Morphometric Analysis of the Human Lower Lumbar Intervertebral Discs and Vertebral Endplates: Experimental Approach and Regression Models

by

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Abstract

Low back pain (LBP) has been a major socioeconomic problem to the modern society for decades. In industry, one of the most challenging issues in occupational ergonomics and health practices has been the reliable and accurate estimation of risks of work-related musculoskeletal disorders (WMSDs), particularly work-related low back pain (WRLBP) and injuries which represent a large portion of all Workers' Compensation (WC) cost. To date, ergonomics evaluation measures developed to pinpoint jobs with elevated risks of WRLBP primarily rely on biomechanical models of the musculoskeletal structures of the human spine to estimate the internal response in terms of muscle induced compressive forces and to characterize the risk associated with the postures and forceful motions. However, morphometric characteristics of the human spine has not yet been thoroughly investigated and incorporated in the development of biomechanical models. In particular, the size of the load-bearing surface (cross-sectional area) of lumbar motion segments has been lacking in the literature, despite the fact that there is strong correlation between the cross-sectional area (CSA) and the ultimate compressive strength. Morphometric data regarding the human spine have been obtained with either direct measurements on cadaveric specimens or using medical imaging techniques, which require strict measurement protocol and incur high cost. In industry, occupational safety and health practitioners would prefer a more cost-effective means to obtain these morphometric data to improve the ergonomic evaluations and risk estimation of WRLBP.

The objective of this study was 1) to develop standardized protocol using magnetic resonance (MR) scans to measure the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs and vertebral endplates, and 2) to develop regression models to predict these CSAs with different hierarchy of model complexity and predictor selection criteria. MR scans were 1) collected from a medical database and 2) performed in a research institute (Auburn University MRI Research Center). MR scans were analyzed using imaging processing software package with a research protocol developed in this dissertation. The protocol standardized the definitions of each geometric dimension and the measurement techniques and achieved excellent measurement reliability.

This dissertation provides comprehensive morphometric data regarding both the linear and planar aspects of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs), which has been lacking in the literature. Results of this dissertation also indicate that it is feasible to perform satisfactory predictions of the CSAs of the human lower lumbar IVDs and EPs using subject variables (characteristics and anthropometric measures). Results of this dissertation also suggest that the discrepancy in historical geometric data regarding the human lower lumbar may not only be attributed to gender alone but also related to other anthropometric measures. In addition, it is also evident that superior model performance can be achieved when certain anthropometric measures, such as the dimensions of ankle and elbow joints, are included as predictors in the prediction equations.

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Chapter 1

INTRODUCTION

This chapter provides the background of and motivation for the prediction of the geometry of human lower lumbar intervertebral discs, and the improvement of ergonomic evaluation assessment methods or "tools" for work-related low back injury by incorporation of personal anthropometric characteristics, such as gender, age, and height. This is followed by a discussion of the research objectives, and an overview of the layout of the dissertation.

1.1 Cost and epidemiological aspects of low back pain

For decades, low back pain (LBP) has been a major socioeconomic burden to modern society, remaining one of the most prevalent health conditions in the world for many years (Andersson, 1981, 1998; Crow & Willis, 2009; Dagenais, Caro, & Haldeman, 2008; Deyo & Tsui-Wu, 1987; Deyo & Weinstein, 2001; Deyo, Mirza, & Martin, 2006; Ekman, Johnell, & Lidgren, 2005; Gore, Sadosky, Stacey, Tai, & Leslie, 2012; Hemmilä, 2002; Jin, Sorock, & Courtney, 2004; Juniper, Le, & Mladsi, 2009; Katz, 2006; Kim, Choi, Chang, Lee, & Oh, 2005; Manchikanti, 2000; Maniadakis & Gray, 2000; Mital Anil, 1999; Sesek, Gilkey, Drinkaus, Bloswick, & Herron, 2003; Walker, 2000; Wieser et al., 2011). In the U.S., both the National Health and Nutrition Examination Survey (NHANES) and National Health Interview Survey (NHIS) reported that on average, more than 25% of population over the age of 18 experienced at least one episode of low back pain in a three-month recall period

(AAOS, 2011). In a systematic review, Walker (2000) evaluated the prevalence of LBP reported in the literature worldwide between 1966 and 1998, and reported that it ranged from 12% to 30% at a single point in time (point prevalence), from 22% to 65% for a one-year recall period, and from 11% to 84% for lifetime. In the United States, low back pain is a common reason for physician office visit, accounting for approximately 2.5% to 15% of such visits (Deyo et al., 2006; Hart, Deyo, & Cherkin, 1995; AAOS, 2011). In 2006, over 44.4 million patients had an office visit with a complaint of low back pain (AAOS, 2011). Although, it is generally believed that most episodes of low back pain are self-limiting and will resolve within 8 to 12 weeks, up to 15% of patients may suffer low back pain conditions that last over 3 months (Liebenson, 1996; Ekman et al., 2005; Rubin, 2007; Manchikanti, 2000), which is generally defined as chronic low back pain (CLBP) (Juniper et al., 2009). Some studies suggest that the initial duration and severity of the first episode of LBP were a strong predictor for the transition to CLBP (Kovacs et al., 2003). On the other hand, high recurrence rates for LBP have also been reported consistently in literature (Rubin, 2007). The experience of a prior episode is a strong predictor of future episodes (Papageorgiou et al., 1996; Waxman, Tennant, & Helliwell, 2000).

The high prevalence and recurrence of low back pain (LBP) results in significant economic costs on the healthcare system. The direct health care cost incurred by individuals with LBP exceeds $9 billion each year in the United States (Murphy & Volinn, 1999; Guo, Tanaka, Halperin, & Cameron, 1999; Luo, Pietrobon, Sun, Liu, & Hey, 2004; Webster & Snook, 1994). The indirect costs are more staggering, estimated to be over $20 billion annually due to lost work productivity alone (e.g., lost work-days, physical

limitations, and activity impairment).(Katz, 2006) Recent estimates of total cost ranged from $20 billion to $624.8 billion US dollars (Katz, 2006; Dagenais et al., 2008; Crow & Willis, 2009; Gore et al., 2012; Soni, 2010). In fact, 75% of attributable health care cost is consumed by less than 5% of patients (Katz, 2006). For patients with chronic low back pain, recent estimates of total cost per case was $8,386 to $17,507 US dollars (Gore et al., 2012) compared to $6,807 US dollars in 1986 and $8,321 US dollars in 1989 (Webster & Snook, 1994).

In addition, low back pain has a tremendous impact on individual quality of life, contributing to job changes and earlier retirement (Kim et al., 2005). Patients suffering low back pain may also experience other side effects, such as leg pain, fatigue, or sleeping problems, which can significantly impact the quality of life for these patients (Hemmilä, 2002; Gore et al., 2012). Kovacs and colleagues (2004) have noted that the duration of back pain episode have more impact on the quality of life than the severity.

It is evident that work-related low back pain (WRLBP) constitutes a large portion of the socioeconomic burden (Andersson, 1981, 1997; Atlas et al., 2000). WRLBP is one of the most devastating musculoskeletal disorders (MSDs) experienced by the US workforce (Marras, 2000). It was reported that 2.6% of US workforce reported a back injury over a 12-month period (Behrens, Seligman, Cameron, Mathias, & Fine, 1994). It has also been estimated that each year about 2% of workforce received compensable medical treatment for back injuries (Andersson, 1997). In 1997, the National Institute for Occupational Safety and Health (NIOSH) reported that over 5% of workforce had been diagnosed with low back injuries, which remain the most prevalent and costly MSD among U.S. industries (NIOSH, 1997). It has been reported that back injuries represented 25% of all Workers'

Compensation (WC) cost (NIOSH, 1997; Hashemi, Webster, & Clancy, 1998). In Washington State, non-traumatic soft-tissue back disorders have also accounted for a large portion of all WC claims between 1992 and 2000, and accounted for $1.5 billion US dollars in direct cost (Hughes & Nelson, 2009). On the other hand, it has been noted that less than 5% of workers accounted for over 70% of the costs of WRLBP (Katz, 2006). It was reported that more than two thirds of these cost were attributable to chronic LBP cases (Marras, Ferguson, Burr, Schabo, & Maronitis, 2007). According to the Workers' Compensation Insurance Rating Bureau (WCIRB) (CHSWC, 2011), the average cost per claim for back injuries increased slightly from 2000 to 2010, averaging over $50,000 US dollar per case. (Figure 1.1)

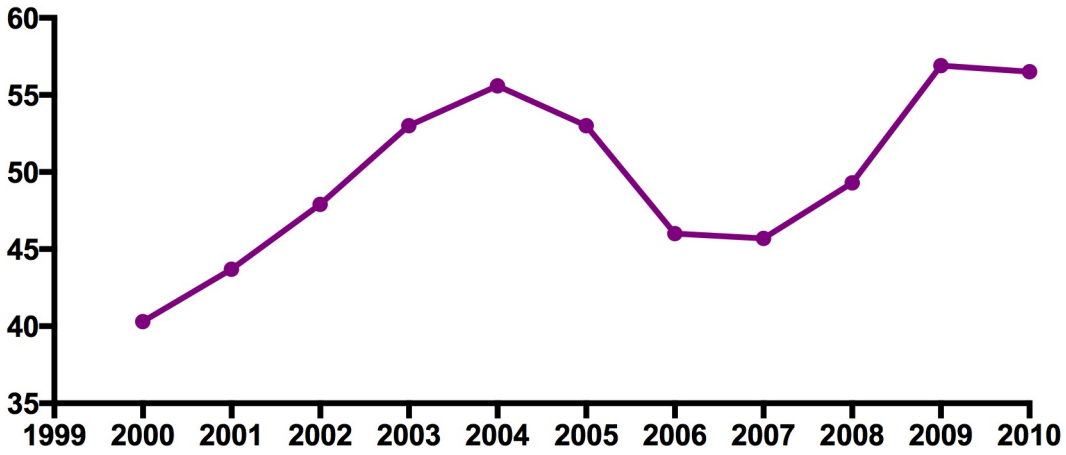


Figure 1.1: Average Cost per Back Injury Claim, 2000-2010 (in thousand US dollars) (CHSWC, 2011)

1.2 Pathological aspects of low back pain

According to the American Academy of Orthopaedic Surgeons (AAOS), back pain manifests itself in various forms or presentations, including injuries such as sprains, strains,

and fractures, disc problems, degenerative and rheumatic disorders (Marras, 2008). A variety of other pathological conditions can also stress the lumbar spine and result in low back pain, which include infectious and neoplastic diseases or inflammatory conditions, congenital malformations, metabolic disorders, and various miscellaneous disorders (Bogduk & Twomey, 1991). In fact, pain in the lumbar spine region may be caused by visceral or vascular disorders in other body regions such as the abdomen or pelvis, which may be symptoms related to the sacroiliac or other pelvic musculoskeletal structures (Bogduk & Twomey, 1991). Therefore, unfortunately, for may patients with low back pain (LBP), precise anatomical diagnoses may not be available due to the confounding etiological factors (Murray, 1939; Deyo & Weinstein, 2001; van Tulder, Koes, & Bombardier, 2002). In general, LBP is defined as pain, muscle tension, or stiffness localized below the costal margin and above the inferior gluteal folds, with or without leg pain (sciatica). LBP is typically classified as being specific or nonspecific (Deyo & Weinstein, 2001). Specific LBP is defined as symptoms caused by a specific pathophysiological mechanism, such as a hernia nuclei pulposi (HNP, known as herniated disc), infection, inflammation, osteoporosis, rheumatoid arthritis, fracture or tumor. Nonspecific LBP is defined as symptoms without clear specific etiology, which in fact accounts for 85% to 90% of low back pain cases (Deyo & Weinstein, 2001; van Tulder et al., 2002; Manek & MacGregor, 2005; Friedman, Chilstrom, Bijur, & Gallagher, 2010).

Even though no single factor can be identified as the source of pain, it has been generally accepted in literature that a majority of low back pain complaints have mechanical exposure as the origin. A single mechanical "event" or complex "events" likely initiates the process which later is worsened by spinal loading or mechanical movements

(Dunlop, 1925; Murray, 1939; Bogduk & Twomey, 1991; Adams, Bogduk, Burton, & Dolan, 2002). A number of studies have reported the detrimental effect of mechanical loading on the lumbar spine (F. G. Evans & Lissner, 1959; Nachemson, 1960; Sonoda, 1962; Nachemson, 1965; Adams, Hutton, & Stott, 1980; Adams & Hutton, 1981, 1982; Hutton & Adams, 1982; Adams & Hutton, 1983; Brinckmann, Johannleweling, Hilweg, & Biggemann, 1987). On the other hand, mechanical loading on the spine may have a beneficial influence, strengthening the back muscles and bone health through weight-training exercises (Dalsky et al., 1988; Adams et al., 2002). In addition, intermittent compressive loading may also be beneficial for the cell metabolism of the intervertebral discs (Ishihara, McNally, Urban, & Hall, 1996; Sauerland, Raiss, & Steinmeyer, 2003; Gallagher & Heberger, 2013), with proper loading frequency and magnitude (MacLean et al., 2003; Walsh & Lotz, 2004). In the context of this dissertation, the term low back pain is referring to pain of mechanical origin as other presentations of pain are beyond the scope of this dissertation.

1.3 Internal exposure and biomechanical models for lumbar spinal loading

A number of studies have indicated that the loading profile experienced by lumbar motion segments in terms of trunk motion, magnitude and rate of loading, and posture substantially influence the susceptibility of the lumbar structures to damage (F. G. Evans & Lissner, 1959; Nachemson, 1960; Sonoda, 1962; Nachemson, 1965; Adams et al., 1980; Adams & Hutton, 1981, 1982; Hutton & Adams, 1982; Adams & Hutton, 1983; Brinckmann et al., 1987). In response to the staggering economic burden facing the industry, a number of studies have sought to develop ergonomic evaluation methods or "tools" to assess the physical demand of manual material handling jobs and the associated

risk of LBP (Chaffin, 1969; NIOSH, 1981; Herrin, Jaraiedi, & Anderson, 1986; Waters, Putz-Anderson, Garg, & Fine, 1993; Marras et al., 1993; Waters et al., 1993; Fathallah, Marras, & Parnianpour, 1998; W. P. Neumann et al., 1999; Norman et al., 1998; Merryweather, Loertscher, & Bloswick, 2009). Among these tools, the Revised NIOSH Lifting Equation (RNLE), developed by the National Institute for Occupational Safety and Health (NIOSH), may be the most frequently used to evaluate the risk of work-related musculoskeletal disorders (MSDs) in industry (Sesek et al., 2003). The development of the RNLE and its predecessor, the Work Practice Guide for Manual Lifting (WPGML) involved basically four design criteria, which are epidemiological, biomechanical, physiological, and psychophyisical approaches (NIOSH, 1981; Waters et al., 1993). For less frequent lifting tasks, the biomechanical criterion, which focuses on the physical limits of the lumbar spine under loading, is regarded as the most important (Waters et al., 1993). The validity of RNLE has been well documented and supported by a number of studies (Marras, Fine, Ferguson, & Waters, 1999; Sesek et al., 2003; Waters, Kemmlert, & Baron, 1998; Waters, Lu, Piacitelli, Werren, & Deddens, 2011). The RNLE also yields very good reliability when individuals are properly field-trained to obtain data for the equations (Waters et al., 1998).

As suggested in recent literature, these biomechanical models are highly dependent on the ability to accurately describe the complex musculoskeletal structure of lumbar region and predict the spinal loading (Jorgensen, 2001; Jorgensen, Marras, Granata, & Wiand, 2001; Marras, Jorgensen, Granata, & Wiand, 2001; Marras, 2008). More complex modeling schemes have been applied to the musculature of the lumbar region, as compared to early studies where single equivalent muscle models were employed (Chaffin, 1969; Garg & Chaffin, 1975). Multiple-muscle biomechanical models have been developed to include

groups of agonist and antagonist muscles (Marras & Sommerich, 1991a, 1991b; A. B. Schultz & Andersson, 1981), using more accurate anatomical descriptions of spinal musculature presented in the literature (Adams et al., 2002; Bogduk & Twomey, 1991; McGill & Norman, 1985; White III & Panjabi, 1990).

1.4 Motivation and research objectives

1.4.1 Motivation

In contrast to the development of complex biomechanical models incorporating accurate inputs of multiple muscle groups, as the other critical component, the spinal column, especially in the lumbar region remains in simplified form in most biomechanical models (Fisher, 1967; Gracovetsky, Farfan, & Lamy, 1981), despite the fact that the anatomical description of the lumbar motion segments has been provided by several studies (Nissan & Gilad, 1984; Twomey & Taylor, 1987; Aspden, 1989; Mosner, Bryan, Stull, & Shippee, 1989; Panjabi et al., 1992). Recent evidence suggests that the morphometric characteristics of the lumbar motion segments are associated with their mechanical properties in response to spinal loading (Natarajan & Andersson, 1999; Robin, Skalli, & Lavaste, 1994; Noailly, Wilke, Planell, & Lacroix, 2007; Niemeyer, Wilke, & Schmidt, 2012). In some studies, attempts have been made to establish estimation models for the compressive strength of lumbar motion segments (Brinckmann, Biggemann, & Hilweg, 1989; Parkinson, Durkin, & Callaghan, 2005). On the other hand, personal factors, such as gender, age, have been shown to influence the morphometry of lumbar motion segments (Aharinejad, Bertagnoli, Wicke, Firbas, & Schneider, 1990; Amonoo-Kuofi, 1991; Gilsanz

et al., 1994; Buckwalter, 1995; Hall, Esses, Noble, & Kamaric, 1998; Aydinlioglu, Diyarbakirli, & Keles, 1999; Al-Hadidi, Badran, Al-Hadidi, & Abu-Ghaida, 2001; van der Houwen et al., 2010; Y. Wang, Battie, & Videman, 2012). Meanwhile, as acknowledged by the National Institute for Occupational Safety and Health (NIOSH), several potential factors did not demonstrate consistent patterns of influence in the literature, and hence were excluded from the final evaluation model (NIOSH, 1981; Waters et al., 1993), most of which are personal factors, including gender, age, and gross anthropometric measures such as height and weight.

