 |
| X | X | X | | X | X | X | X | | | X | | X | X | X | 11 | 8.4 | 0.845 | 0.781 | 5.122 |
| X | | | X | X | X | X | X | X | | X | | X | X | X | 11 | 8.4 | 0.845 | 0.781 | 5.122 |
| | X | | | X | X | X | X | X | X | X | | X | X | X | 11 | 8.5 | 0.844 | 0.780 | 5.133 |
| X | X | | | X | X | X | X | X | X | X | | X | X | X | 12 | 9.4 | 0.853 | 0.782 | 5.145 |
| X | X | X | | X | X | X | X | X | | X | | X | X | X | 12 | 9.5 | 0.852 | 0.781 | 5.122 |
| X | X | | | X | X | X | X | X | | X | X | X | X | X | 12 | 9.6 | 0.851 | 0.780 | 5.133 |
| X | X | | X | X | X | X | X | X | | X | | X | X | X | 12 | 9.7 | 0.850 | 0.779 | 5.141 |
| X | | X | | X | X | X | X | X | X | X | | X | X | X | 12 | 9.9 | 0.849 | 0.776 | 5.173 |
| X | X | X | | X | X | X | X | X | X | X | | X | X | X | 13 | 11.0 | 0.855 | 0.776 | 5.175 |
| X | X | | | X | X | X | X | X | X | X | X | X | X | X | 13 | 11.3 | 0.853 | 0.773 | 5.210 |
| X | X | | X | X | X | X | X | X | X | X | | X | X | X | 13 | 11.4 | 0.853 | 0.772 | 5.219 |
| X | X | X | X | X | X | X | X | X | | X | | X | X | X | 13 | 11.5 | 0.852 | 0.771 | 5.237 |
| X | X | X | | X | X | X | X | X | | X | X | X | X | X | 13 | 11.5 | 0.852 | 0.771 | 5.237 |
| X | X | X | | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.855 | 0.766 | 5.293 |
| X | X | X | X | X | X | X | X | X | X | X | | X | X | X | 14 | 13.0 | 0.855 | 0.765 | 5.296 |
| X | X | | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.3 | 0.853 | 0.762 | 5.333 |
| X | X | X | X | X | X | X | X | X | | X | X | X | X | X | 14 | 13.5 | 0.852 | 0.760 | 5.361 |
| X | | X | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.6 | 0.851 | 0.759 | 5.369 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.855 | 0.754 | 5.423 |

# Appendix - F.3: Best subset regression models for the CSA of the total ESMM at the L5/S1 level

| Variable | | | | | | | | | | | | | | | Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender | Height | Weight | Sitting Height | Shoulder Width | Fat-free Weight | Arm Length | Head | Chest | Elbow | Wrist | Knee | Ankle | Hand | Intercept | # of Parameters | Mallows' Cp | $R^2$ | Adj. $R^2$ | s ($=\sqrt{MSE}$) |
| | | | | | | | X | | | | | | | X | 2 | 21.9 | 0.310 | 0.289 | 8.444 |
| | | | | | | | | | | | | X | | X | 2 | 22.0 | 0.308 | 0.287 | 8.453 |
| | | | | X | | | | | | | | | | X | 2 | 24.9 | 0.271 | 0.249 | 8.679 |
| | | | | | X | | | | | | | | | X | 2 | 27.2 | 0.241 | 0.218 | 8.857 |
| | X | | | | | | | | | | | | | X | 2 | 28.3 | 0.226 | 0.203 | 8.940 |
| | | | | | | | | | | X | | X | | X | 3 | 17.7 | 0.390 | 0.352 | 8.624 |
| | | | | | | | | | | | | X | X | X | 3 | 18.5 | 0.380 | 0.341 | 8.126 |
| X | | | | | | | | | | | | X | | X | 3 | 19.4 | 0.368 | 0.329 | 8.248 |
| | | | | | | | X | | | | | X | | X | 3 | 21.2 | 0.344 | 0.303 | 8.359 |
| X | | | | | | | X | | | | | | | X | 3 | 21.4 | 0.342 | 0.301 | 8.374 |
| | | | | X | | | | | | | | X | X | X | 4 | 13.1 | 0.477 | 0.426 | 7.584 |
| | | | | X | | | | | | X | | X | | X | 4 | 13.3 | 0.473 | 0.423 | 7.694 |
| X | | | | | | | X | | | | | X | | X | 4 | 14.6 | 0.457 | 0.404 | 7.728 |
| | X | | | | | | | | | X | | X | | X | 4 | 15.2 | 0.449 | 0.396 | 7.781 |
| | | | | | | | X | | | X | | X | | X | 4 | 15.5 | 0.445 | 0.392 | 7.896 |
| X | | | | X | | | | | | X | | X | | X | 5 | 10.0 | 0.543 | 0.482 | 7.268 |
| | | | | X | | | | | | X | | X | X | X | 5 | 10.7 | 0.534 | 0.472 | 7.274 |
| | X | | | | | X | | | | X | | X | | X | 5 | 12.0 | 0.517 | 0.452 | 7.412 |
| X | | | | | | | X | | | X | | X | | X | 5 | 12.1 | 0.516 | 0.451 | 7.416 |
| X | | | | X | | | | | | | | X | X | X | 5 | 12.2 | 0.514 | 0.450 | 7.428 |
| X | | | | X | | | | | | X | | X | X | X | 6 | 9.7 | 0.574 | 0.500 | 7.805 |
| | X | | | | | X | | | | X | X | X | | X | 6 | 9.7 | 0.573 | 0.499 | 7.884 |
| | X | | | X | | | | | | X | | X | X | X | 6 | 9.8 | 0.572 | 0.499 | 7.909 |
| X | | | | X | | | X | | | X | | X | | X | 6 | 9.8 | 0.571 | 0.497 | 7.984 |
| X | | | | X | | | | | | X | X | X | | X | 6 | 10.2 | 0.567 | 0.492 | 7.135 |
| | X | | | X | | | | | | X | X | X | X | X | 7 | 8.1 | 0.620 | 0.539 | 6.798 |
| | X | | | X | | X | | | | X | X | X | | X | 7 | 8.2 | 0.618 | 0.537 | 6.817 |
| | X | X | | | X | X | | | | X | | X | | X | 7 | 9.1 | 0.608 | 0.523 | 6.913 |
| X | X | | | X | | X | | | | X | | X | | X | 7 | 9.2 | 0.605 | 0.521 | 6.932 |
| X | | | | X | | | | | | X | X | X | X | X | 7 | 9.4 | 0.604 | 0.519 | 6.947 |
| ***X*** | ***X*** | | | ***X*** | | ***X*** | | | | ***X*** | ***X*** | ***X*** | | ***X*** | ***8**** | ***6.3*** | ***0.670*** | ***0.584*** | ***6.455*** |
| ***X*** | ***X*** | ***X*** | | | ***X*** | ***X*** | | | | ***X*** | | ***X*** | | ***X*** | ***8**** | ***7.1*** | ***0.659*** | ***0.571*** | ***6.560*** |
| X | X | | | X | | | | | | X | X | X | X | X | 8 | 7.2 | 0.658 | 0.569 | 6.576 |
| | X | X | | X | X | | | | | X | | X | X | X | 8 | 8.3 | 0.643 | 0.551 | 6.712 |
| X | | X | | X | X | | | | | X | | X | X | X | 8 | 8.5 | 0.641 | 0.548 | 6.733 |
| ***X*** | ***X*** | ***X*** | | ***X*** | ***X*** | ***X*** | | | | ***X*** | | ***X*** | | ***X*** | ***9**** | ***6.0*** | ***0.700*** | ***0.608*** | ***6.268*** |
| X | X | X | | X | X | | | | | X | | X | X | X | 9 | 6.5 | 0.693 | 0.599 | 6.342 |
| X | X | | | X | | X | | | | X | X | X | X | X | 9 | 7.7 | 0.677 | 0.578 | 6.539 |
| X | | X | X | X | X | | | | | X | | X | X | X | 9 | 7.7 | 0.677 | 0.578 | 6.560 |
| X | X | | | X | X | X | | | | X | X | X | | X | 9 | 8.1 | 0.673 | 0.572 | 6.550 |
| X | X | X | | X | X | X | | | | X | | X | X | X | 10 | 6.6 | 0.718 | 0.617 | 6.240 |
| X | X | X | | X | X | | | | X | X | | X | X | X | 10 | 7.0 | 0.713 | 0.610 | 6.257 |
| X | X | X | | X | X | X | | | X | X | | X | | X | 10 | 7.1 | 0.712 | 0.608 | 6.268 |
| X | X | X | | X | X | X | | | | X | X | X | | X | 10 | 7.5 | 0.706 | 0.600 | 6.335 |
| X | X | X | | X | X | X | | X | | X | | X | | X | 10 | 7.7 | 0.704 | 0.598 | 6.352 |
| X | X | X | | X | X | X | | | X | X | | X | X | X | 11 | 7.3 | 0.734 | 0.624 | 6.142 |
| X | X | X | | X | X | X | | | | X | X | X | X | X | 11 | 8.3 | 0.722 | 0.607 | 6.281 |
| X | X | X | | X | X | X | | X | | X | | X | X | X | 11 | 8.4 | 0.720 | 0.604 | 6.320 |
| X | X | X | X | X | X | X | | | | X | | X | X | X | 11 | 8.4 | 0.720 | 0.604 | 6.338 |
| X | X | X | | X | X | X | X | | | X | | X | X | X | 11 | 8.6 | 0.718 | 0.601 | 6.325 |
| X | X | X | | X | X | X | | X | X | X | | X | X | X | 12 | 9.2 | 0.737 | 0.611 | 6.247 |
| X | X | X | | X | X | X | | | X | X | X | X | X | X | 12 | 9.2 | 0.736 | 0.609 | 6.259 |
| X | X | X | X | X | X | X | | | X | X | | X | X | X | 12 | 9.3 | 0.736 | 0.609 | 6.260 |