While a consistent relationship has not been established, evidence has indicated that these personal factors may influence the geometry of the human lumbar spine, which is important to biomechanical models. Therefore, there is an urgent need for the incorporation of accurate anatomical descriptions of lumbar motion segments to improve the current ergonomic evaluation tools such that the estimation of risks of work-related low back pain (WRLBP) will be on an individual level, rather than on a population basis and possibly more accurate. Unfortunately, in order to specify the injury risk for each individual worker, the acquisition of an accurate morphomteric description of the lumbar spine is essential to serve this purpose. So far, several approaches have been used to measure the geometric dimensions of the lumbar spine, including direct measurement using cadaveric specimens and measurements performed with imaging technology modalities (e.g., X-ray, computed tomography, and magnetic resonance imaging). Unfortunately, it may be financially impractical to rely on these techniques to determine an individual's spinal morphoometry when evaluating the personalized risk of work-related low back pain (WRLBP). In industry, occupational ergonomics and health practitioners would prefer a

more cost-effective, efficient, and non-invasive means to apply such concepts to their ergonomic evaluations.

1.4.2 Research objectives

The literature review and experiments designed, conducted, and analyzed in this dissertation covered the following objectives:

1. to develop a research protocol to standardized the measurement for the lower lumbar spinal morphometry to provide reliable, accurate, and precise morphometric data regarding primarily the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs),
2. to obtain morphometric data regarding the CSAs of the lower lumbar IVDs and EPs using both archived magnetic resonance (MR) scans and asymptomatic subjects and perform statistical analyses to characterize the spinal morphometry,
3. to investigate the statistical correlations between subject variables (characteristics and anthropometric measures) and the spinal morphometry and to develop regression models for the CSAs of the lower lumbar IVDs and EPs,
4. to compare the performance of the regression models with respect to the model complexity, predictability, and predictor selection criteria.

1.4.3 Dissertation organization

The chapters of this dissertation were organized according to the manuscript format. The dissertation is comprised of six chapters. Chapter One is a traditional introduction, and Chapter Six is a traditional conclusion. Chapter Two provides a comprehensive

literature review of the importance of the geometric characteristics of the lumbar motion segments and the relation to the biomechanical models, followed by the review of the results, measurement protocols and findings reported in previous morphometric studies. New epidemiological evidence regarding personal risk factors was also reviewed, as well as the typical damage incurred by mechanical loading. Each of the remaining chapters is a stand-alone manuscript describing the purpose, methods, results, and discussion. Chapter Three provides comprehensive morphometric analyses regarding the linear and planar aspects of the spinal geometry measured on archived medical magnetic resonance (MR) scans and the comparison with the data reported in the literature. Chapter Four developed regression models using subject characteristics and gross anthropometric measures to predict the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs) and then validated these models with another dataset. Chapter 5 performed morphometric analyses regarding the IVD_CSAs and EP_CSAs of a relatively young and healthy sample with no known low back pain or previous low back injury and then developed multi-hierarchy regression models in terms of complexity and model performance. The overall conclusion, limitations of the studies, recommendations for future studies are discussed in Chapter Six. The appendices list details outlining the recruitment, consent and participation of human subjects, and also the specific protocols used for each experiment.

Chapter 2

BIOMECHANICS OF LUMBAR INTERVERTEBRAL DISC WITH RESPECT TO THE MORPHOMETRIC CHARACTERISTICS

2.1 Introduction

It has been well supported in the literature that people performing heavy manual lifting tasks can generate large muscle forces (A. B. Schultz & Andersson, 1981; Freivalds, Chaffin, Garg, & Lee, 1984; Dolan & Adams, 1993), and hence be exposed to a great amount of spinal loading measured by intradiscal pressure *in vivo* (Wilke, Neef, Caimi, Hoogland, & Claes, 1999; Wilke, Neef, Hinz, Seidel, & Claes, 2001). Therefore, it is not surprising to learn that forceful manual lifting tasks have been associated with elevated risk of work-related low back pain (NIOSH, 1997). In the literature, a great amount of interest and effort has been devoted to characterizing the translation of external loading into internal response which then can be compared with available spine tolerance data such that the risks of potential injuries or disorders can be assessed and job recommendations can be developed (NIOSH, 1981; Waters et al., 1993). Numerous studies provide important tolerance data (Adams & Dolan, 1995; Dolan & Adams, 2001; Gallagher, 2003), that has been used to develop more complex biomechanical models and provide us better insights regarding the stress response of the human spine to loads experienced during lifting tasks (A. B. Schultz & Andersson, 1981; Freivalds et al., 1984; Marras & Sommerich, 1991a,

1991b; Chaffin, Andersson, & Martin, 2006). In addition, the output of these biomechanical models has been incorporated in ergonomic evaluation assessment methods or "tools", some of which are commonly used in industry and have helped establish safe work practices for lifting tasks (NIOSH, 1981; Waters et al., 1993; Merryweather et al., 2009; "University of Michigan, 3D Static Strength Prediction Program (3D SSPP)", 2012). However, since biomechanical models in general are representations of the complex phenomena and interactions between the human body and external loads, assumptions have to be made to reduce the complexity to allow researchers to assess the possible consequences (Chaffin et al., 2006). It should be noted that one of the fundamental simplifications assumed by the biomechanical models and ergonomic tools is a simplified description of spine geometry, especially the intervertebral discs and spinal curvature. Typical assumptions are to either model the spine as a single straight line despite the volume and curvature of the spine (Merryweather et al., 2009), or to employ an "average" profile of spine geometry measured for an "average person" to represent the entire population (Chaffin, 1969). This simplification hinders the translation of external loads to the actual tolerance data of spinal tissues, which have been obtained by testing individual specimens. It has been noted that there is a large variance among the tolerance data indicating possible confounding effects introduced by age, gender, and degeneration (Jager & Luttmann, 1989). Since the tolerance data has been dominantly reported as force-based measurements, especially the compressive strength (F. G. Evans & Lissner, 1959; Sonoda, 1962; Markolf & Morris, 1974), it may explain why the geometric dimensions of intervertebral disc in particular are simplified as as single pivot points where the compressive forces are applied. In the literature, it has been noted that spine geometry is essential to model spinal movements

accurately (Gallagher, 2003). On the other hand, bone mineral content, as a function of bone mineral density and the size of the load-bearing surface, determines the ultimate compressive strength of a lumbar motion segment (Brinckmann et al., 1989). Some studies also suggested that geometric characteristics may also influence the mechanical responses of lumbar motion segments to physiologic loads (Natarajan & Andersson, 1999). Therefore, it will be very beneficial to have accurate descriptions of spine geometry as inputs and explore the possibility of relating the structural characteristics to the mechanical properties. As for the practice of ergonomic evaluations in industry, it will also be important to explore the benefit of incorporating spine geometry in terms of a model's effectiveness to improve risk assessment of work-related low back pain.

However, while a number of studies to date have provided the geometry data regarding the intervertebral discs *ex vivo* (cadaver) and *in vivo* (live individual), and some important insights have been achieved (Nissan & Gilad, 1984; Twomey & Taylor, 1987), there is a lack of standardized measurement protocol, such as definitions and modality (X-ray, Computed Tomography, and Magnetic Resonance Imaging) of measurements, which prevent direct comparison or further generalization of findings. In addition, an accurate description of spinal geometry is a prerequisite to characterize exposure levels associated with manual material handling (MMH) tasks with respect to the different spinal structures among individual workers, hence the risk of musculoskeletal disorders (MSDs). To measure the internal spinal geometry internal, medical imaging techniques would be ideal, providing accurate reconstruction of the region of interest which helps to obtain reliable measurements. However, in industry, occupational ergonomics and health practitioners would prefer a more cost-effective, efficient, and non-invasive means to

approach the internal spinal morphometry. Therefore, there is an urgency for a cost-effective and easily-accessible means to provide reliable and accurate descriptions of the lumbar motion segments (the intervertebral discs and vertebral endplates) and for a better understanding and characterization of the variations of spinal morphometry within the working population.

The purpose of this review is to examine current epidemiological evidence of work-related low back pain (WRLBP) regarding personal risk factors, and to summarize and compare the findings reported in the literature with respect to the internal responses of the lumbar motion segments to external loads as well as the influence of disc degenration. This review also addressed the development of biomechanical models of human spine and the ergonomic evaluation measures with respect to the strength and weakness in risk estimation. Finally, this review summarized and evaluated morphometric studies in the literature with respect to the measurement protocols, the techniques, and the results.

2.2 Epidemiology of personal risk factors

As noted by the National Institute for Occupational Safety and Health (NIOSH), considerable variations have been evident not only between individuals regarding their capacity to perform the physical act of lifting but also within any given individual over time (NIOSH, 1981). As mentioned in Chapter One, several personal risk factors were excluded from the NIOSH lifting guidelines. Despite the limitation of epidemiological studies, recent literature has reported more evidence depicting a clearer relationship regarding the influence of these personal risk factors. Hence, it is necessary to revisit these personal risk factors and to review their association with work-related low back pain.

Manchikanti (2000), after a comprehensive review of epidemiological evidence reported in over 200 papers, concluded that age was a factor with "probable" association with low back pain, and gender and obesity were "possible" risk factors.

2.2.1 Gender

NIOSH perspective

During the development of the NIOSH lifting guidelines, the literature review revealed a possible association between gender and the risk of overexertion injury experienced by the workforce. The earlier epidemiological evidence indicated that females were more likely to report low back pain than males when required to perform heavy, physical jobs. However, according to Chaffin and Park (1973), when performing equally demanding, light-to-moderate lifting jobs, no gender difference was found in terms of the incidence of low back injury cases. Therefore, though there was evidence indicating that females had approximately 70% of males' aerobic capacity and 60% of males' lifting strength, the final biomechanical design criterion identified strength as the major risk factor not gender, and compensated the female population for their strength limitation on a overall population basis (NIOSH, 1981; Waters et al., 1993). In other words, presumed lifting capacities were decreased for the entire population of female workers. This would tend to overestimate risk to male workers.

Recent evidence

A recent systematic review summarized the epidemiological studies and concluded that physical demands may have significant impact on the incidence of work-related low back pain (WRLBP) as females were more susceptible when performing heavy, physical

jobs (Garg & Moore, 1992). It was also noted that male victims of WRLBP exhibited more severe injuries given the evidence that they filed more workers' compensation claims and underwent surgical procedures nearly twice as often as their female counterparts (Garg & Moore, 1992). In another systematic review, little or no evidence was reported between male and female populations in terms of susceptibility to WRLBP (Frymoyer, 1992). Later, Behrens and colleagues (1994), after reviewing the statistics of the 1988 Occupational Health Supplement, part of the National Health Review Survey, reported that the prevalence of back pain was 1.7% for females and 3.2% for males from injury at work , and was 3.6% for females and 5.2% for males from repeated activities at work. However, according to the National Center for Health Statistics (NCHS), over the past decade, females experienced a higher prevalence of low back pain than males (NCHS, 2011). Another national survey also reported the same difference in the prevalence of low back pain of both genders (Gore et al., 2012).

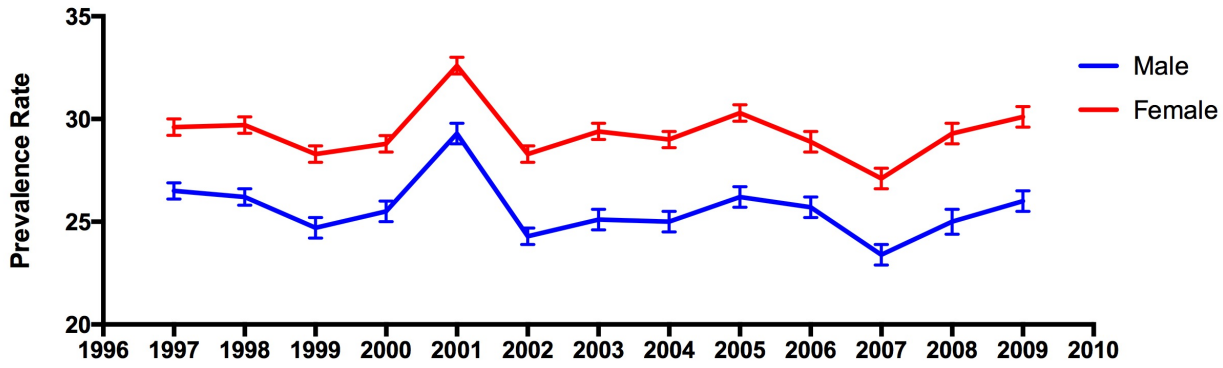


Figure 2.1: Low back pain among adults 18 years of age and over by gender: United States, selected years 1997-2009 (NCHS, 2011, Table 52)

A comprehensive review found that only 2 out of 24 studies investigating gender effects found significant correlations (S. A. Ferguson & Marras, 1997). It was also noted

that the results were considerably associated with the surveillance measures used in these studies (S. A. Ferguson & Marras, 1997). Based on the low back injury statistics reported by Bureau of Labor Statistics (BLS), Mital and colleagues (1999) concluded that from 1993 to 1995, male workers reported about 66% of all injuries to the lumbar region. Marras (2000) later suggested the interaction between gender and age, where the risk of low back pain might peak earlier for male than for female. It was also reported that lifting tasks might generate different mechanical consequences for male and female such as anterior-posterior shear force (Marras, Davis, Heaney, Maronitis, & Allread, 2000). Manchikanti (2000) also noticed that the conflicting evidence of gender influence and suggested strong correlation between personal and occupational factors. In another review, however, van Tulder and colleagues (2002) reported no strong evidence indicating the significance of gender. In a recent review, Rubin (2007) confirmed the inconsistency in the incidences of low back pain between genders, and also suggested that the difference may be only significant for older populations. In a recent study using clinical settings, Waterman and colleagues (2012) compared the statistics of LBP-related emergency room visit and reported no significant difference in incidence rate based on gender.

2.2.2 Age

NIOSH perspective

The NIOSH guidelines acknowledged age as a potential risk factor. However, age was less well understood at the time. With limited epidemiological evidence, only speculation was drawn that older workers had less capacity to withstand physical stresses introduced by lifting tasks. It was suggested that age could be confounded by job experience as older

workers may perfect their lifting techniques in handling heavy loads while younger workers with experience may overly stress themselves by employing less efficient lifting styles (NIOSH, 1981).

Recent evidence

Garg (1992) summarized several features describing the influence of age, where the first episode of low back pain (LBP) usually began early in life, the incidence would peak between the 30s and 50s, and the recurrences, duration and severity increased with age. It was also noted that most surgical procedures were performed for victims between the age of 35 and 45. With etological evidence, Frymoyer (1992) reported similar findings among victims of sciatica and disc herniation. In the same study, it was reported that the site of disc herniation along the lumbar spine changed with aging process where herniation at lower lumbar levels occurred in earlier ages and herniation at upper levels was more common among older populations (Frymoyer, 1992). The statistics, reported by Behrens and colleagues (1994), confirmed the earlier findings in which back pain was more common for victims between the ages of 30 and 64. Battié and colleagues (1995) reported that the introduction of age into multivariate analysis could increase the explained variability from 7% to 16% in disc degeneration with MRI-derived diagnosis. Ferguson and Marras (1997) also reported that more studies (11 out of 31 studies) found significant evidence for an aging effect. Mital and colleagues (1999) reported more specific findings that between the ages of 25 and 34, more low back injuries were documented (about 33%) comparing to 30% between the ages of 35 and 44, 15% between the ages of 45 and 54, and 7% above the age 55. Manchikanti (2000) estimated that the elderly had the highest prevalence of LBP (27%) compared to adults (15%), and children and adolescents (12%). Manek and

MacGregor (2005) discovered that there was growing evidence to indicate that the onset of the first episode of LBP occurred earlier in life than previous reported in the literature, which was later supported by Rubin (2007). Waterman and colleagues (2012) found that the peak of incidence in life differed between male and female victims and reported that LBP peaked between 25 and 29 years of age, while the highest incidence was experienced for victims between 20 and 39 years of age. According to the National Center for Health Statistics (NCHS), older populations (45 to 64 years) experienced higher prevalence rates for low back pain than the younger populations (18 to 44 years) (NCHS, 2011). Another national survey also reported the same difference in the prevalence rate for low back pain between the two age groups (Gore et al., 2012).