| X | X | X | | X | X | X | X | | X | X | | X | X | X | 12 | 9.3 | 0.735 | 0.608 | 6.272 |
| X | X | X | X | X | X | X | | | | X | X | X | X | X | 12 | 10.1 | 0.725 | 0.593 | 6.390 |
| X | X | X | X | X | X | X | | X | X | X | | X | X | X | 13 | 11.1 | 0.738 | 0.595 | 6.369 |
| X | X | X | | X | X | X | | X | X | X | X | X | X | X | 13 | 11.1 | 0.737 | 0.594 | 6.379 |
| X | X | X | | X | X | X | X | X | X | X | | X | X | X | 13 | 11.1 | 0.737 | 0.593 | 6.384 |
| X | X | X | X | X | X | X | | | X | X | X | X | X | X | 13 | 11.2 | 0.737 | 0.593 | 6.385 |
| X | X | X | | X | X | X | X | | X | X | X | X | X | X | 13 | 11.2 | 0.736 | 0.592 | 6.398 |
| X | X | X | X | X | X | X | | X | X | X | X | X | X | X | 14 | 13.0 | 0.739 | 0.577 | 6.510 |
| X | X | X | X | X | X | X | X | X | X | X | | X | X | X | 14 | 13.1 | 0.738 | 0.576 | 6.519 |
| X | X | X | | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.1 | 0.738 | 0.575 | 6.527 |
| X | X | X | X | X | X | X | X | | X | X | X | X | X | X | 14 | 13.1 | 0.737 | 0.574 | 6.535 |
| X | X | X | X | X | X | X | X | X | | X | X | X | X | X | 14 | 14.0 | 0.726 | 0.557 | 6.668 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.739 | 0.556 | 6.671 |

# Appendix G

## Best subset regression models for the ESMLA distance

# Appendix - G.1: Best subset regression models for the ESMLA distance at the L3/L4 level

| **Variable** | | | | | | | | | | | | | | | **Statistics** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gender** | **Height** | **Weight** | **Sitting Height** | **Shoulder Width** | **Fat-free Weight** | **Arm Length** | **Head** | **Chest** | **Elbow** | **Wrist** | **Knee** | **Ankle** | **Hand** | **Intercept** | **# of Parameters** | **Mallows' Cp** | **$R^2$** | **Adj. $R^2$** | **s ($=\sqrt{MSE}$)** |
| | | | | | | | | | | | | X | | X | 2 | 28.6 | 0.737 | 0.729 | 0.237 |
| | | | | | | | | | | X | | | | X | 2 | 42.3 | 0.677 | 0.667 | 0.263 |
| | | | | X | | | | | | | | | | X | 2 | 44.8 | 0.666 | 0.656 | 0.267 |
| | X | | | | | | | | | | | | | X | 2 | 48.4 | 0.650 | 0.640 | 0.273 |
| | | | | | X | | | | | | | | | X | 2 | 50.3 | 0.642 | 0.631 | 0.277 |
| | | | | X | | | | | | | | X | | X | 3 | 21.2 | 0.779 | 0.765 | 0.226 |
| | X | | | | | | | | | | | X | | X | 3 | 21.7 | 0.777 | 0.763 | 0.222 |
| | | | X | | | | | | | | | X | | X | 3 | 23.6 | 0.768 | 0.754 | 0.226 |
| | | | | | | X | | | | | | X | | X | 3 | 24.0 | 0.767 | 0.752 | 0.227 |
| | | | | | X | | | | | | | X | | X | 3 | 26.4 | 0.756 | 0.741 | 0.232 |
| | | | | X | | | X | | | | | X | | X | 4 | 19.2 | 0.797 | 0.777 | 0.215 |
| | | | X | X | | | | | | | | X | | X | 4 | 19.7 | 0.794 | 0.774 | 0.216 |
| X | | | | X | | | | | | | | X | | X | 4 | 19.7 | 0.794 | 0.774 | 0.216 |
| | X | | | X | | | | | | | | X | | X | 4 | 20.5 | 0.791 | 0.771 | 0.218 |
| | X | | | | | | X | | | | | X | | X | 4 | 21.5 | 0.787 | 0.766 | 0.223 |
| | | | X | X | | | X | | | | | X | | X | 5 | 12.5 | 0.835 | 0.813 | 0.197 |
| | X | | | X | | | X | | | | | X | | X | 5 | 16.7 | 0.816 | 0.792 | 0.208 |
| | | | X | | X | | X | | | | | X | | X | 5 | 17.0 | 0.815 | 0.790 | 0.208 |
| X | | | X | X | | | | | | | | X | | X | 5 | 18.6 | 0.808 | 0.782 | 0.213 |
| X | | | | X | | | X | | | | | X | | X | 5 | 19.0 | 0.806 | 0.780 | 0.213 |