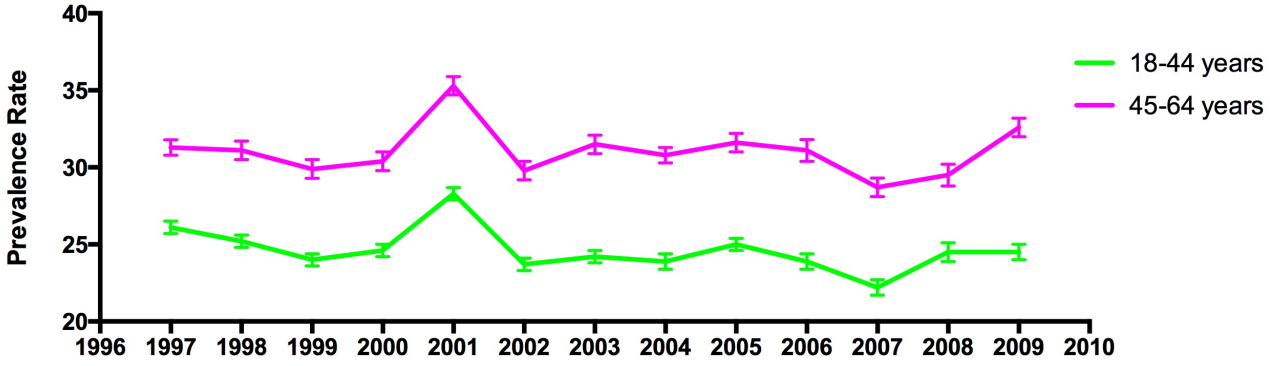


Figure 2.2: Low back pain among adults 18 years of age and over by age: United States, selected years 1997-2009 (NCHS, 2011, Table 52)

2.2.3 Anthropometry

NIOSH perspective

It has been noted in the NIOSH lifting guidelines that body weight and height were the two attributes that posed complex effects on the risk of injury an individual may

experience during manual material handling tasks. It was reported that the heavier body weight resulted in elevated physiological response measured by metabolic energy expenditure. Meanwhile, it was also suggested there was a relationship between body weight and strength such that a heavier individual may have more musculature and capability to lift. However, epidemiological studies found no correlation between body weight and incidence of low back pain (Chaffin & Park, 1973). One study indicated taller people may have more low back pain incidents (Tauber, 1970). Despite minimal empirical evidence at the time, the guidelines still urged the need to consider anthropometry in relation to the physical characteristics of the prospective workplace in terms of reach and mobility.

Recent evidence

Compared to gender and age, anthropometric characteristics (e.g., height, weight, and obesity) are not common attributes in epidemiological studies and thus have received much less attention. Recently, more epidemiological evidence has been found depicting the significance of these characteristics on the prevalence of low back pain. (Heliövaara, 1987; Böstman, 1993; T. S. Han, Schouten, Lean, & Seidell, 1997; Kopec, Sayre, & Esdaile, 2003; Webb et al., 2003; Rubin, 2007; Hoy, Brooks, Blyth, & Buchbinder, 2010). In an 11-year follow-up study of 332 men and women patients of lumbar disc herniation, taller body height and increased body mass index were found to be associated with elevated risk of lumbar intervertebral disc herniation (Heliövaara, 1987). According to this study, it was reported that females with 170 cm body height or more and males with 180 cm body height or more were 3 times more likely to experience sciatica caused by herniation of lumbar intervertebral disc (Heliövaara, 1987). Heliövaara (1987) also found that increased

body mass index was an independent risk factor for lumbar disc herniation in only male patients. Later, another long-term cohort study for lumbar disc herniation studied a much larger sample of patients (1,128 patients) aged between 20 and 59 years, and reported that except for the one age group (from 50 to 59 years), patients who underwent surgery for a disc herniation had significantly heavier body height and elevated obesity level (Böstman, 1993). Further, the investigation also revealed that young female group (from 20 to 29 years) exhibited the most contrast in body mass index (Böstman, 1993). Han and colleagues (1997) also reported that only obese females had a significantly elevated risk of low back pain in a 2-year cohort study with more than 12,000 Dutch subjects. Another large scale cohort study in the United Kingdom has also identified obesity as an independent predictor of back pain and its severity (Webb et al., 2003). Recently, Kopec and colleagues (2003) in their cohort study found that height was a significant predictor in men only. In a recent review, Rubin (2007) also noted that obesity was an independent predictor for the development and severity of LBP, but reported that the association may be stronger in females than in males.

On the other hand, some studies have also suggested that the influence of anthropometric characteristics were not unanimously significant and may be minimal with respect to low back pain (Andersson, 1981; Frymoyer, 1992; Garg & Moore, 1992; S. A. Ferguson & Marras, 1997; Leboeuf-Yde, 2000; Manchikanti, 2000; Mangwani, Giles, Mullins, Salih, & Natali, 2010). Even though Andersson (Andersson, 1981) noted the increased risk of low back pain associated with tallness and obesity, it was also suggested that in general body height, weight may have no strong correlation at all due to the conflicting evidence reported in the literature over 30 years. The conflicting evidence has

also been noted by several other researchers (Frymoyer, 1992; Garg & Moore, 1992; S. A. Ferguson & Marras, 1997; Leboeuf-Yde, 2000; Manchikanti, 2000). Ferguson and Marras (1997) reported that less than 20% of literature found relationship between anthropometry and the symptoms of low back pain. Leboeuf-Yde (2000) conducted a systematic literature review of epidemiological studies published between 1965 and 1997, and found that only 32% of studies (21 out of 65) reported significant positive association between body weight and LBP. Manchikanti (2000) reported that though the influence of body height may be significant for certain specific low back disorders (e.g., sciatica), the overall influence was non-related. Recently, evidence has been reported that obesity has no significant association with neither the intensity of low back pain nor the recovery from the pain (Mangwani et al., 2010). It was generally believed that obesity affects the biomechanics of the human body in terms of the compressive force applied as well as the its physiological capability to perform repetitive lifting tasks (Ayoub & Mital, 1989).

2.2.4 Summary

More epidemiological evidence has been reported in recent literature regarding the associations between subject characteristics (gender, height, weight, etc.) and the risk of low back pain. In general, while it is still unclear whether the susceptibility of low back pain differs between two genders (Frymoyer, 1992), it is evident that male workers report more low back pain incidents (Mital Anil, 1999; Marras, 2000). While in general, the incidence of low back pain peaks between the 30s and 50s (Garg & Moore, 1992; Behrens et al., 1994), new evidence has indicated that the onset of the first episode of low back pain may occur earlier in life (MacGregor, Andrew, Sambrook, & Spector, 2004; Rubin, 2007).

New evidence also suggests that the risk of low back pain may be closely related to subject anthropometric characteristics (Heliövaara, 1987; Böstman, 1993; Webb et al., 2003). These studies indicate an urgent need to consider these relationships in occupational ergonomic practices to better characterize the risk of work-related low back pain (WRLBP).

2.3 Development of biomechanical models and ergonomic tools for lifting tasks

2.3.1 Biomechanical design criterion

The nature of a lifting task requires an individual to generate energy by metabolism, which is then converted to work and applied to the object. Therefore, by investigating the biomechanical and physiological aspects of the lifting, the actual physical stress on the human body such as muscles and joints could be estimated accurately (NIOSH, 1981). With comprehensive anthropometric measurements, researchers have been able to characterize the weight distribution of body segments as well as the locations of centers of mass (Dempster, 1955; Drillis, Contini, & Bluestein, 1964; Clauser, McConville, & Young, 1969), which has become extremely important for the development of comprehensive biomechanical models with respect to kinetic and kinematic analyses (Chaffin et al., 2006).

A number of studies have been performed to develop biomechanical models to characterize the influence of external loads lifted. These biomechanical models vary in capability to analyze complex spinal motions. Some models are designed for simple two-dimensional (2D) sagittal-plane motions and, therefore, employ more assumptions regarding spinal musculature in order to provide easy and quick calculation of compressive force (Chaffin, 1969; Freivalds et al., 1984; Merryweather et al., 2009). With advances in

modeling spinal musculature (McGill & Norman, 1985; Moga, Erig, Chaffin, & Nussbaum, 1993; Nussbaum & Chaffin, 1996; Jorgensen et al., 2001; Jorgensen, 2001; Marras et al., 2001; Jorgensen, Marras, & Gupta, 2003),three-dimensional (3D) biomechanical models have been developed to better capture the complexity of the musculature by characterizing the contributions of multiple spinal muscle groups such that the interactions of complex spinal motions and loads can be estimated (Gracovetsky et al., 1981; A. B. Schultz & Andersson, 1981; Marras & Sommerich, 1991a, 1991b).

Ergonomic evaluation assessment methods or "tools", on the other hand, have to account for other aspects associated the lifting tasks. According to the National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 1981; Waters et al., 1993), three design criteria were integrated into the NIOSH lifting guidelines: (1) biomechanical, (2) physiological, and (3) psychophysical aspects of manual lifting tasks. The final model determined the risk by aggregating these aspects to determine a recommended weight limit for a specific task (Waters et al., 1993). The calculated load value was deemed as safe if 99th percentile healthy female and 75th percentile healthy male workers could perform the sustained lifting task for over a substantial period of time without an elevated risk of developing work-related low back pain (Waters et al., 1993).

In the first NIOSH guideline, the cut-off point for compressive force applied to the intervertebral disc was 3.4 kN (770 lbs), above which point potential tissue damage was assumed could occur (NIOSH, 1981). This compressive tolerance value was estimated by analyzing the compressive strength data reported in two studies (F. G. Evans & Lissner, 1959; Sonoda, 1962). Evans and Lissner (1959) reported the maximum compressive load that the lumbosacrum column could sustain with 8 embalmed specimens (from 47 to 85

years, average 75.6 years of age) and 3 unembalmed specimens (from 37 to 58 years, average 48.7 years of age), in which embalmed specimens exhibited larger compressive loads sustaining 882 lbs (610 to 1350 lbs) (400 kg, 277 kg to 612 kg) of force than the unembalmed spines (average 544 lbs, range from 290 to 690 lbs) (247 kg, 131 kg to 313 kg). Later, Sonoda (1962) isolated the motion segments containing one intervertebral disc and two adjacent endplates from 26 Japanese specimens (from 22 to 76 years of age) and performed a compressive loading test. It was reported that the maximum compressive load was 1500 kg in the lumbar intervertebral discs from 40 to 59 years of age (Sonoda, 1962). The influence of age was also characterized. Younger lumbar vertebral bodies (from 20 to 39 years) had a larger maximum compressive load limit (730 kg) than the mid-age group (from 40 to 59 years) estimated at 78% of younger group,and than the older group (60 to 79 years) at 49% (Sonoda, 1962). It was also noted that the maximum compressive load in female vertebral bodies corresponded to about 83% of that in males (Sonoda, 1962).

On the other hand, according to Chaffin and Park (1973) who estimated the compressive force associated with lifting tasks using biomechanical models, it was noted that lifting tasks with compressive loads over 650 kg had significantly increased incidence of low back pain, which then was incorporated in the guideline as an essential criterion to establish the maximum permissible limit (MPL). After a comprehensive review of evidence, an action limit (AL) for manual lifting tasks was established at 3.4 kN using a 350 kg compressive load as the criterion for the upper limit (NIOSH, 1981). This biomechanical design criterion was maintained during the revision process for the second version of the NIOSH lifting guidelines, with the evidence reported in field studies which supported the association between compressive force and the incidence of low back pain (Waters et al.,

1993). This value is within the range of compressive failure forces reported in cadaver studies in the literature (Figure 2.3)(Chaffin et al., 2006). Jäger and Luttmann (1989) reported a mean value of 4.36 kN with a standard deviation of 1.88 kN compressive force collected for 307 lumbar segments from various studies.

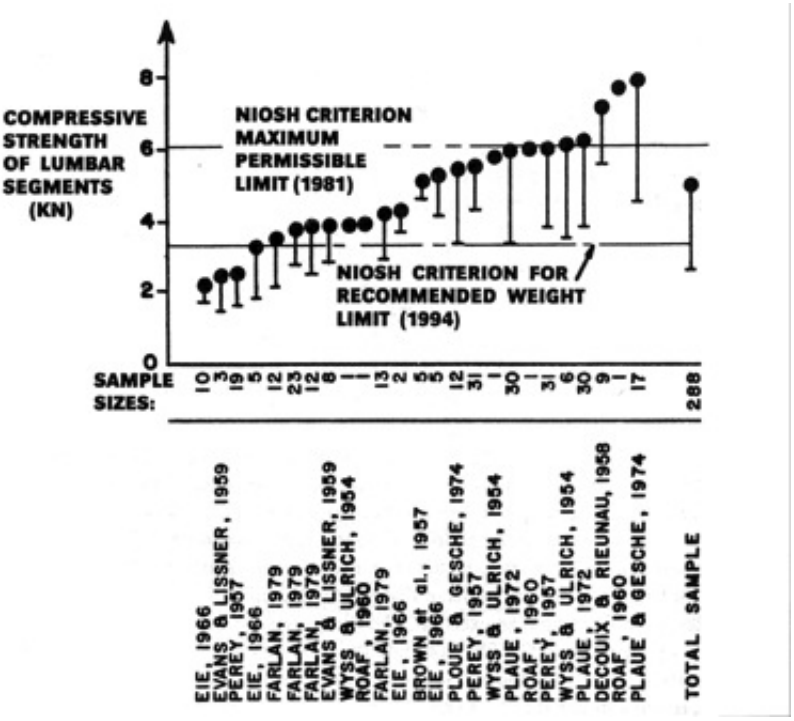


Figure 2.3: Results of cadaver studies examining compressive forces of lumbar vertebral segments (figure from Chaffin et al. 2006, based on data presented in Jäger and Luttmann 1987)

2.3.2 Choice of measure: compressive force or compressive stress

In the literature, a lumbar motion segment has generally been referred to as one intervertebral disc and the two adjacent cranial and caudal vertebral bodies (Adams & Hutton, 1982; Brinckmann et al., 1989), though in few studies it has also been reported as a specimen with multiple-level discs (F. G. Evans & Lissner, 1959). A majority of studies in the literature to date have reported compressive force as the primary outcome measure

for the ultimate strength that a lumbar motion segment can sustain (F. G. Evans & Lissner, 1959; Sonoda, 1962; Adams et al., 1980; Adams & Hutton, 1982; Hutton & Adams, 1982; Adams & Hutton, 1983; Brinckmann et al., 1987; Biggemann, Hilweg, & Brinckmann, 1988; Brinckmann et al., 1989). Compressive force is a very useful measure in biomaterial testing. Typically, lumbar motion segments are placed directly in (F. G. Evans & Lissner, 1959) or enclosed in a customized apparatus (Hutton & Adams, 1982; Brinckmann et al., 1989) and then a universial testing machine with force gauge is used to measure the specimen to failure.

However, mechanical theory states that the tolerance of one material to compressive loading is an intrinsic property that is related to its density, volume, cross-sectional area, and other physical characteristics. These properties can vary tremendously from one material to another. In addition, the ultimate strength, as measured by force, is also dependent on the size of the test sample. For example, a steel rod with larger cross-sectional area will sustain higher compressive force than a rod of the same material with a smaller cross-sectional area. A number of studies have suggested that the compressive spinal loadings are evenly distributed over the load-bearing surface in healthy intervertebral discs (Farfan, 1973; Adams, McNally, & Dolan, 1996; Dolan & Adams, 2001).

The intrinsic properties of the spinal motion segments may explain the large variation among compressive force data reported in the literature, not to mention the uniqueness and various conditions of human tissues. There have been a few studies attempting to characterize the intrinsic properties by normalizing the compressive force with the cross-sectional area (Sonoda, 1962; Kazarian & Graves, 1977; Porter, Adams, & Hutton, 1989). Also, a number of studies have documented the cross-sectional areas of the spinal

motion segments while reporting the the compressive force (Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989). Therefore, this dissertation has attempted to summarize these data by normalizing with the author's reported cross-sectional areas (CSAs). Table 2.1 summarizes the demographic data reported in these studies. Table 2.2 summarizes the compressive forces, cross-sectional areas, and compressive stresses reported or computed from the data reported in these studies.