| | | | X | X | | | X | | | X | | X | | X | 6 | 12.2 | 0.845 | 0.818 | 0.194 |
| | | | X | X | | | X | | | | X | X | | X | 6 | 12.3 | 0.844 | 0.818 | 0.194 |
| | | | X | X | | | X | X | | | | X | | X | 6 | 12.8 | 0.842 | 0.815 | 0.196 |
| | | | X | X | X | | X | | | | | X | | X | 6 | 13.4 | 0.840 | 0.812 | 0.197 |
| X | | | X | X | | | X | | | | | X | | X | 6 | 13.5 | 0.839 | 0.812 | 0.198 |
| | | | X | X | | | X | X | | | X | X | | X | 7 | 11.0 | 0.859 | 0.829 | 0.188 |
| | | | X | X | X | | X | | | X | | X | | X | 7 | 11.5 | 0.857 | 0.826 | 0.190 |
| | | | X | X | | | X | | | X | X | X | | X | 7 | 11.5 | 0.857 | 0.826 | 0.190 |
| | | | X | X | | | X | X | | X | | X | | X | 7 | 11.9 | 0.855 | 0.824 | 0.199 |
| | | | X | X | | | X | X | X | | | X | | X | 7 | 12.1 | 0.854 | 0.823 | 0.192 |
| | | | ***X*** | ***X*** | | | ***X*** | ***X*** | | ***X*** | ***X*** | ***X*** | | ***X*** | ***8**** | ***8.7*** | ***0.878*** | ***0.847*** | ***0.178*** |
| | | | X | X | X | | X | | | X | X | X | | X | 8 | 9.6 | 0.874 | 0.841 | 0.181 |
| | | | X | X | | | X | X | X | | X | X | | X | 8 | 10.1 | 0.872 | 0.839 | 0.183 |
| X | | | X | X | | | X | X | | | X | X | | X | 8 | 10.5 | 0.870 | 0.837 | 0.185 |
| | | X | X | X | | | X | | | X | X | X | | X | 8 | 11.0 | 0.868 | 0.834 | 0.186 |
| | | ***X*** | ***X*** | ***X*** | ***X*** | | ***X*** | ***X*** | | ***X*** | | ***X*** | | ***X*** | ***9**** | ***8.2*** | ***0.889*** | ***0.855*** | ***0.173*** |
| X | | | X | X | | | X | X | | X | X | X | | X | 9 | 9.1 | 0.885 | 0.850 | 0.177 |
| | | | X | X | X | | X | X | | X | X | X | | X | 9 | 9.2 | 0.885 | 0.849 | 0.177 |
| | X | | X | X | | | X | X | | X | X | X | | X | 9 | 9.5 | 0.883 | 0.847 | 0.178 |
| | | | X | X | | X | X | X | | X | X | X | | X | 9 | 9.6 | 0.883 | 0.847 | 0.178 |
| ***X*** | | ***X*** | ***X*** | ***X*** | ***X*** | | ***X*** | ***X*** | | ***X*** | | ***X*** | | ***X*** | ***10**** | ***6.6*** | ***0.905*** | ***0.870*** | ***0.164*** |
| X | | | X | X | | X | X | X | | X | X | X | | X | 10 | 9.4 | 0.893 | 0.854 | 0.174 |
| X | | | X | X | X | | X | X | | X | X | X | | X | 10 | 9.4 | 0.893 | 0.854 | 0.174 |
| | | X | X | X | X | | X | X | | X | X | X | | X | 10 | 9.5 | 0.892 | 0.854 | 0.174 |
| | | | X | X | X | | X | X | X | X | X | X | | X | 10 | 9.7 | 0.891 | 0.852 | 0.175 |
| X | | X | X | X | X | X | X | X | | X | | X | | X | 11 | 8.0 | 0.908 | 0.869 | 0.165 |
| X | | X | X | X | X | | X | X | | X | X | X | | X | 11 | 8.1 | 0.907 | 0.868 | 0.165 |
| X | X | X | X | X | X | | X | X | | X | | X | | X | 11 | 8.1 | 0.907 | 0.868 | 0.165 |
| X | | X | X | X | X | | X | X | X | X | | X | | X | 11 | 8.6 | 0.905 | 0.865 | 0.168 |
| X | | X | X | X | X | | X | X | | X | | X | X | X | 11 | 8.6 | 0.905 | 0.865 | 0.167 |
| X | | X | X | X | X | X | X | X | | X | X | X | | X | 12 | 9.4 | 0.910 | 0.867 | 0.166 |
| X | X | X | X | X | X | | X | X | | X | X | X | | X | 12 | 9.6 | 0.909 | 0.866 | 0.167 |
| X | | X | X | X | X | X | X | X | | X | | X | X | X | 12 | 9.7 | 0.909 | 0.865 | 0.167 |
| X | | X | X | X | X | X | X | X | X | X | | X | | X | 12 | 9.9 | 0.908 | 0.864 | 0.169 |
| X | | X | X | X | X | | X | X | X | X | X | X | | X | 12 | 9.9 | 0.908 | 0.864 | 0.169 |
| X | | X | X | X | X | X | X | X | | X | X | X | X | X | 13 | 11.2 | 0.911 | 0.863 | 0.169 |
| X | | X | X | X | X | X | X | X | X | X | X | X | | X | 13 | 11.2 | 0.911 | 0.863 | 0.169 |
| X | X | X | X | X | X | | X | X | X | X | X | X | | X | 13 | 11.3 | 0.910 | 0.862 | 0.169 |
| X | X | X | X | X | X | X | X | X | | X | X | X | | X | 13 | 11.4 | 0.910 | 0.861 | 0.170 |
| X | X | X | X | X | X | | X | X | | X | X | X | X | X | 13 | 11.5 | 0.910 | 0.860 | 0.172 |
| X | | X | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.912 | 0.857 | 0.172 |
| X | X | X | X | X | X | X | X | X | | X | X | X | X | X | 14 | 13.2 | 0.911 | 0.856 | 0.173 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | | X | 14 | 13.2 | 0.911 | 0.856 | 0.173 |
| X | X | X | X | X | X | | X | X | X | X | X | X | X | X | 14 | 13.3 | 0.911 | 0.855 | 0.173 |
| X | X | X | X | X | X | X | X | X | X | X | | X | X | X | 14 | 13.7 | 0.909 | 0.853 | 0.175 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.912 | 0.850 | 0.176 |

## Appendix - G.2: Best subset regression models for the ESMLA distance at the L4/L5 level

| Variable | | | | | | | | | | | | | | | Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender | Height | Weight | Sitting Height | Shoulder Width | Fat-free Weight | Arm Length | Head | Chest | Elbow | Wrist | Knee | Ankle | Hand | Intercept | # of Parameters | Mallows' Cp | $R^2$ | Adj. $R^2$ | s $(=\sqrt{MSE})$ |
| | | | | | | | | | | | | X | | X | 2 | 18.1 | 0.728 | 0.719 | 0.232 |
| | | | | | | | | | | X | | | | X | 2 | 35.7 | 0.631 | 0.619 | 0.268 |
| | | | | | X | | | | | | | | | X | 2 | 36.2 | 0.627 | 0.616 | 0.269 |
| | | X | | | | | | | | | | | | X | 2 | 39.9 | 0.607 | 0.595 | 0.277 |
| | X | | | | | | | | | | | | | X | 2 | 41.1 | 0.600 | 0.588 | 0.279 |
| | | | X | | | | | | | | | X | | X | 3 | 14.6 | 0.758 | 0.743 | 0.223 |
| | X | | | | | | | | | | | X | | X | 3 | 15.9 | 0.751 | 0.735 | 0.224 |
| | | | | | X | | | | | | | X | | X | 3 | 17.1 | 0.744 | 0.728 | 0.227 |
| | | | | X | | | | | | | | X | | X | 3 | 17.4 | 0.743 | 0.727 | 0.227 |
| | | X | | | | | | | | | | X | | X | 3 | 17.9 | 0.740 | 0.724 | 0.228 |
| X | | | | | X | | | | | | | X | | X | 4 | 13.3 | 0.777 | 0.755 | 0.215 |
| X | | | X | | | | | | | | | X | | X | 4 | 14.1 | 0.772 | 0.750 | 0.217 |
| X | | | | X | | | | | | | | X | | X | 4 | 14.4 | 0.771 | 0.749 | 0.218 |
| X | X | | | | | | | | | | | X | | X | 4 | 14.5 | 0.770 | 0.747 | 0.218 |
| | | | X | | | | | | | | X | X | | X | 4 | 14.6 | 0.770 | 0.747 | 0.219 |
| X | | | X | | X | | | | | | | X | | X | 5 | 11.4 | 0.798 | 0.772 | 0.208 |
| | | | X | | X | | X | | | | | X | | X | 5 | 12.1 | 0.794 | 0.767 | 0.210 |
| X | | | | | X | | | | | | X | X | | X | 5 | 12.9 | 0.790 | 0.762 | 0.212 |
| X | | X | | | | | | | | | X | X | | X | 5 | 12.9 | 0.790 | 0.762 | 0.212 |
| X | | | X | X | | | | | | | | X | | X | 5 | 13.0 | 0.789 | 0.761 | 0.212 |
| | | | X | | X | | X | | X | | | X | | X | 6 | 8.8 | 0.824 | 0.793 | 0.198 |
| X | | | X | | X | | | | | | X | X | | X | 6 | 9.1 | 0.822 | 0.791 | 0.199 |
| | | | X | | X | | X | | | X | | X | | X | 6 | 10.1 | 0.816 | 0.785 | 0.202 |
| X | | X | X | | | | | | | | X | X | | X | 6 | 10.2 | 0.816 | 0.784 | 0.202 |
| X | | | X | | X | | X | | | | | X | | X | 6 | 10.5 | 0.814 | 0.782 | 0.203 |
| | | ***X*** | ***X*** | | | | ***X*** | | ***X*** | | ***X*** | ***X*** | | ***X*** | ***7**** | ***7.2*** | ***0.844*** | ***0.810*** | ***0.189*** |