Table 2.1: Demographic data reported in cadaver studies

			Age (years)				Body weight (kg)			
	Gender	N	Mean	SD	Min	Max	Mean	SD	Min	Max
Sonoda (1962)	F + M	26	-	-	22	76	-	-	-	-
Farfan (1973)	-	13	62.20	15.53	32	85	-	-	-	-
Kazarian and Graves (1977)	M	4	30.75	5.50	26	38	-	-	-	-
Hansson, Roos, and Nachemson (1980)	F	21	57.67	11.08	34	74	-	-	-	-
	M	15	59.73	15.35	31	79	-	-	-	-
Hutton and Adams (1982)	F	5	52.00	12.43	40	73	67.00	17.22	47.00	90.00
	M	13	38.31	11.95	22	59	68.46	13.99	39.00	86.00
Biggemann et al. (1988)	F	12	49.15	21.70	20	79	-	-	-	-
	M	16	49.93	17.16	22	77	-	-	-	-
Brinckmann et al. (1989)	F	22	-	-	-	-	49.86	18.36	20	79
	M	31	-	-	-	-	48.00	16.16	19	77
Porter et al. (1989)	M	9	21.89	4.78	16	32	72.44	5.85	67.00	86.00

"-": data not available

Table 2.2: Ultimate compressive strength data reported and summarized from the literature*

Study		Spinal Segment	N	Compressive Force	Cross-sectional Area	Compressive Stress	Compressive Stress$^{\heartsuit}$ (N/mm^2)
Sonoda (1962)	IVD$^{\spadesuit}$	Cervical	26	320 (-)	326 (7)	1.08 (-)	10.59 (-)
(kg, mm^2, kg/mm^2)		Upper Thoracic		450 (-)	432 (13)	1.02 (-)	10.00 (-)
		Lower Thoracic		1150 (-)	870 (34)	1.08 (-)	10.59 (-)
		Lumbar		1500 (-)	1088 (18)	1.12 (-)	10.98 (-)
	VB$^{\diamondsuit}$	Cervical	26	315 (-)	-	1.03 (-)	10.10 (-)
		Upper Thoracic		308 (-)	-	0.72 (-)	7.06 (-)
		Middle Thoracic		345 (-)	-	0.61 (-)	5.98 (-)
		Lower Thoracic		458 (-)	-	0.54 (-)	5.30 (-)
		Lumbar		505 (-)	-	0.47 (-)	4.61 (-)
Farfan (1973)	IVD	T11/T12	1	1000	2.47	400	2.76
(lb, in^2, lb/in^2)		L1/L2	10	832 (266.82)	2.03 (0.32)	446.80 (145.45)	3.08 (1.00)
		L2/L3	3	746.67 (167.73)	2.32 (0.20)	327 (105.70)	2.25 (0.73)
		L3/L4	4	835 (270)	2.15 (0.30)	387.25 (96.50)	2.67 (0.66)
		L4/L5	5	1010 (222.26)	2.07 (0.41)	513 (199.28)	3.53 (1.37)
	VB	Thoracolumbar	13	955.38 (289.84)	2.09 (0.27)	438.08 (150.15)	3.02 (1.03)
Kazarian and Graves (1977)	VB	Thoracic	61	1475.75 (741.17)	1.73 (0.59)	847.18 (263.51)	5.84 (1.82)
(lb, in^2, psi)							
Hansson et al. (1980)	IVD	T12/L1	32	3261.28 (1196.15)	15.06 (2.48)	-	2.15 (0.93)
(N, cm^2)		L1/L2	33	3796.34 (1611.45)	16.51 (2.67)	-	2.39 (0.93)
		L2/L3	29	4109.65 (1866.71)	17.92 (2.67)	-	2.30 (0.94)
		L3/L4	15	4806.53 (2103.00)	19.62 (3.40)	-	2.47 (0.95)
Hutton and Adams (1982)	IVD	L1/L2	3	7790.00 (3889.18)	14.13 (2.91)	-	5.42 (1.75)
(N, cm^2)		L2/L3	10	6625.90 (2435.08)	17.49 (3.59)	-	3.78 (1.17)
		L3/L4	6	7982.00 (3068.47)	15.58 (2.66)	-	4.99 (1.28)
		L4/L5	10	7513.90 (2515.31)	18.18 (3.69)	-	4.11 (1.18)
		L5/S1	4	11627.5 (1465.41)	17.52 (2.23)	-	6.67 (0.77)
Biggemann et al. (1988)	EP	Thoracic	6	5.73 (2.44)	12.92 (1.17)	-	4.40 (1.73)
(kN, cm^2)		L1	7	3.67 (0.73)	12.37 (2.07)	-	3.05 (0.87)
		L2	5	5.34 (1.67)	15.50 (2.66)	-	3.56 (1.39)
		L3	6	5.82 (1.67)	16.05 (3.00)	-	3.68 (1.07)
		L4	5	7.08 (2.75)	15.44 (2.46)	-	4.52 (1.57)
		L5	7	4.80 (0.95)	16.14 (2.63)	-	3.04 (0.77)
Brinckmann et al. (1989)	EP	Thoracic	33	4.58 (1.67)	13.12 (2.50)	-	3.50 (1.12)
(kN, cm^2)		L1/L2	12	4.90 (1.97)	14.42 (2.94)	-	3.54 (1.61)
		L2/L3	23	5.57 (1.60)	16.51 (3.36)	-	3.44 (1.04)
		L3/L4	7	6.10 (1.67)	16.23 (4.70)	-	4.06 (1.47)
		L4/L5	23	5.70 (1.89)	16.93 (2.70)	-	3.41 (1.18)
Porter et al. (1989)	IVD	L2/L3	9	8756.44 (2414.01)	16.82 (1.35)	518.46 (124.42)	5.18 (1.24)
(N, cm^2, N/cm^2)		L4/L5	9	9597.67 (1425.92)	18.50(1.74)	520.55 (73.86)	5.20 (0.74)

*: 1 kg/mm^2 = 9.81 N/mm^2, 1 psi = 6.89×10^{-3} N/mm^2

IVD: intervertebral disc; VB: vertebral body; EP: vertebral endplate

$^{\heartsuit}$: IVDcomputed in this dissertation with data reported in the literature

$^{\spadesuit}$: compressive force and cross-sectional area measured with specimens between 22 and 76 years of age

$^{\diamondsuit}$: compressive force and stress reported for specimens between 40 and 59 years of age, area measured with specimens between 20 and 59 years of age

As shown in Figure 2.4, the lumbar ultimate compressive strength, when reported as compressive force, varies within a wide range across all lumbar levels, which agrees with the findings reported by Jager and Luttmann (1989). Compressive stress, as another biomechanical measure, exhibited similar characterization of ultimate strength possessed by lumbar motion segments across different spinal levels (Figure 2.5). In addition, the normalization process reduced the variance found in the data of compressive force to some extent. On the other hand, the normalized data of ultimate compressive strength (compressive stress) exhibited a different pattern of variation. It may provide a different paradigm to characterize the mechanical properties of the lumbar motion segments, as reported in some previous studies (Sonoda, 1962; Edmondston, Singer, Day, Breidahl, & Price, 1994; Singer, Edmondston, Day, Breidahl, & Price, 1995). Edmondston et al. (1994) tested 12 thoracolumbar vertebral bodies from an older population (mean: 73 years; range: 51-90 years) and reported that across the lower thoracic and upper lumbar region, the compressive ***force*** increased progressively in craniocaudal direction, while the compressive ***stress*** reduced proportionally. Singer et al. (1995) also noted the increase in compressive ***force*** and the decrease in compressive ***stress*** and suggested that the decrease in compressive ***stress*** was consistent, despite the wide range in age and bone density (Singer et al., 1995).

As shown in Table 2.3, these studies employed similar loading profiles, such as a low rate of displacement or slow increase in the compressive force applied.

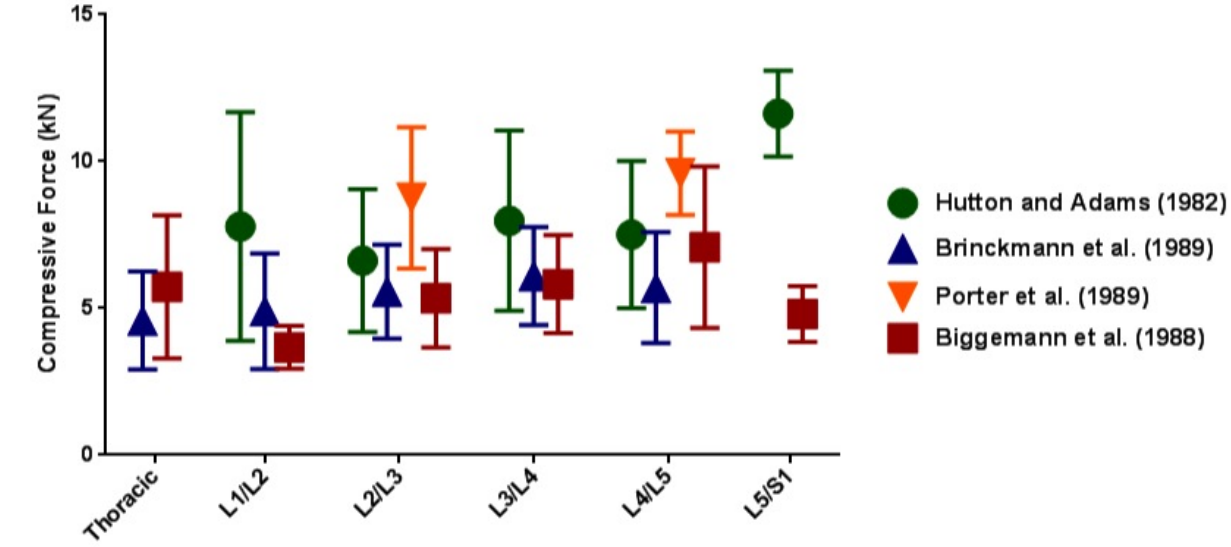


Figure 2.4: Summary of compressive forces reported in cadaver studies with particular reference to the intervertebral discs

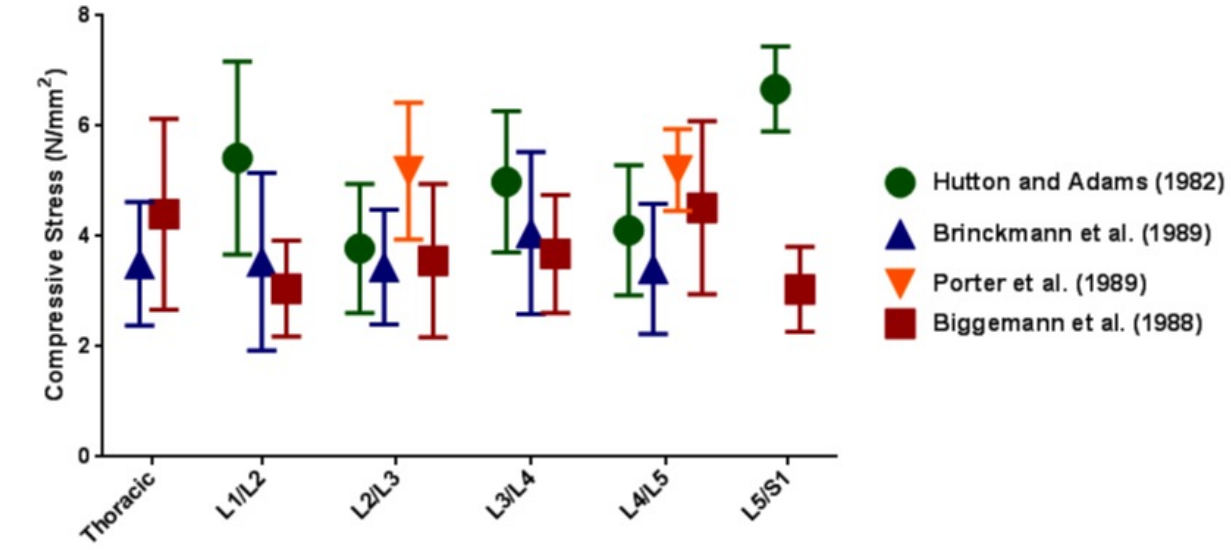


Figure 2.5: Summary of compressive stresses computed from data reported in cadaver studies with particular reference to the intervertebral discs

Table 2.3: Summary of cadaver studies with respect to the experiment protocols and results

Authors	**Testing Protocol**				**Primary Findings Regarding Spine Geometry**
	Specimen	**Preparation**	**Loading Profile**	**Orientation**	
Sonoda (1962)	26 fresh cadavers; all soft tissue removed	2cm gypsum enclosure	5kg initial, 20kg incremental load; pure axial loading	One intervertebral disc (IVD) with two partial vertebral bodies (VBs)	1. Large variance in compressive forces across the different spinal regions; 2. Large difference in cross-sectional areas measured; 3. Less variance in compressive stress; 4. Reduced compressive force with aging; 5. Female vertebral bodies corresponded to about 83% of male vertebral bodies in compressive force
Kazarian and Graves (1977)	4 healthy male cadavers; all soft tissue removed; deeply frozen in 36 hrs	A cylindrical aluminum block, test fixture chamber	Displacement rate: 1. 2100 in./min, 2. 21 in./min, 3. 0.21 in./min; pure axial loading	One VB with two partial IVDs sliced through the midsections	1. Compressive forces exhibited a decreasing trend with decreasing displacement rate; 2. Two subjects had significantly greater compressive forces than the other two; 3. However, dimensional data were not reported for specific subjects
Hansson et al. (1980)	36 fresh lumbar segments; all soft tissue removed; deep frozen	Metal plates covering both endplates	Displacement rate: 5mm/min; pure axial loading	One VB with two 3-mm thick IVDs	1. Significant positive correlation between compressive force and bone mineral content (BMC) ; 2. **Significant linear positive relationship between compressive stress and BMC**; 3. Different relationships between male and female subjects; 4. reported ratio of 229 N
Hutton and Adams (1982)	18 lumbar spines, 15 deeply frozen and 3 fresh; no bone disease	Custom-made apparatus	Preloaded with 1 kN; 3 kN/s incremental load; loaded in slightly flexed position	Two VBs and the intervening soft tissue with no posterior ligaments	1. Compressive strength decreased with aging; 2. Compressive strength increased significantly with increasing body weight for male subjects; 3. For average young men, intra-abdominal pressure not necessary to avoid crushing the spine
Biggemann et al. (1988)	32 thoracolumbar spines	Simulated *in vivo* environment with 36.5 degree; custom-made apparatus with metal cups filled with cement	1 kN/s incremental load; pure axial loading	Two VBs with intact posterior elements and one intact IVD	1. Ultimate compressive strength correlated with the product of bone density and the area of fractured endplate; 2. suggested that larger area may compensate for a low bone density; 3. **suggested an *in vivo* prediction for the compressive strength of vertebral bodies**
Brinckmann et al. (1989)	53 fresh thoracolumbar spines	Simulated *in vivo* environment with 36.5 degree; custom-made apparatus with metal cups filled with cement	Preloaded with 1 kN for 15 min; 1 kN/s incremental load; pure axial loading	Two VBs with intact posterior elements and one intact IVD	1. *In vivo* prediction: **Compressive strength (kN) = 0.32 + 0.00308×density×endplate area**; 2. On average, endplate area increased in the cranio-caudal direction by 0.5±1.9 cm^2 per endplate; 3. Noticeable dependence of the prediction on age, gender and anatomical level; 4. Fracture occurred preferentially in the cranial endplate of the caudal vertebral body regardless of orientation
Porter et al. (1989)	9 fresh lumbar spine, deeply frozen	two cups of dental plaster	3 kN/s incremental load; loaded in slightly flexed position	Two VBs and the intervening soft tissue with no posterior ligaments	1. Significant increase in compressive strength with physical activity for adult spines; 2. Degeneration status reported as nondegenerated; 3. Endplate fracture found as common failure mode
Gallagher et al. (2007)	18 lumbar spines, frozen	humidified chamber, cumstom-made apparatus	static and dynamic loading, three flexion angles	L1/L2, L3L4, L5/S1 motion segments with ligaments confined to a single segment	1. Younger segments survived much longer due to the larger bone mineral content (BMC); 2. Increasing BMC had protective influence

2.3.3 Prediction of compressive strength

In the literature, studies have suggested several factors (e.g., the spine geometry, bone mineral density, and bone mineral content) that are strongly correlated with the compressive strength of motion segments (Hansson et al., 1980; Biggemann et al., 1988; Brinckmann et al., 1989; Genaidy, Waly, Khalil, & Hidalgo, 1993; Edmondston et al., 1994; Singer et al., 1995; Parkinson et al., 2005; Gallagher et al., 2007). Table 2.4 summarizes the regression models developed in the literature to predict the ultimate compressive strength of the motion segment *in vivo*.

Hansson et al. (1980) reported a significant positive linear relationship between the ultimate compressive strength of lumbar vertebrae and the bone mineral content measured by dual photon absorptiometry (DPA). In this study, it was found that 3.33 (0.09) g/cm of lumbar vertebral bone mineral content (BMC) corresponded to 3850 (163) N of ultimate strength. The correlation remained across all four lumbar vertebrae levels (from L1 to L4). It was also noted that the BMC was higher in male specimens. Despite the fact that both gender groups had similar mean and range of age, other anthropometric data were not reported, such as height and body weight.

Biggemann et al. (1988) measured the trabecular bone mineral content and the cross-sectional areas of fractured endplates using single energy quantitative computed tomography (QCT), which measures the trabecular bone within the vertebral body. They tested several linear regression models for compressive strength (in force) with respect to bone mineral density (BMD) and endplate area. It was found that the linear model

resulted in greater explanatory power and a smaller standard error of the estimate using the product of BMD and endplate area than using BMD alone.

Later, Brinckmann et al. (1989) tested more single-level thoracolumbar motion segments and provided an *in vivo* regression model using the product of bone mineral density (BMD) and the cross-sectional area of endplate. It was also noted that BMD remained constant across the thoracolumbar region while the cross-sectional area increased in craniocaudal direction, suggesting that the increase in compressive strength (in force) may be due to the increase in the size of load-bearing surface. It was also noted that the ultimate strength increased at approximately 0.3 kN per lumbar disc level in craniocaudal direction.

Genaidy et al. (1993) summarized the data reported in the literature and developed two regression models with gross anthropometric variables, demonstrating a feasible solution to estimate the compressive strength with a non-invasive and cost-effective means. Unfortunately, there is a substantial difference in their capabilities to explain the variance (Table 2.4).

Edmondston et al. (1994) determined the thoracolumbar vertebral trabecular density (VTD) and the vertebral body cross-sectional area (CSA) by single-energy QCT, and the total mineral mass and total area density (BMD and BMC) by dual energy x-ray absorptimetry (DXA). In this study, both techniques demonstrated good reproducibility. In this study, BMC and BMD, measured by DXA, demonstrated significant correlation with compressive strength (in force), both of which were improved more than VTD was used. However, when using compressive stress as the failure mode, VTD demonstrated improved correlation while BMC failed to exhibit significant correlation. Unlike the previous studies,

the product of VTD and cross-sectional area failed to demonstrate significant correlation with compressive strength (in force or in stress). In addition, it was also noted that BMC remained constant across the upper thoracic levels (from T1 to T4) and then increased towards lumbar region (from T5 to L2), while BMD demonstrated a U-shaped distribution where the lowest values were found in the mid-thoracic region. Unfortunately, the study only tested 12 specimens and these differences across the spine were not statistically tested.

Singer et al. (1995) employed the same methodology, but tested the complete thoracolumbar region (from T1 to L5) and found stronger correlations between BMC and BMD and the compressive strength (in force) and weaker correlations between VTD and compressive strength (in force). It was noted that when VTD was multiplied by CSA, the correlation became much stronger with compressive strength but failed to improve with compressive stress. In addition, it was noted that the BMC exhibited a steady increase in the craniocaudal direction, while VTD demonstrated a decreasing pattern.

Later, Parkinson et al. (2005), using porcine cervical spinal vertebral units (10 C3/C4 and 10 C4/C5 units), reported that neither bone mineral content nor bone mineral density was significantly correlated with the ultimate compressive force, while only endplate area as the primary variable in the final regression model.

Table 2.4: Regression models to predict the compressive strength of a motion segment

Authors	**Techniques**	**R^2**	***In vivo* Prediction Model**	**S.E.**	**p value**
Hansson et al. (1980)	DPA	0.74	-	0.89	0.01
Biggemann et al. (1988)	QCT	-	CS: BMD	1.40	-
		-	CS: BMD×A(photo)	0.78	-
		-	CS: BMD×A(CT)	0.94	-
Brinckmann et al. (1989)	QCT	0.64	All specimen, CS = 0.32 + 0.00308×D×A	1.06	-
		0.64	Male, CS = 0.42 + 0.00314×D×A	1.08	-
		0.64	Female, CS = 0.45 + 0.00315×D×A	0.98	-
		0.62	Under 50 years, CS = 0.80 + 0.00290×D×A	1.03	-
		0.42	Over 50 years, CS = 0.70 + 0.00262×D×A	1.05	-
		0.70	T10-L1, CS = 0.20 + 0.00301×D×A	0.88	-
		0.58	L2-L5, CS = 0.59 + 0.00298×D×A	1.13	-
Genaidy et al. (1993)	-	0.48	SCTL = -13331.2 - (73.7×AGE) - (962.6×G) + (403.0×LMS) + (79.8×BW)	-	-
	-	0.83	SCTL = 7222.41 - (1047.71×AGE Group) - (1279.18×G) + (56.73×PP)	-	-
Edmondston et al. (1994)	QCT, DXA	0.24	CS: BMC	1.08	<0.0001
		0.56	CS: BMD	0.81	<0.0001
		0.14	CS: VTD	1.15	<0.05
		0.16	Compressive stress: BMD	2.28	<0.05
		0.36	Compressive stress: VTD	1.99	<0.0001
Singer et al. (1995)	QCT, DXA	0.66	CS: BMC	-	0.0001
		0.74	CS: BMD	-	0.0001
		0.08	CS: VTD	-	<0.0001
		0.69	CS: VTD×CSA	-	<0.0001
		0.10	Compressive stress: BMC	-	<0.0001
		0.35	Compressive stress: BMD	-	<0.0001
		0.50	Compressive stress: VTD	-	<0.0001
		0.29	Compressive stress: VTD×CSA	-	<0.0001
Parkinson et al. (2005)	DXA	0.53	CS = 0.65470 + 0.01361 × A	-	0.0003

QCT = quantitative computed tomography
DPA = dual photon absorptiometry
DXA = dual energy x-ray absorptiometry
CS = compressive strength (kN)
D = density (mg/ml, K_2HPO_4)
A = endplate area (cm^2)
SCTL = spinal compression tolerance limits (N)
AGE = age (years)
AGE Group = 1 for age group 20-29 years, 2 for 30-39 years, 3 for 40-49 years, and 4 for 50 years and above
G = gender (male = 1, female = 2)
LMS = lumbar motion segment (L1/L2 = 44, L2/L3 = 45, L3/L4 = 46, L4/L5 = 47, L5/S1 = 48)
BW = body weight (kg)
PP = population percentile (e.g., 50)

2.3.4 Intradiscal pressure

To investigate the internal response or "mechanical disturbance" of the lumbar motion segments to external loads, Nachemson (1960) first proposed a method using pressure disturbance (known as intradiscal pressure) as the primary measure. However, as noted by Nachemson and colleagues (1979), the large variance in cadaver segment mechanical behavior reported in the literature usually overshadows the influence of other factors, such as age and gender. In the literature, intradiscal pressure measurement has been performed in a number of studies to investigate the influence of external loads with respect to load magnitude and characteristics of spinal motions *ex vivo* (Nachemson, 1963, 1965; Nachemson et al., 1979; Ferrara, Triano, Sohn, Song, & Lee, 2005) and *in vivo* (Nachemson & Morris, 1964; Andersson, Schultz, & Nachemson, 1983; Sato, Kikuchi, & Yonezawa, 1999; Wilke et al., 1999, 2001) (Table 2.5 and 2.6). These studies have provided an essential reference as an empirical database. It is evident that forceful lifting tasks result in tremendously high intradiscal pressure within the lower lumbar nucleus (Wilke et al., 1999, 2001), which may consequently lead to tissue damage or permanent changes referring to the ultimate compressive stress computed in Table 2.2.

Table 2.5: Summary of studies investigating the intradiscal pressure with respect to the subject characteristics

Authors	**Levels**	**N**	**Gender**	**Age**	**Height**	**Weight**	**Health**	**Dengeneration**
Nachemson and Morris (1964)	L3/L4, L4/L5	9 6	F M	43.2 (8.35) 44.33 (8.0)	163.67 (11.17) 173.58 (7.13)	64.54 (17.15) 71.00 (10.31)	Chronic low back pain; surgeries; spinal diseases	Normal
Andersson et al. (1983)	L3/L4	4	F + M	21.8	174	62.8	Good health, no history of back injury or significant back pain	no abnormality found on routine examination
Sato et al. (1999)*	L4/L5	8	-	25 (2)	173 (6)	73 (11)	Healthy, no previous or ongoing back problems	No degeneration
		28	10 F + 18 M	45 (19-74)	165 (155-182)	68 (45-88)	Low back pain or sciatica	9 normal, 11 grade 2, 8 grade 3, 8 grade 4
Wilke et al. (1999, 2001)	L4/L5	1	M	45	168	70	Healthy	No degeneration or dehydration
Polga et al. (2004)	T6/T7 to T10/T11	6	2 F + 4 M	28 (19-47)	178 (163-191)	73 (54-81)	Healthy	No pathology
Lisi et al. (2006)	L3/L4	2	M	41/42	5.6/5.11	130/180	Healthy	No abnormality

* Disc degeneration graded according to DeCandido, Reinig, Dwyer, Thompson, and Ducker (1988)

Table 2.6: Summary of studies investigating the intradiscal pressure with respect to the experimental designs and research findings

Authors	Technique	Insertion	Position/Activity	Results	Pressure
				kg/cm^2	MPa
Nachemson and Morris (1964)	Specially constructed needle with a pressure-sensitive polyethylene membrane at its tip, connected to an electromanometer for the pressure recordings	Posterolateral approach with the subject in the sitting position into the center of the L3/L4 or L4/L5	Sitting	12.03	1.18
			Sitting Valsalva Mneuver	14.41	1.41
			Sitting + 9.1 kg	14.39	1.41
			Sitting + 22.7 kg	19.13	1.88
			Standing	8.92	0.87
				kPa	MPa
Andersson et al. (1983)	A subminiature pressure transducer built into the tip of a needle	A guiding cannula inserted from the right posteriorly into the center of the third lumbar disc; cannula penetrated the annulus fibrosus	Standing	270	0.27
			Lying	110	0.11
				kPa	MPa
Sato et al. (1999)	Sensing diaphragm mounted on the side of a 178-mm long, 1.2-mm-diameter stainless steel needle	Inserted in the center of the nucleus pulposus	Lying prone	91	0.09
			Lateral decubitus (lying laterally)	151	0.15
			Upright standing	539	0.54
			Standing, flexion	1324	1.32
			Standing, extension	600	0.6
			Upright sitting unsupported	623	0.62
			Sitting, flexion	1133	1.13
			Sitting , extension	737	0.74
				MPa	MPa
Wilke et al. (1999, 2001)	Flexible-pressure transducer, 1.5 mm in diameter; piezeoresistant pressure sensor integrated in a 7-mm-long metal tip; guided through a relatively stiff polymer tube with an inner diameter of 2.0 mm and an outer diameter of 3.3 mm	Implanted from a dorsolateral transforaminal approach into the center of the nucleus pulposus of the L4/L5 intervertebral disc	Lying supine	0.1	0.1
			Lying laterally	0.12	0.12
			Lying prone	0.11	0.11
			Relaxed standing	0.5	0.5
			Standing, performing vasalva	0.92	0.92
			Standing, bending forward	1.1	1.1
			Sitting relaxed	0.46	0.46
			Sitting with maximum flexion	0.83	0.83
			Jogging	0.35-0.95	0.35-0.95
			Walking barefoot	0.53-0.65	0.53-0.65
			Walking with tennis shoes	0.53-0.65	0.53-0.65
			Climbing stairs	0.30-1.20	0.30-1.20
			Walking down stairs	0.30-0.90	0.30-0.90
			Lifting 20 kg, bent over with flexed back	2.3	2.3
			Lifting 20 kg with flexed knees	1.7	1.7
			Holding 20kg close to the body	1.1	1.1
			Holding 20 kg, 60 cm away from the chest	1.8	1.8
			Increase during night (over 7 hrs)	0.10-0.24	0.10-0.24
			Finger tip to floor exercises	1.6	1.6
			One-handed carrying 20 kg	1	1
			Carring 20 kg with both hands	0.9	0.9
			Lifting two 20 kg loads with both hands	2.1	2.1

In general, measurement of intradiscal pressure offers reliable data when the intervertebral discs are normal or slightly degenerated (Nachemson, 1960). It has also been noted that when there are large irregularities in the nucleus pulposus, or ruptures in the annulus fibrosus or vertebral endplate, the hydrostatic properties of the motion segment change dramatically (Nachemson, 1960; Nachemson & Morris, 1964). The severity of the disc degeneration also significantly influences intradiscal pressure (Horst & Brinckmann, 1981; Adams et al., 1996; Adams, Freeman, Morrison, Nelson, & Dolan, 2000; Dolan & Adams, 2001). Adams et al. (1996) reported that when subjected to a 2 kN compressive force, severely degenerated discs exhibited significantly reduced intradiscal pressure across the disc in anteroposterior (A-P) direction (Figure 2.6). According to the "stress profiles" reported in the literature, the highest compressive stresses usually appear in the middle of the annulus (Dolan & Adams, 2001).

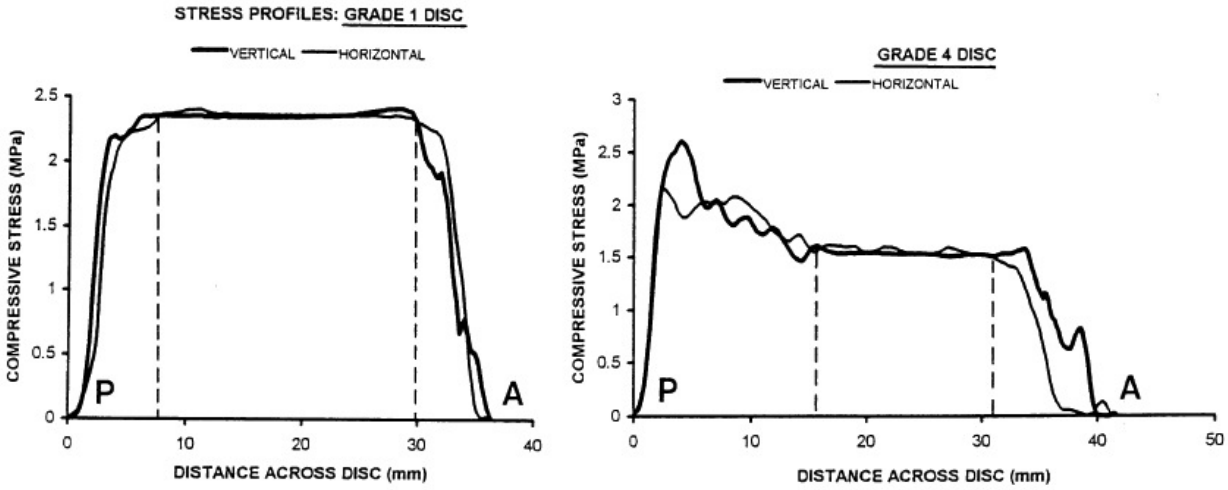


Figure 2.6: Profiles of vertical and horizontal compressive stress along the anteroposterior direction. Antherior (A) on the right. Vertical dashed lines indicate the extent of the hydrostatic nucleus

On the other hand, Nachemson (1960) reported that the measured intradiscal pressure value in the nucleus pulposus was about 50% higher than the applied compressive force divided by the cross-sectional area of the disc. The difference between the two values suggests the need to investigate the functional load-bearing surface of the motion segment, since the peripheral annulus has less contribution to the compressive strength. Disc height and lordotic postures also influence the stress distribution within the disc (Dolan & Adams, 2001; Guehring et al., 2006).

Although *in vivo* intradiscal pressure measurement provides a direct means to determine the internal response in the human spinal motion segments to external loadings or exposures to various forceful activities (Sato et al., 1999), the measuring protocols have very restrictive requirements and should only be performed in well-controlled laboratory conditions. It also poses long-term potential health risk because the annulus fibrosus is punctuated to let in the guiding tube, even though *ex vivo* studies reported no significant change of short-term mechanical behavior (Markolf & Morris, 1974).

2.3.5 Summary

Current biomechanical models have relatively less input regarding the internal geometric characteristics of individuals. There is strong evidence indicating that the ultimate compressive strength of the spinal motion segment is affected primarily by an individual's age, the load-bearing cross-sectional area of the segment, and its bone mineral content. The latter two factors are difficult to obtain and usually require special techniques (e.g., x-ray, QCT, and DXA). The data regarding ultimate compressive force, stress, and

intradiscal pressure have significant potential to improve the validity of biomechanical models for the assessment of occupational musculoskeletal disorders (MSDs).

2.4 Internal exposure and response of lumbar intervertebral disc

No matter what measure is used to characterize the impact of external loads, the internal response of the lumbar motion segment determines the onset and process of tissue deformation, fatigue, or other pathological changes. The principal functions of the intervertebral disc are to allow movement between vertebral bodies and to transmit loads from one vertebral body to the next (Bogduk & Twomey, 1991), which provide the spine the mechanical properties to perform complex, load-bearing movements (S. J. Ferguson & Steffen, 2003; Raj, 2008). Therefore, it is impossible to appreciate the importance of lumbar intervertebral disc with respect to these functions without a review of its structural and mechanical properties.

2.4.1 Anatomy of lumbar motion segments

The lumbar intervertebral discs are located between the vertebral bodies, linking them together to form the major joints of the lumbar spine, which make up approximately one-third of its height (White III & Panjabi, 1990; Bogduk & Twomey, 1991; Raj, 2008; D. A. Neumann, 2010). Generally, each disc is bounded anteriorly and posteriorly by the anterior and posterior longitudinal ligaments and axially by the cranial and caudal cartilaginous vertebral endplates (Figure 2.7) (Netter, 2006).

The intervertebral discs are complex structures comprised of three distinct components, the annulus fibrosus (AF), the nucleus pulposus (NP) and the cartilaginous

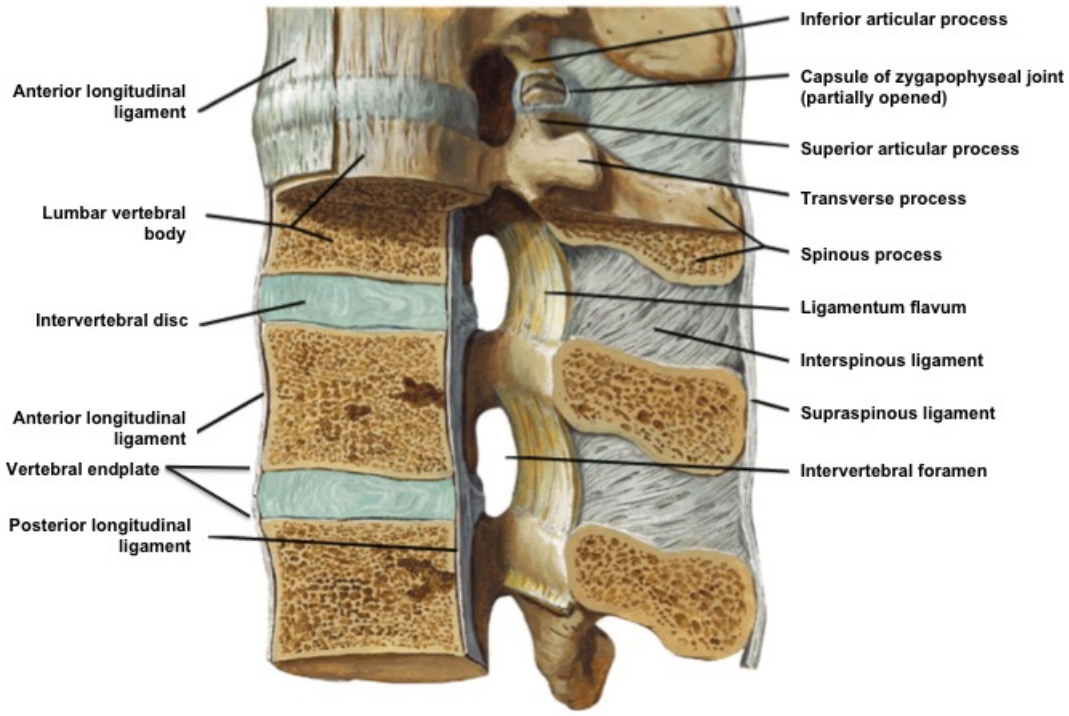


Figure 2.7: Anatomy of the human lumbar spine. (Netter, 2006, p. 158)

vertebral endplate (VEP) (Figure 2.8) (Bogduk & Twomey, 1991, p. 12), which are biomechanically relavent to this dissertation.