| | | | ***X*** | | ***X*** | | ***X*** | | | ***X*** | ***X*** | ***X*** | | ***X*** | ***7**** | ***7.8*** | ***0.840*** | ***0.806*** | ***0.191*** |
| X | | | X | | X | | X | | | | X | X | | X | 7 | 8.2 | 0.838 | 0.804 | 0.193 |
| X | | | X | | X | | X | | X | | | X | | X | 7 | 8.3 | 0.838 | 0.803 | 0.194 |
| | | | X | | X | | X | | X | | X | X | | X | 7 | 8.3 | 0.837 | 0.803 | 0.194 |
| ***X*** | | | ***X*** | | ***X*** | | ***X*** | | | ***X*** | ***X*** | ***X*** | | ***X*** | ***8**** | ***6.1*** | ***0.861*** | ***0.825*** | ***0.183*** |
| ***X*** | | | ***X*** | | ***X*** | | ***X*** | | ***X*** | | ***X*** | ***X*** | | ***X*** | ***8**** | ***6.6*** | ***0.858*** | ***0.822*** | ***0.184*** |
| X | | X | X | | | | X | | X | | X | X | | X | 8 | 7.5 | 0.853 | 0.815 | 0.187 |
| | | | X | | X | | X | | X | X | X | X | | X | 8 | 7.6 | 0.852 | 0.814 | 0.187 |
| | | | X | | X | X | X | | X | | X | X | | X | 8 | 8.3 | 0.849 | 0.810 | 0.190 |
| X | | | X | | X | | X | X | X | | X | X | | X | 9 | 6.5 | 0.870 | 0.829 | 0.179 |
| X | | | X | | X | | X | | X | X | X | X | | X | 9 | 6.5 | 0.870 | 0.829 | 0.180 |
| X | | | X | X | X | | X | | | X | X | X | | X | 9 | 6.6 | 0.869 | 0.829 | 0.180 |
| X | | | X | | X | | X | X | | X | X | X | | X | 9 | 7.2 | 0.866 | 0.824 | 0.183 |
| X | | | X | | X | X | X | | X | | X | X | | X | 9 | 7.4 | 0.865 | 0.823 | 0.183 |
| X | | | X | | X | | X | X | X | X | X | X | | X | 10 | 6.8 | 0.879 | 0.836 | 0.176 |
| X | | | X | X | X | | X | | X | X | X | X | | X | 10 | 7.4 | 0.876 | 0.831 | 0.179 |
| X | | | X | X | X | | X | X | | X | X | X | | X | 10 | 7.5 | 0.875 | 0.831 | 0.179 |
| X | | | X | X | X | X | X | | | X | X | X | | X | 10 | 8.0 | 0.873 | 0.827 | 0.189 |
| X | X | | X | X | X | | X | | | X | X | X | | X | 10 | 8.0 | 0.873 | 0.827 | 0.189 |
| X | | | X | X | X | | X | X | X | X | X | X | | X | 11 | 7.6 | 0.886 | 0.839 | 0.175 |
| X | | X | X | X | X | | X | X | | X | X | X | | X | 11 | 8.5 | 0.881 | 0.831 | 0.178 |
| X | | X | X | | X | | X | X | X | X | X | X | | X | 11 | 8.6 | 0.880 | 0.830 | 0.179 |
| X | | | X | | X | | X | X | X | X | X | X | X | X | 11 | 8.6 | 0.880 | 0.830 | 0.180 |
| X | | | X | X | X | X | X | | X | X | X | X | | X | 11 | 8.7 | 0.880 | 0.830 | 0.179 |
| X | | X | X | X | X | | X | X | X | X | X | X | | X | 12 | 9.3 | 0.887 | 0.833 | 0.177 |
| X | | | X | X | X | X | X | X | X | X | X | X | | X | 12 | 9.4 | 0.887 | 0.833 | 0.178 |
| X | X | | X | X | X | | X | X | X | X | X | X | | X | 12 | 9.5 | 0.887 | 0.832 | 0.178 |
| X | | | X | X | X | | X | X | X | X | X | X | X | X | 12 | 9.5 | 0.886 | 0.832 | 0.178 |
| X | | | X | | X | X | X | X | X | X | X | X | X | X | 12 | 10.3 | 0.882 | 0.826 | 0.182 |
| X | | | X | X | X | X | X | X | X | X | X | X | X | X | 13 | 11.2 | 0.888 | 0.827 | 0.188 |
| X | | X | X | X | X | X | X | X | X | X | X | X | | X | 13 | 11.2 | 0.888 | 0.827 | 0.188 |
| X | X | X | X | X | X | | X | X | X | X | X | X | | X | 13 | 11.3 | 0.888 | 0.826 | 0.182 |
| X | | X | X | X | X | | X | X | X | X | X | X | X | X | 13 | 11.3 | 0.887 | 0.826 | 0.181 |
| X | X | | X | X | X | | X | X | X | X | X | X | X | X | 13 | 11.4 | 0.887 | 0.826 | 0.181 |
| X | | X | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.889 | 0.820 | 0.184 |