The nucleus pulposus (NP) is a hydrated gelatinous structure, usually located in the center of each disc (Adams et al., 2002). The lumbar nucleus, however, is located more posteriorly (White III & Panjabi, 1990). The NP consists a mixture of water, collagen fibers, cartilage cells, and proteoglycans, in a very loose and translucent network in healthy disc (White III & Panjabi, 1990). Histologically, the NP contains multiple types of randomly organized collagen fibers (Inoue, 1981; Bogduk & Twomey, 1991), whose relative abundance level is a function aging (Eyre & Muir, 1977). On average, 70% to 90% of the lumbar nucleus content is water (White III & Panjabi, 1990). About 65% of its dry weight is constituted by proteoglycans, through which collagen fibers intersperse and constitute

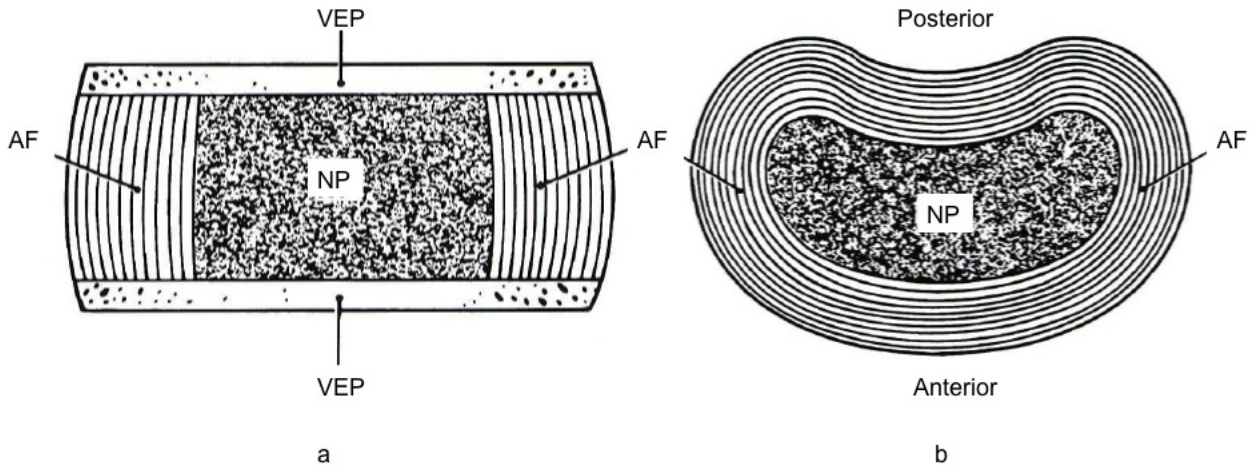


Figure 2.8: The basic structure of a lumbar intervertebral disc (**a**: frontal section; **b**: transverse section). (Bogduk & Twomey, 1991, page 12)

about 15% to 20% of the dry weight of the nucleus (Bogduk & Twomey, 1991). Morphologically, the lumbar nucleus takes about 30% to 50% of the total cross-sectional area of the disc (White III & Panjabi, 1990).

The annulus fibrosus (AF) is the thick outer ring which is on the periphery of the disc and is gradually differentiated from the nucleus and forms the outer border of the intervertebral disc as shown in Figure 2.9 (White III & Panjabi, 1990). Like the nucleus, the AF is also abundant of water, amounting to 60% to 70% of its weight (Bogduk & Twomey, 1991). Unlike the nucleus, the AF is orderly and organized with different concentrations of the similar biological components. Collagen fibers account for 50% to 60% of the dry weight, compared to proteoglycans which make up about 20% of the dry weight (Bogduk & Twomey, 1991). The collagen fibers are arranged in a circumferential pattern in the annulus fibrosus (Adams et al., 2002). Typically, there are 10 to 20 alternating bands of collagen sheets (known as lamellae) which consist of fibers parallel and tilted with respect to the spine (Hickey & Hukins, 1980; White III & Panjabi, 1990;

Bogduk & Twomey, 1991). The tilt angle is approximately 60 to 65 degree relative to the vertical in successive lamellae (Hickey & Hukins, 1980; White III & Panjabi, 1990; Bogduk & Twomey, 1991).

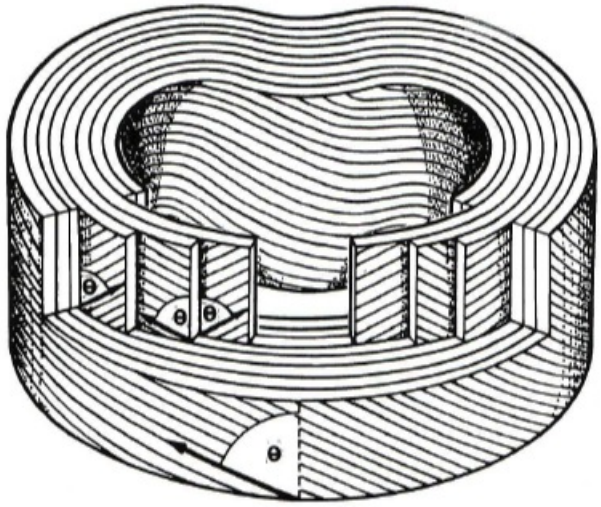


Figure 2.9: The detailed architecture of the annulus fibrosus ($\theta \approx 65$ degree). (Bogduk & Twomey, 1991, page 13)

The cartilaginous vertebral endplates (VEPs), covering the cranial and caudal aspects of the intervertebral discs, as shown in Figure 2.10, is a layer of cartilage that covers the entire nucleus pulposus but fails to cover the entire surface of the annulus fibrosus, leaving a narrow bony rim known as the ring apophysis in adult discs (White III & Panjabi, 1990; Adams et al., 2002).

In the central region that covers the nucleus pulposus, its chemical structure consists of a higher concentration of water and a lower collagen fibers, while exhibiting a reciprocal pattern over the annulus fibrosus (Bogduk & Twomey, 1991). Histologically, the VEP is composed of both hyaline cartilage which presents towards the vertebral body and fibrocartilage occurring towards the nucleus pulposus (Bogduk & Twomey, 1991).

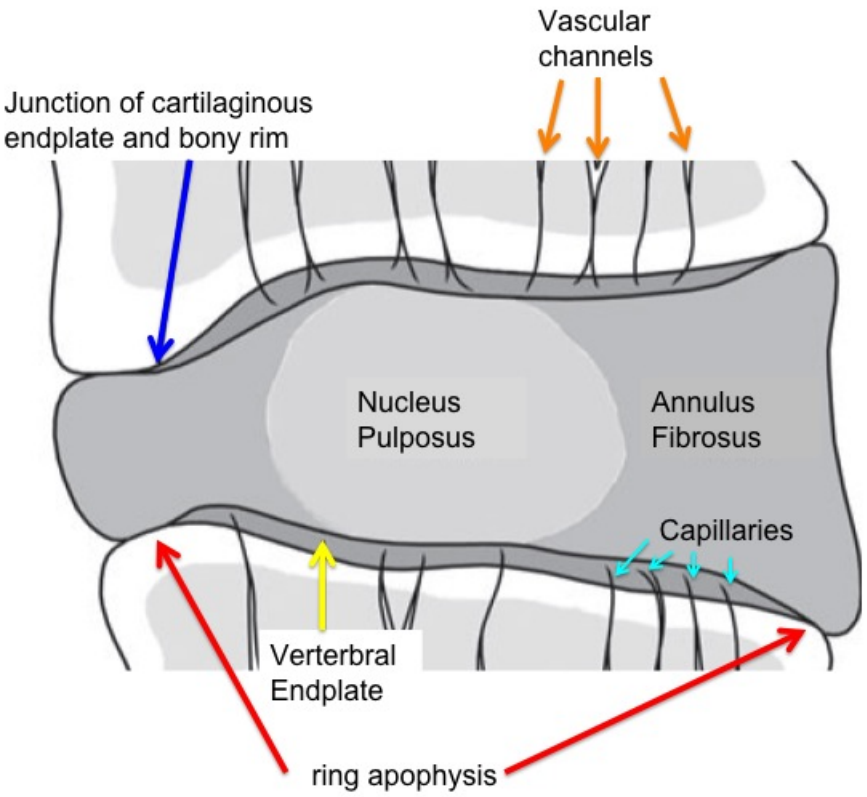


Figure 2.10: The sagittal section of the intervertebral disc. (Courtesy of: Prithvi Raj, MD)

Generally, these collagen fibers orient horizontally and parallel to the vertebral bodies. Across the thickness of the endplate, the tissue presents resembling the nearer structures such that it contains more collagen nearer bone and more water and proteoglycans nearer the nucleus pulposus (Roberts, Menage, & Urban, 1989). Normally, the healthy adult VEP has no nerves and very few capillaries branching from the interosseous arteries in the vertebral body (Inoue, 1981; Raj, 2008). It has been reported that the endplates serve as the major nutritional pathway for material transfer to the intervertebral disc (Ogata & Whiteside, 1981; Roughley, 2004).

2.4.2 Response of lumbar motion segments to mechanical loading

The lumbar spine is well suited to sustain mechanical movements such as flexion, extension, torsion, and compression (Adams et al., 2002). Within intact lumbar motion segments, the annulus fibrosus (AF) is viewed as the essential structural component for their mechanical properties (Markolf & Morris, 1974; Koeller & Hartman, 1989; Adams et al., 2002). Biomechanically, the collagen fibers within the lamellae are organized in a parallel scheme within the annulus fibrosus (Hickey & Hukins, 1980; Marchand & Ahmed, 1990; Bogduk & Twomey, 1991), such that these lamellae are more stiff and can sustain a great amount of compressive load (Nachemson, 1963; Nachemson et al., 1979; Hickey & Hukins, 1980). However, being collagenous, the AF has the propensity to bend or "buckle" and loses its stiffness and loading-bearing capacity (Panjabi, Krag, & Chung, 1984; Brinckmann, 1986; Adams et al., 1996; S. J. Ferguson & Steffen, 2003) when the nucleus pulposus (NP) is not intact (Nachemson, 1960). The abundant presence of water endows the NP with fluid properties, such that it can deform under pressure (Adams et al., 2002). Since its volume cannot be compressed, the NP tends to reduce in height and expand in a radial fashion, outwards towards the AF. Circumferentially surrounded by the collagen lamelle, the radial expansion of the NP braces the AF from the inside, preventing it from buckling inwards (Bogduk & Twomey, 1991). The other direction in which the NP exerts the pressure is towards the vertebral endplates. However, because the endplates contain more collagen towards vertebral body (Roberts et al., 1989), they will also resist deformation such that they serve to transmit part of the applied load from the cranial

vertebra to the caudal one, thereby reducing the load experienced by the AF (Bogduk & Twomey, 1991).

The mechanical functions of the nucleus pulposus (NP) and annulus fibrosus (AF) provides great advantage with respect to the load-bearing capacities of the lumbar motion segments (Nachemson, 1960, 1963). The essence of this mechanism is the hydrostatic property of the nucleus, which serves to absorb and store energy, and to help the disc return to a normal state when a load is released (White III & Panjabi, 1990). Meanwhile, as a side effect of increased hydrostatic pressure in the disc when prolonged loading is applied, the water content is squeezed out of the disc slowly (Chan, Ferguson, & Gantenbein-Ritter, 2011). A number of studies have found that the fluid is drawn back into the disc after the pressure is released when an individual is in the supine position (Adams, Dolan, & Porter, 1990; Botsford, Esses, & Ogilvie-Harris, 1994; McMillan, Garbutt, & Adams, 1996).

In the literature, a number of cadaver studies have reported the negative health effects or pathological changes in motion segments due to excessive physiological compressive loading (Hutton & Adams, 1982; Adams & Hutton, 1983; Brinckmann et al., 1989; Adams, 1995; Adams et al., 2000; Gallagher, Marras, Litsky, & Burr, 2005, 2006). Hutton and Adams (1982) observed that endplate fracture was the most commonly observed failure mode when vertebrae-disc-vertebrae motion segments were tested, which was supported later by Brinckmann et al. (1989). In addition, Adams and Hutton (1983) performed 4 hours of fatigue loading and observed that more than half of the motion segments had plainly visible distortions in the lamellae of the annulus fibrosus. It has been concluded that the failure of the motion segment is initiated by the nucleus pulposus causing the vertebral endplate to bulge into the vertebra (Adams, 1995; Adams et al.,

2000, 2002). According to the endplate fracture patterns derived from the Brinckmann et al. (1989) (Figure 2.11), endplate depression has been identified as the most frequent mode of damage (Brinckmann et al., 1989; Gallagher et al., 2005). In addition, a more common site of failure is the caudal endplate of the disc (Brinckmann et al., 1989), due to less support by the trabecular bone (Adams et al., 2002; Zhao, Pollintine, Hole, Adams, & Dolan, 2009). Bone mineral density (BMD) also plays an important role affecting the damage to the endplate (Hansson et al., 1980).

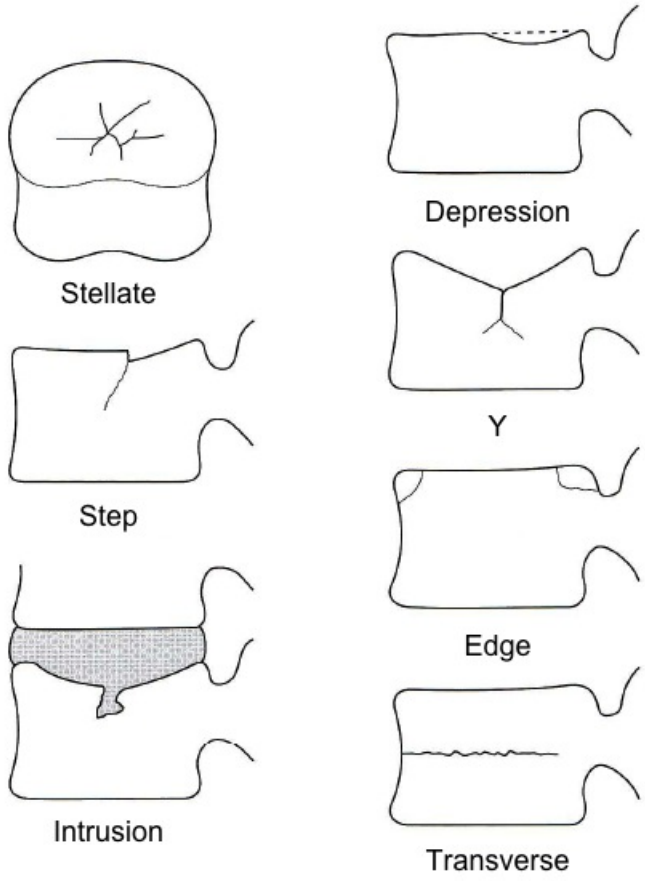


Figure 2.11: Classification system of compressive failure in vertebral endplate, derived from Brinckmann et al. (1989)

On the other hand, since the 1970s, finite element analysis (FEA) has become an important tool for the investigation of the biomechanical behavior of intervertebral discs

(Robin et al., 1994). In general, the distinctive components of a motion segment have been modeled as individual mechanical elements to characterize their structural/functional behaviors (Schmidt et al., 2007; Nerurkar, Elliott, & Mauck, 2010). However, results of these analyses in the literature are highly dependent upon the models used. There are three major inputs of data for an FE model, namely: geometric, material and boundary (Suwito et al., 1992). As summarized by Suwito et al. (1992), geometric data are comprised of a topologic description of the problem and specifications of the global dimension of the component and its discretization with an FE mesh. Material data includes mechanical properties such as Young's modulus, Poisson's ratio, density, etc. for each finite element. Boundary data are specifications of forces and constraints at some boundary nodes. In order to approach the real scenarios within the spinal segments, many restrictions and hypotheses are made to varying degrees, and therefore, the validity of the analytical results derived is questionable.

In a typical finite element model, the complete structure of the spine is characterized as independent elements with specific mechanical properties (e.g., cortical bone, cancellous bone, ligament, annulus, nucleus, and endplates) (Robin et al., 1994). In the literature to date, a number of finite element models (FEMs) have been developed with complex constitutive models and mathematical relationships between tissue deformation and stress (Suwito et al., 1992; Martinez, Oloyede, & Broom, 1997; Nerurkar et al., 2010), in order to provide better understanding of the mechanical influence of: 1) some physiological loadings (Schmidt et al., 2007; Natarajan, Lavender, An, & Andersson, 2008; Kuo et al., 2010; Iyer et al., 2010; Chan et al., 2011), 2) some degenerative processes (Natarajan, Ke, & Andersson, 1994; Hussain, Natarajan, An, & Andersson, 2010), and 3) some surgical

procedures (Meakin, 2001; Noailly, Lacroix, & Planell, 2005; Rohlmann, Zander, Bock, & Bergmann, 2008; Rohlmann, Mann, Zander, & Bergmann, 2009; Nerurkar et al., 2010).

2.5 Degeneration of lumbar motion segments

2.5.1 Epidemiology of disc degeneration

Throughout an individual's life, the structure of the lumbar intervertebral disc changes greatly, especially during juvenile development and adult aging (Urban, Roberts, & Ralphs, 2000; Roughley, 2004; Raj, 2008). In general, degeneration of lumbar intervertebral discs has been known as a aging process (Bogduk & Twomey, 1991; Pearce, Thompson, Bebault, & Flak, 1991; Adams et al., 2002), and several biochemical changes are inevitable (Adams & Dolan, 2012). With aging, the concentration of proteoglycans in the nucleus pulposus decreases from 65% of the dry weight to about 30% by the age of 60 (Lipson & Muir, 1981; Bogduk & Twomey, 1991). The lumbar intervertebral discs gradually lose the capability to retain water due to the decline of the aggrecan content (Urban et al., 2000; Roughley, 2004), which is responsible for maintaining tissue hydration (Raj, 2008). Meanwhile, the aging causes collagen content to increase in both the nucleus pulposus and annulus fibrosus and they begin to resemble each other with respect to collagen type (Bogduk & Twomey, 1991). In addition, the vertebral endplates are also subjected to the effects of aging, resulting in eventual failure of the nutritional supply, reduced blood supply, and compromised ability to transfer cell waste products (Buckwalter, 1995; Urban et al., 2000; Tian & Qi, 2010).