| X | X | | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.2 | 0.888 | 0.819 | 0.185 |
| X | X | X | X | X | X | | X | X | X | X | X | X | X | X | 14 | 13.2 | 0.888 | 0.819 | 0.186 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | | X | 14 | 13.2 | 0.888 | 0.819 | 0.186 |
| X | X | X | X | | X | X | X | X | X | X | X | X | X | X | 14 | 14.1 | 0.883 | 0.810 | 0.189 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.889 | 0.812 | 0.189 |

## Appendix - G.3: Best subset regression models for the ESMLA distance at the L5/S1 level

| Variable | | | | | | | | | | | | | | | Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gender | Height | Weight | Sitting Height | Shoulder Width | Fat-free Weight | Arm Length | Head | Chest | Elbow | Wrist | Knee | Ankle | Hand | Intercept | # of Parameters | Mallows' Cp | $R^2$ | Adj. $R^2$ | s ($=\sqrt{MSE}$) |
| | | | | | | | | | | | | ***X*** | | ***X*** | ***2**** | ***1.7*** | ***0.763*** | ***0.756*** | ***0.244*** |
| | | | | | | | | | | X | | | | X | 2 | 6.4 | 0.730 | 0.721 | 0.261 |
| | | X | | | | | | | | | | | | X | 2 | 15.7 | 0.662 | 0.652 | 0.292 |
| | | | | | X | | | | | | | | | X | 2 | 16.2 | 0.659 | 0.649 | 0.293 |
| | X | | | | | | | | | | | | | X | 2 | 20.5 | 0.628 | 0.616 | 0.307 |
| | ***X*** | | | | | | | | | | | ***X*** | | ***X*** | ***3**** | ***0.5*** | ***0.787*** | ***0.774*** | ***0.235*** |
| | | ***X*** | | | | | | | | | | ***X*** | | ***X*** | ***3**** | ***0.9*** | ***0.784*** | ***0.771*** | ***0.237*** |
| | | | | | X | | | | | | | X | | X | 3 | 1.3 | 0.781 | 0.768 | 0.239 |
| | | | | X | | | | | | | | X | | X | 3 | 1.5 | 0.779 | 0.766 | 0.240 |
| | | | | | | | | | | X | | X | | X | 3 | 1.6 | 0.779 | 0.765 | 0.240 |
| | ***X*** | | | | | | ***X*** | | | | | ***X*** | | ***X*** | ***4**** | ***1.6*** | ***0.793*** | ***0.773*** | ***0.236*** |
| | X | | | | | | | X | | | | X | | X | 4 | 1.6 | 0.793 | 0.773 | 0.236 |
| | X | | | | | | | | | | | X | X | X | 4 | 1.7 | 0.793 | 0.773 | 0.236 |
| | | ***X*** | | | | | ***X*** | | | | | ***X*** | | ***X*** | ***4**** | ***1.8*** | ***0.792*** | ***0.772*** | ***0.236*** |
| | X | X | | | | | | | | | | X | | X | 4 | 1.8 | 0.792 | 0.772 | 0.237 |
| | | | X | | X | | X | | | | | X | | X | 5 | 0.9 | 0.813 | 0.788 | 0.228 |
| | X | | | | | | X | X | | | | X | | X | 5 | 1.8 | 0.807 | 0.781 | 0.232 |
| | | X | X | | | | X | | | | | X | | X | 5 | 1.9 | 0.805 | 0.779 | 0.232 |
| | | X | | | | | | | X | X | | X | | X | 5 | 2.0 | 0.805 | 0.779 | 0.233 |
| | ***X*** | ***X*** | | | | | ***X*** | | | | | ***X*** | | ***X*** | ***5**** | ***2.2*** | ***0.803*** | ***0.777*** | ***0.234*** |
| | | | X | | X | | X | | | | | X | X | X | 6 | 1.7 | 0.822 | 0.791 | 0.226 |
| | | | X | | X | | X | | X | | | X | | X | 6 | 1.7 | 0.821 | 0.791 | 0.226 |
| | X | | | | X | | X | | | | | X | X | X | 6 | 1.8 | 0.821 | 0.790 | 0.227 |
| | | X | X | | | | X | | | | X | X | | X | 6 | 1.9 | 0.820 | 0.789 | 0.227 |
| | X | | | X | | | X | | | | | X | X | X | 6 | 2.0 | 0.819 | 0.788 | 0.228 |
| | | X | X | | | | X | | X | | X | X | | X | 7 | 1.7 | 0.836 | 0.801 | 0.221 |
| | | | X | X | X | | X | | | | | X | X | X | 7 | 2.5 | 0.830 | 0.794 | 0.225 |
| | X | | | X | X | | X | | | | | X | X | X | 7 | 2.5 | 0.830 | 0.793 | 0.225 |
| | X | X | | | | | X | | X | | X | X | | X | 7 | 2.7 | 0.829 | 0.792 | 0.225 |