On the other hand, several other risk factors have been associated with the etiology of disc degeneration and may actually accelerate the degenerative changes, including genetic inheritance (R. J. Berry, 1961; Battié et al., 1995; Jones, White, Sambrook, & Eisman, 1998; Videman et al., 1998; Annunen et al., 1999; Kawaguchi et al., 1999; Sambrook, MacGregor, & Spector, 1999; Battié, Videman, & Parent, 2004; Battié, Videman, Levalahti, Gill, & Kaprio, 2007; Livshits et al., 2011; Kalb, Martirosyan, Kalani, Broc, & Theodore, 2012), occupation (W. Evans, Jobe, & Seibert, 1989; Videman & Battié, 1999; Walsh & Lotz, 2004), obesity (Samartzis et al., 2011; Samartzis, Karppinen, Chan, Luk, & Cheung, 2012), and other life style factors such as cigarette smoking (Battié et al., 1991).

Genetic Influence

The influence of genetic predisposition was not reviewed and included in the design criteria in the NIOSH guidelines, possibly due to the inadequate epidemiological evidence. In fact, according to several comprehensive reviews, it was evident that genetic predisposition was associated with the risk of low back pain (Manchikanti, 2000; Battié et al., 2004; Kalb et al., 2012). Berry (1961) investigated the etiological aspects of intervertebral disc protrusion in mice with the pintail mutation and found a correlation with the reduction in size of the nucleus pulposus in the adult mice. In an epidemiological study, Battié (1995) evaluated 115 male identical twins in Finland for disc degeneration with magnetic resonance imaging (MRI) scans and reported that genetic influence was a primary factor, but also suggested possible unpredictable interactions with age and job history. Later, Videman and colleagues (1998) studied the associations between variations in the vitamin D receptor gene and measures of disc degeneration on MRI in 85 pairs of male monozygotic (identical) twins, where two intragenic polymorphisms of the vitamin D

receptor genes were found associated with disc degeneration. Biological evidence was reported by Jones and colleagues (1998) that the allelic variation in the receptor gene also had strong associations with the severity of osteophytosis in an older population. A strong association between collagen 9 gene mutation (*Trp allele*) and the presence of severe degeneration and sciatica has also been reported (Annunen et al., 1999). Kawaguchi and colleagues evaluated 64 young females with and without low back pain using MRI and reported a strong correlation between disc degeneration and the aggrecan gene. A study comparing monozygotic (identical) and dizygotic (non-identical) twins suggested a 74% heritability of disc degeneration (Sambrook et al., 1999). According to a recent study, the genetic influence was significant but less so in a population of men of mixed age at about 35% (Battié et al., 2007). A recent cohort study in England evaluated a mixed population (identical, non-identical twins, and single individuals) and reported significant genetic influence at about 43.5% (Livshits et al., 2011).

Occupation

In the literature, an individual's occupation has been noted as an important factor associated with his/her risk of low back pain (Garg & Moore, 1992; Frymoyer, 1992; Rubin, 2007). A number of studies have also suggested that the physical demand associated with jobs is influential on the degeneration of the intervertebral discs (W. Evans et al., 1989), even though a dose-response relationship has not been well established (Videman & Battié, 1999). Evans and colleagues (1989) recruited and evaluated 38 ambulating female employees whose jobs involved heavy walking and 21 sedentary female employees for their level of lumbar disc degeneration and reported a significant difference in degeneration level between the two groups (W. Evans et al., 1989). In 1999, Videman and Battié (1999)

concluded that physical loading performed during job tasks should be optimized in order to achieve a balance between prevention of weakening the musculoskeletal weakening and damage due to degenerative changes.

Obesity

In the literature of low back pain epidemiology, it has been evident that obesity is a significant risk factor (Heliövaara, 1987; Webb et al., 2003; Mangwani et al., 2010). Two recent large scale cohort studies evaluated male and female adult Chinese volunteers, and reported that obesity was significantly associated with the severity of disc degeneration, from juvenile level to end-stage degeneration with disc space narrowing (Samartzis et al., 2012).What is the other one?

2.5.2 Degenerative changes

In the literature, the relationship between the occurrence of spinal degeneration and low back pain (LBP) is somewhat controversial (Andersson, 1981; Buckwalter, 1995; van Tulder, Assendelft, Koes, & Bouter, 1997; Luoma et al., 2000; Roughley, 2004; Waterman et al., 2012). Although Andersson (1981) concluded that evidence failed to establish a clear correlation between light or moderated degenerative changes and incidence of LBP, there was an association between degenerative changes and certain "skeletal defects". For example, while degenerative effects were associated with spondylosthesis and Scheuermann's disease, there was not an association with LBP. Van Tulder and colleagues (1997) investigated the influence of degenerative changes reported in the literature and reported the overall inconclusiveness of evidence among these changes with respect to the nonspecific LBP prevalence. In the same study, some degenerative changes, such as disc

space narrowing, osteophytes, and sclerosis were found to be associated with the elevated risk of LBP, while it was noted that there was a lack of control for confounding factors such as the measurement of degenerative changes in the literature. Later, with MRI examination, Luoma and colleagues (2000) conducted a large cohort study with more than 1,800 male subjects (40 to 45 years of age) and reported that degenerative changes (e.g. reflected by signal intensity or anterior and posterior bulging of discs) were strongly associated with an increased risk of LBP. Recently, de Schepper and colleagues (2010) conducted a larger scale cohort study with an older population of male and female subjects (average 65 years) and reported that disc narrowing was more strongly associated with LBP than osteophytes, while pointing out the relationship worsened at the L5/S1 level. Kalichman and colleagues (2010) conducted a cohort study with over 3,000 subjects in four different age groups and reported contradictory finding that spinal stenosis was significantly associated with LBP rather than disc narrowing as found by other researchers. It has also been suggested that early degenerative changes in adolescence may predict the evolution of severe degeneration and disc herniation in adulthood (Waris, Eskelin, Hermunen, Kiviluoto, & Paajanen, 2007). A recent large scale cohort study found that contiguous, multilevel disc degeneration (CMDD) had a more pronounced association with LBP and its severity than skipped level disc degeneration (SLDD) (Cheung, Samartzis, Karppinen, & Luk, 2012).

Among these factors associated with the degenerative changes, mechanical loading of the spine has been noted to have an influential impact on the degeneration process, accelerating the deterioration and severity (Battié et al., 2004; Adams & Dolan, 2012). Therefore, it is essential to understand the origin and course of disc degeneration, as well as its influence on the health and integrity of the spine. This understanding can help lead

to improved ergonomic evaluation tools and help to establish better engineering controls to lower the risk of low back pain in industry.

In the literature, there has been evidence indicating two distinct phenotypes of intervertebral disc degeneration, driven by endplate and annulus fibrosus (Adams & Dolan, 2012). The former phenotype involves defects in endplates and inwards collapse of the annulus fibrosus which is usually characterized by circumferential tears between the lamellae and internal bulging (or "buckling") of the annulus into the nucleus (Adams & Dolan, 2012). The latter one, more frequently exhibited in the lower lumbar spine, usually involves a radial fissure progressing outwards from the nucleus frequently in posterior or posterolateral direction (Adams & Dolan, 2012). In general, the two phenotypes of disc degeneration have different onset timings, since the endplate-driven degeneration often starts to develop in younger stage (before 30 years) compared to the annulus-driven one which usually develop gradually after age 30 years (Adams & Dolan, 2012). In addition, endplate-driven degenerations are more frequently found in thoracic and upper lumbar spine, possibly associated with repetitive or traumatic compressive loading, while annulus-driven degenerations are more frequently found in the lower lumbar spine which is more vulnerable to physiological damage introduced by repetitive spinal flexions and extensions (Adams et al., 1980; Adams & Hutton, 1983; Adams et al., 2000). In general, MRI techniques have been frequently employed to diagnose the disc degeneration (Sether, Yu, Haughton, & Fischer, 1990; Yu, Haughton, & Rosenbaum, 1991; Parkkola & Kormano, 1992).

2.5.3 Influence of disc degeneration on mechanical properties

Markolf and Morris (1974) statically tested 2 intact discs and 22 visually-classified degenerated discs from 8 fresh cadaveric spinal segments to investigate the contributions of the components of the intervertebral discs to the structure's compressive strength. They compared intact discs, discs with saline injection, discs with damaged annulus fibrosus, discs with no nucleus, and disc without both the nucleus and central endplates. According to the results, puncturing the annulus caused a sharp decrease in compressive stiffness. Interestingly, the extrusion of the nucleus functioned as an agent to seal the lesion, nearly restoring it to its full capacity after a saline injection. Even with a completely removed nucleus, there was a very small decrease in compressive stiffness which indicated that the annulus fibrosus was the major component contributing to compressive strength. However, their results failed to identify any influence introduced by degeneration. The specimens tested were a mixed pool of thoracic and lumbar discs with no further information regarding the dimensions and degeneration statuses. Also, the classification criterion for a normal disc was applied as "clearly the nuclei were white and moist", lacking a reliable grading system. Acaroglu et al. (1995) reported significant effects of degeneration on the tensile failure properties of the lumbar annulus fibrosus with 48 specimens of L3/L4 intervertebral discs, particularly depending on the relative position of the annulus fibrosus with the disc. Unfortunately, there was a huge range of age (2 to 88 years) and no information was provided regarding the geometric dimensions and specific degeneration status of the specimens.

Several studies also reported the influence of disc degeneration on spinal motion and the intradiscal pressure. Nachemson et al. (1979) reported that less-degenerated discs had a greater range of flexion and extension, but similar behavior in lateral flexion and torsion, when compared to moderately degenerated discs. It was also found that the intradiscal pressure measured within the nucleus decreased as the degeneration worsened in extension and lateral flexion (Nachemson et al., 1979). However, Nachemson et al. (1979) had only 36 segments defined as less-degenerated and 6 segments as moderate-degenerated, thus a relatively small sample size. In addition, it was also evident that the moderately degenerated discs had much larger dimensions, and hence proportionately larger cross-sectional areas might have compensated for the effect of degeneration. Adams et al. (1996) measured the intradiscal pressure within cadaver lumbar discs and reported an reduction in size of the central region of lumbar nucleus as well as the reduced intradiscal pressure associated with disc degeneration.

2.5.4 Summary

In general, strong evidence has been reported in the literature that disc degeneration has a great impact on the mechanical properties of the lumbar motion segment. There has also been evidence indicating the possible influence of disc degeneration on the spinal geometry. Secondly, the initiation and severity of disc degeneration are associated with many factors, especially the mechanical loading and aging process. Different degenerative changes have been found associated with different components of the lumbar motion segements. The status of disc degeneration is usually diagnosed using medical imaging technology, particularly the MRI techniques.

2.6 Morphometry of lumbar motion segments

2.6.1 Significance of lumbar spinal morphometry

As summarized earlier in this dissertation, bone mineral content (BMC) of the lumbar motion segment is the best measure to predict the ultimate compressive strength of lumbar motion segments (Gallagher et al., 2007). As one of the critical conponents, the cross-sectional area (CSA) of the lumbar motion segments also has an influence on the ultimate compressive strength of the lumbar motion segment (Brinckmann et al., 1989; Genaidy et al., 1993). Some researchers have reported linear regression models estimating the compressive strength of porcine spinal segments solely with the cross-sectional area of the endplate (Parkinson et al., 2005). Briggs, Greig, Wark, Fazzalari, and Bennell (2004) has concluded in their review that the size of the vertebral body is correlated with the incidence of osteoporosis and is a strong predictor of risk of vertebral fracture. On the other hand, finite element (FE) models developed to characterize the biomechanics of the spinal tissues, require accurate geometric data of the finite elements to better grasp their mechanical behavior and offer better explanations to spinal pathologies linked to mechanical factors (Noailly et al., 2007). A number of studies have reported the significance of geometric characteristics (Robin et al., 1994; Lu, Hutton, & Gharpuray, 1996; Natarajan & Andersson, 1999; Noailly et al., 2007; Niemeyer et al., 2012). Robin et al. (1994) developed a multiple-spinal-level three-dimensional lower lumbar (L1 to L4) FE model and reported that the length and width of the vertebral body and disc height had the greatest influence. Lu et al. (1996) developed a single-spinal-level three-dimensional FE model of L2/L3 intervertebral disc with three disc heights (8mm, 10mm, and 12mm) and

fixed input of cross-sectional area (CSA, 1,300 mm^2) and nucleus-to-CSA ratio (38%). It was noted that the variation of the disc height had significant influence on axial displacement and posterolateral disc bulge under pure axial compression. Later, Natarajan and Andersson (1999) also developed a single-level 3D FE model presenting three disc heights and three CSAs and reported that discs with large disc-height-to-CSA ratio was associated with larger motion, higher annular fiber stresses, and larger disc bulge. Noailly et al. (2007) developed a bi-spinal-level 3D FE model and analyzed the sensitivity of different inputs of geometric characteristics. It was noted that these characteristics affected the stress distribution and strain energy in the zygapophysial joints, the ligaments, and the intervertebral discs. In a recent study, Niemeyer et al. (2012) examined the impact of the variability in 40 geometric characteristics and reported that disc height, endplate width, and depth were the statistically significant geometric characteristics.

2.6.2 Geometry of the lumbar motion segment

In the literature, geometric dimensions of the spinal motion segment have been reported primarily in studies investigating morphometric characteristics (Panjabi et al., 1992). Some studies investigating the ultimate strength of motion segments, also provided geometric data, primarily the cross-sectional area (Hutton & Adams, 1982; Brinckmann et al., 1989). The geometric dimensions of the lumbar motion segments reported in the literature (35 studies in total) are summarized in greater detail below (Table 2.7 to 2.18). As summarized, transverse anatomical geometric dimensions frequently reported in the literature are the anteroposterior diameter (APD), frontal diameter (FD), and cross-sectional area (CSA) of the lumbar vertebral bodies (VBs) (Table 2.7 to 2.10) and

the intervertebral discs (IVDs) (Table 2.11 to 2.13). Three transverse anatomical planes are frequently referred to measure the geometric dimensions, namely: the cranial, caudal, and midline sections, of which the first two are more commonly used to measure the geometry of vertebral endplates.

In the sagittal plane, common geometric dimensions measured include: anterior height (AH), medial height (MH), and posterior height (PH) of the vertebral bodies (Table 2.14 to 2.15) and the intervertebral discs (Table 2.16 to 2.18).