| | | | X | | X | | X | | X | | | X | X | X | 7 | 2.8 | 0.828 | 0.791 | 0.226 |
| | | X | X | X | | | X | | X | | X | X | | X | 8 | 3.1 | 0.840 | 0.799 | 0.222 |
| | | X | X | | | | X | | X | X | X | X | | X | 8 | 3.1 | 0.840 | 0.799 | 0.222 |
| | X | X | | | | X | X | | X | | X | X | | X | 8 | 3.4 | 0.838 | 0.796 | 0.223 |
| | X | X | | | | | X | | X | | X | X | X | X | 8 | 3.4 | 0.838 | 0.796 | 0.224 |
| | X | X | | X | | | X | | | | X | X | X | X | 8 | 3.6 | 0.837 | 0.795 | 0.224 |
| | X | X | | | | | X | | X | X | X | X | X | X | 9 | 4.1 | 0.847 | 0.800 | 0.221 |
| | X | X | | X | | | X | | X | | X | X | X | X | 9 | 4.3 | 0.846 | 0.798 | 0.222 |
| | | X | X | | | | X | | X | X | X | X | X | X | 9 | 4.5 | 0.845 | 0.797 | 0.223 |
| | X | X | | | | X | X | | X | X | X | X | | X | 9 | 4.5 | 0.845 | 0.797 | 0.223 |
| | | X | X | X | | | X | | X | | X | X | X | X | 9 | 4.5 | 0.845 | 0.797 | 0.223 |
| | X | X | | X | | | X | | X | X | X | X | X | X | 10 | 5.5 | 0.852 | 0.799 | 0.222 |
| | | X | X | X | | | X | | X | X | X | X | X | X | 10 | 5.7 | 0.850 | 0.796 | 0.223 |
| | X | X | | | | | X | X | X | X | X | X | X | X | 10 | 6.0 | 0.849 | 0.794 | 0.225 |
| | X | X | | | | X | X | | X | X | X | X | X | X | 10 | 6.0 | 0.848 | 0.794 | 0.225 |
| | X | X | | X | | | X | X | X | | X | X | X | X | 10 | 6.0 | 0.848 | 0.794 | 0.225 |
| | X | X | | X | | | X | X | X | X | X | X | X | X | 11 | 7.3 | 0.854 | 0.793 | 0.225 |
| | X | X | | X | | X | X | | X | X | X | X | X | X | 11 | 7.3 | 0.853 | 0.792 | 0.226 |
| | X | X | X | X | | | X | | X | X | X | X | X | X | 11 | 7.3 | 0.853 | 0.792 | 0.226 |
| X | X | X | | X | | | X | | X | X | X | X | X | X | 11 | 7.4 | 0.853 | 0.791 | 0.226 |
| | X | X | | X | X | | X | | X | X | X | X | X | X | 11 | 7.5 | 0.852 | 0.791 | 0.226 |
| | X | X | | X | | X | X | X | X | X | X | X | X | X | 12 | 9.1 | 0.855 | 0.785 | 0.229 |
| | X | X | X | X | | | X | X | X | X | X | X | X | X | 12 | 9.2 | 0.854 | 0.784 | 0.230 |
| X | X | X | | X | | X | X | | X | X | X | X | X | X | 12 | 9.2 | 0.854 | 0.784 | 0.230 |
| | X | X | X | X | | X | X | | X | X | X | X | X | X | 12 | 9.2 | 0.854 | 0.784 | 0.230 |
| X | X | X | | X | | | X | X | X | X | X | X | X | X | 12 | 9.2 | 0.854 | 0.784 | 0.230 |
| X | X | X | | X | | X | X | X | X | X | X | X | X | X | 13 | 11.1 | 0.855 | 0.776 | 0.234 |
| | X | X | | X | X | X | X | X | X | X | X | X | X | X | 13 | 11.1 | 0.855 | 0.776 | 0.234 |
| | X | X | X | X | | X | X | X | X | X | X | X | X | X | 13 | 11.1 | 0.855 | 0.776 | 0.234 |
| | X | X | X | X | X | | X | X | X | X | X | X | X | X | 13 | 11.1 | 0.854 | 0.775 | 0.235 |
| X | X | X | X | X | | X | X | | X | X | X | X | X | X | 13 | 11.2 | 0.854 | 0.775 | 0.235 |
| | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.855 | 0.766 | 0.240 |
| X | X | X | X | X | | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.855 | 0.765 | 0.240 |
| X | X | X | | X | X | X | X | X | X | X | X | X | X | X | 14 | 13.0 | 0.855 | 0.765 | 0.240 |
| X | X | X | X | X | X | | X | X | X | X | X | X | X | X | 14 | 13.1 | 0.855 | 0.765 | 0.240 |
| X | X | X | X | X | X | X | X | | X | X | X | X | X | X | 14 | 13.1 | 0.854 | 0.764 | 0.240 |
| X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | 15 | 15.0 | 0.855 | 0.754 | 0.245 |