Table 2.7: Transverse geometric dimensions of lumbar vertebral bodies reported in the literature from 1983 to 1989

Authors	**Notes**	**L1**			**L2**			**L3**			**L4**			**L5**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Postacchini, Ripani, and Carpano (1983)	Cr Italian	29 (3)	41 (4)		31 (3)	43 (5)		30 (3)	44 (4)		32 (3)	47 (4)		33 (3)	49 (4)	
	Cr Indian	25 (2)	36 (3)		27 (2)	37 (3)		28 (2)	40 (3)		29 (2)	41 (4)		29 (2)	43 (4)	
Nissan and Gilad (1984); Gilad and Nissan (1986)	Cranial	33.5 (2.8)			34.4 (2.8)			34.7 (2.7)			34.3 (2.7)			34.2 (2.7)		
	Caudal	34.1 (2.9)			34.7 (3.0)			34.6 (2.8)			34.9 (2.8)			33.9 (2.7)		
van Schaik, Verbiest, and van Schaik (1985)	Ca All							34.0 (2.5)	43.7 (4.1)		35.2 (3.0)	45.0 (3.8)		35.9 (2.9)	47.9 (4.5)	
	Ca F							32.6	41.2		33.3	42.6		34.2	45.1	
	Ca M							35.1	45.8		37.2	47.5		37.3	50.1	
J. L. Berry, Moran, Berg, and Steffee (1987)	Cr	31.9 (3.7)	45.2 (4.6)		33.3 (3.7)	47.7 (4.7)		33.9 (3.3)	49.6 (3.2)		34.9 (3.4)	51.2 (5.6)		35.1 (2.8)	53.4 (4.4)	
	Md	28.9 (3.5)	39.5 (3.8)		29.9 (3.3)	44.8 (3.1)		31.6 (3.3)	42.3 (3.5)		32.5 (2.9)	40.8 (3.2)		32.4 (2.8)	46.1 (4.5)	
	Ca	32.3 (3.5)	49.1 (3.7)		33.4 (3.4)	54.8 (4.8)		34.2 (3.3)	53.8 (3.7)		35.6 (3.1)	50.9 (4.6)		34.5 (3.0)	52.7 (4.3)	
Biggemann et al. (1988) Fractured EPs	F			1260 (248)						1420 (138)			1345 (21)			1480 (147)
	M			1180 (42)			1550 (266)			1812 (266)			1575 (219)			1866 (35)
Brinckmann et al. (1989) Fractured EPs	Cr F			1253 (160)			1422 (175)			1372 (196)			1521 (220)			
	Ca F			1323 (175)			1500 (156)			1440 (145)			1573 (248)			
	Cr M			1575 (320)			1744 (385)			1843 (577)			1816 (222)			
	Ca M			1615 (335)			1803 (359)			1983 (685)			1889 (230)			

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.8: Transverse geometric dimensions of lumbar vertebral bodies reported in the literature from 1990 to 1999

Authors	**Notes**	**L1**			**L2**			**L3**			**L4**			**L5**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Mosekilde (1990)	F									1228 (74)						
<50 years	M									1368 (131)						
between 50 and 75 years	F									1256 (213)						
	M									1568 (164)						
>75 years	F									1214 (160)						
	M									1564 (212)						
Aharinejad et al. (1990) MSD, MTD	Cranial	29.0 (2.4)	39.7 (4.3)		31.1 (2.5)	41.6 (4.3)		34.6 (4.2)	47.7 (5.9)		38.0 (6.6)	52.5 (10.5)		37.6 (4.6)	54.5 (6.0)	
Panjabi et al. (1992)	Cr	34.1 (1.34)	41.2 (1.03)	1057 (61)	34.6 (1.10)	42.6 (0.74)	1136 (62)	35.2 (1.10)	44.1 (0.88)	1195 (55)	35.5 (0.88)	46.6 (1.20)	1239 (58)	34.7 (1.17)	47.3 (1.20)	1237 (58)
	Ca	35.3 (1.27)	43.3 (0.78)	1117 (49)	34.9 (0.74)	45.5 (1.10)	1197 (51)	34.8 (1.24)	48.0 (1.24)	1290 (64)	33.9 (0.85)	49.5 (1.38)	1273 (52)	33.2 (0.92)	49.4 (1.41)	1218 (59)
Gilsanz et al. (1995)	Fractured			866 (110)			927 (135)			1042 (135)			1073 (118)			
Midline	Unfractured			978 (90)			1002 (116)			1096 (124)			1165 (109)			
Drerup, Granitzka, Assheuer, and Zerlett (1999)	Ca									1600 (136)						

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.9: Transverse geometric dimensions of lumbar vertebral bodies reported in the literature from 2000 to 2011

Authors	**Notes**	**L1**			**L2**			**L3**			**L4**			**L5**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Zhou, McCarthy, McGregor, Coombs, and Hughes (2000)	Cr All							32.3 (3.3)	43.2 (4.3)		34.6 (3.6)	48.5 (4.7)		35.7 (3.7)	52.2 (5.1)	
	Ca All							35.3 (3.6)	51.7 (4.8)		36.2 (3.7)	52.5 (4.7)		36.0 (4.0)	53.1 (6.0)	
	Cr F							30.8 (3.1)	40.9 (3.6)		33.2 (3.3)	46.7 (4.7)		34.3 (3.5)	50.4 (4.4)	
	Ca F							33.7 (3.1)	49.3 (4.1)		34.4 (2.8)	50.4 (4.2)		34.3 (3.3)	50.4 (4.9)	
	Cr M							34.1 (2.6)	46.1 (3.2)		36.4 (3.2)	50.8 (3.7)		37.6 (3.1)	54.5 (4.9)	
	Ca M							37.4 (3.1)	54.8 (3.6)		38.6 (3.4)	55.1 (4.1)		38.3 (3.8)	56.7 (5.3)	
subset of 5 F and 5 M	Ca All							36.4 (2.6)	51.3 (3.8)	1492.0 (173.8)						
	Ca F							35.2 (2.8)	48.2 (2.9)	1385.6 (188.0)						
	Ca M							37.5 (1.9)	54.3 (1.3)	1598.4 (65.8)						
Seidel, Popplau, Morlock, Puschel, and Huber (2008)	Cr									1561 (176)			1579 (198)			1606 (200)
	Ca									1600 (181)			1584 (182)			1506 (190)
van der Houwen et al. (2010)	Cr F	26.6	33.7		27.1	33		26.3	34.7		26.1	37.7		27.7	38.1	
	Ca F	25.3	29.7		26	32.7		25.4	37.9		28.1	41.1		25.1	41.8	
	Cr M	29	38.7		28.9	38.1		29.7	40.2		28.9	42.4		27.6	43.9	
	Ca M	29.7	39.7		29	41.1		30.4	40.6		30.6	48.9		27.4	46.6	
Kang, Song, Lee, Yang, and Song (2011)	Cr All		40.05 (3.96)			41.85 (4.13)			44.63 (4.12)			46.77 (3.86)			53.30 (4.95)	
	Cr F		35.55 (2.19)			37.30 (2.58)			40.71 (2.70)			43.77 (3.30)			49.72 (4.59)	
	Cr M		41.98 (2.80)			43.80 (2.96)			46.31 (3.44)			48.06 (3.37)			54.83 (4.31)	
Midline	x-ray		38.76 (4.15)			40.64 (4.28)			44.29 (4.19)			45.51 (4.31)			51.33 (3.81)	

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.10: Transverse geometric dimensions of lumbar vertebral bodies reported in the literature from 2011 to present

Authors	**Notes**	**L1**			**L2**			**L3**			**L4**			**L5**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Karabekir et al. (2011)	F	33.4 (3.1)	48.9 (7.3)		35.2 (3.6)	51.7 (7.2)		36.0 (2.8)	53.4 (5.8)		37.7 (4.4)	56.2 (4.9)		39.0 (2.2)	57.4 (4.0)	
	M	35.6 (3.1)	48.6 (4.6)		36.7 (3.6)	50.8 (4.6)		37.3 (4.3)	52.8 (5.7)		39.7 (3.1)	53.8 (4.0)		39.6 (3.3)	54.5 (5.0)	
Mahato (2011)	Normal		39.53 (5.53)			42.00 (5.50)			45.08 (5.07)			48.37 (4.80)			55.37 (5.89)	
	Accessory		41.12 (3.73)			43.71 (3.37)			46.68 (2.66)			50.59 (3.74)			56.88 (3.85)	
	Fused		41.98 (4.44)			44.47 (3.17)			46.93 (2.05)			55.53 (6.07)			58.60 (5.47)	
H. Chen, Jiang, Ou, Zhong, and Lv (2011)	avg. F	25.6 (2.5)			26.0 (2.6)			25.7 (3.1)								
	avg. M	29.4 (2.2)			29.3 (2.6)			29.1 (2.8)								
	Cr F	25.7 (2.7)	34.4 (2.6)		26.0 (2.4)	36.0 (2.8)		25.6 (3.1)	37.2 (3.4)							
	Ca F	25.4 (2.3)	37.7 (3.1)		26.0 (2.8)	38.3 (3.2)										
	Cr M	29.4 (2.1)	38.4 (4.0)		29.2 (2.6)	41.4 (4.0)		29.1 (2.7)	42.4 (3.8)							
	Ca M	29.4 (2.4)	42.7 (3.5)		29.3 (2.6)	44.5 (4.0)										

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.11: Transverse geometric dimensions of lumbar intervertebral discs reported in the literature from 1960 to 1989

Authors	**Notes**	**L1/L2**			**L2/L3**			**L3/L4**			**L4/L5**			**L5/S1**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Nachemson (1960)	F			1332 (122)			1472 (147)			1539 (154)			1610 (180)			
	M			1785 (260)			1821 (232)			1961 (253)			1852 (127)			
Farfan (1973)		38.10 (8.03)	52.70 (7.00)	1659.19 (567.30)	38.10 (6.01)	54.61 (7.66)	1714.93 (487.16)	35.98 (2.97)	55.88 (4.25)	1633.06 (224.84)	38.73 (1.27)	59.05 (4.34)	1855.16 (184.76)			
Hansson et al. (1980)	F			1608 (277)			1714 (255)			1805 (306)						
	M			1702 (257)			1877 (281)			2086 (372)						
Hutton and Adams (1982)	F			1110			1583 (225)			1280 (100)			1520 (100)			
	M			1565 (177)			1820 (396)			1700 (192)			1892 (376)			1752 (223)
Colombini, Occhipinti, Grieco, and Faccini (1989)										1988 (351)			2143 (389)			1888 (318)
Porter et al. (1989)	M						1682 (134)						1850 (174)			

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.12: Transverse geometric dimensions of lumbar intervertebral discs reported in the literature from 1990 to 1999

Authors	Notes	L1/L2			L2/L3			L3/L4			L4/L5			L5/S1		
		APD	FD	CSA	APD	FD	CSA	APD	FD	CSA	APD	FD	CSA	APD	FD	CSA
Amonoo-Kuofi	10s, F	33.9			35.2			36.5			37.7			34.7		
(1991)		(2.3)			(1.4)			(1.9)			(2.9)			(1.8)		
	M	33.0			34.4			35.4			36.7			33.7		
		(2.9)			(3.7)			(1.9)			(1.2)			(1.1)		
Cr EPs	20s, F	36.0			38.0			38.4			39.0			37.7		
		(1.1)			(1.2)			(1.9)			(2.1)			(2.0)		
	M	41.1			42.0			42.2			43.1			41.7		
		(2.1)			(2.1)			(2.1)			(2.5)			(2.6)		
	30s, F	36.7			38.9			39.2			39.1			38.2		
		(2.1)			(2.0)			(1.8)			(1.6)			(1.9)		
	M	41.0			41.6			42.0			42.1			40.9		
		(1.9)			(1.7)			(1.9)			(2.7)			(2.6)		
	40s, F	39.2			40.2			41.7			42.0			40.1		
		(2.0)			(1.7)			(2.3)			(2.1)			(2.6)		
	M	44.4			45.0			45.8			47.7			46.3		
		(2.3)			(2.2)			(2.2)			(2.8)			(2.8)		
	50+, F	38.7			40.7			42.7			41.9			40.1		
		(2.2)			(2.0)			(2.1)			(2.7)			(2.1)		
	M	40.9			42.6			42.7			44.2			42.6		
		(1.7)			(1.4)			(1.9)			(1.5)			(3.0)		
Aydinlioglu et	10s, F	35.5			36.0			37.3			37.3			36.8		
al. (1999)		(1.4)			(1.4)			(1.8)			(1.8)			(1.1)		
	M	47.0			46.5			48.0			47.3			46.7		
		(1.3)			(0.9)			(2.2)			(2.4)			(3.0)		
Avg. EPs	20s, F	39.8			41.2			43.0			43.6			43.5		
		(3.4)			(3.5)			(3.5)			(2.9)			(2.8)		
	M	45.3			46.3			47.3			47.9			46.9		
		(4.7)			(5.2)			(5.4)			(5.7)			(4.5)		
	30s, F	42.1			43.4			44.3			43.4			43.4		
		(3.6)			(3.2)			(2.9)			(5.6)			(3.1)		
	M	45.1			46.0			46.6			47.1			46.8		
		(2.9)			(3.4)			(3.7)			(3.4)			(3.7)		
	40s, F	40.5			41.7			42.6			43.8			42.3		
		(3.2)			(4.5)			(3.7)			(2.9)			(2.6)		
	M	46.5			47.6			47.9			48.1			47.8		
		(2.2)			(2.2)			(2.7)			(1.9)			(2.8)		
	50+, F	43.7			45.3			45.8			46.7			46.1		
		(4.4)			(4.9)			(4.5)			(3.3)			(3.0)		
	M	46.2			47.8			48.2			49.0			48.8		
		(2.6)			(2.2)			(2.4)			(1.9)			(2.5)		

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.13: Transverse geometric dimensions of lumbar intervertebral discs reported in the literature from 2000 to present

Authors	**Notes**	**L1/L2**			**L2/L3**			**L3/L4**			**L4/L5**			**L5/S1**		
		APD	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**	**APD**	**FD**	**CSA**
Turk and Celan (2004)	Patients												1796 (240)			1688 (206)
	M w/LBP												1859 (138)			1740 (117)
	M w/out LBP												2079 (195)			1926 (165)
Y. Wang et al. (2012)	Cr	35.5 (2.9)	47.6 (4.0)	1410 (220)	36.2 (2.8)	50.3 (3.6)	1540 (230)	35.6 (2.8)	51.5 (3.4)	1560 (210)	36.1 (2.8)	53.6 (3.7)	1670 (240)	34.7 (3.2)	52.3 (4.7)	1580 (300)
	Ca	35.7 (2.3)	47.0 (3.5)	1440 (210)	35.7 (3.1)	48.0 (3.1)	1490 (240)	35.8 (2.8)	51.3 (3.7)	1580 (240)	35.5 (2.9)	53.0 (4.1)	1610 (250)	33.8 (3.5)	51.2 (4.5)	1510 (280)

APD (cm): anteroposterior diameter; FD(cm): frontal diameter; CSA (cm^2): cross-sectional area; Cr: cranial aspect; Ca: caudal aspect; Md: midline aspect

Table 2.14: Height of lumbar vertebral bodies reported in the literature from 1983 to 2000

Authors	Notes	L1			L2			L3			L4			L5		
		AH	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**
Postacchini et al. (1983)	Italian	26 (2)			27 (5)			28 (3)			28 (3)			30 (4)		
	Indian	21 (2)			22 (2)			23 (1)			23 (2)			24 (1)		
Nissan and Gilad (1984); Gilad and Nissan (1986)		25.4 (2.2)	27.1 (2.1)		27.2 (2.0)	28.0 (2.1)		27.9 (2.1)	27.9 (2.1)		27.4 (2.2)	27.1 (2.3)		28.3 (2.1)	25.7 (2.5)	
J. L. Berry et al. (1987)		25.0 (2.9)	25.8 (2.1)		27.9 (1.9)	25.2 (2.2)		27.4 (1.7)	26.0 (1.6)		26.7 (1.5)	26.4 (1.7)		28.7 (1.0)	23.1 (1.0)	
Aharinejad et al. (1990)		27.6 (1.2)	30.0 (5.3)		29.8 (8.5)	27.6 (8.0)		28.2 (8.4)	27.0 (7.0)		28.8 (5.9)	27.0 (4.9)		29.5 (5.4)	27.9 (4.7)	
Gilsanz et al. (1995)	Fractured			24.4 (1.4)			24.8 (2.0)			25.0 (2.2)			25.1 (2.3)			
32 paris	Unfractured			24.2 (1.6)			25.3 (1.8)			25.6 (1.7)			25.6 (2.1)			
56 pairs	Fractured	18.5 (2.7)	24.0 (2.2)	13.6 (3.9)	19.3 (6.7)	24.2 (3.1)	14.5 (5.1)	22.0 (4.4)	25.5 (2.2)	17.7 (4.3)	23.0 (4.1)	23.2 (3.8)	14.5 (4.4)			
	Unfractured	24.6 (1.9)	25.7 (2.0)	22.0 (1.9)	26.5 (1.4)	25.8 (1.2)	23.0 (1.7)	27.7 (2.1)	28.6 (1.6)	24.9 (1.6)	27.0 (1.3)	24.2 (1.8)	22.0 (2.8)			
Zhou et al. (2000)	Total							30.2 (2.1)	29.6 (2.4)		30.1 (2.4)	28.7 (2.3)		30.8 (2.5)	25.9 (2.0)	
	F							29.9 (2.3)	28.7 (2.2)		29.5 (2.4)	27.9 (2.3)		30.2 (2.6)	25.3 (1.9)	
	M							30.6 (1.8)	30.7 (2.1)		31.0 (2.1)	29.6 (1.9)		31.5 (2.1)	26.7 (1.9)	

AH (cm): anterior height; MH (cm): middle height; PH (cm): posterior height

Table 2.15: Height of lumbar vertebral bodies reported in the literature from 2001 to 2011

Authors	**Notes**	**L1**			**L2**			**L3**			**L4**			**L5**		
		AH	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**
Al-Hadidi et al. (2001)	20s, F(12)			24			25.7			25.7			26			27.5
	M(6)			27			25.9			29			27			26.4
	30s, F(15)			23			23.8			27.7			23.7			23.1
	M(21)			23.6			24.9			25.4			24.9			24.9
	40s, F(18)			24.9			25			24.6			24.1			24
	M(39)			26.4			27.3			27.5			24.1			25.2
	50s, F(12)			24.5			25.4			24.8			24.7			23.5
	M(12)			25.8			27.6			28			27.4			24
	60s, F(15)			22.8			24			25.2			24.5			22.4
	M(12)			27			27.4			27			27.4			24.9
Campbell-Kyureghyan, Jorgensen, Burr, and Marras (2005)	F + M			30.2 (3.3)			31.3 (3.4)			31.0 (3.4)			31.4 (3.2)			29.1 (3.1)
Karabekir et al. (2011)	F	22.4 (1.1)	22.7 (1.3)		24.4 (2.1)	23.4 (1.7)		25.0 (2.3)	23.0 (1.7)		24.5 (2.7)	22.0 (1.9)		25.2 (2.6)	21.5 (1.5)	
	M	24.6 (2.2)	25.4 (2.7)		26.4 (2.4)	25.4 (2.7)		26.2 (2.2)	25.2 (1.9)		27.1 (2.3)	24.6 (2.2)		28.4 (2.3)	24.3 (1.3)	
Mahato (2011)	Normal	25.13 (2.38)			27.31 (3.06)			28.21 (2.40)			27.99 (2.08)			26.91 (3.39)		
	Accessory	25.00 (2.36)			26.70 (2.11)			27.23 (2.42)			26.94 (2.60)			25.88 (4.26)		
	Fused	27.29 (0.88)			29.51 (2.11)			27.48 (3.21)			28.12 (2.09)			23.49 (2.68)		

AH (cm): anterior height; MH (cm): middle height; PH (cm): posterior height

Table 2.16: Height of lumbar intervertebral discs reported in the literature from 1973 to 1991

Authors	Notes	L1/L2			L2/L3			L3/L4			L4/L5			L5/S1		
		AH	PH	MH	AH	PH	MH	AH	PH	MH	AH	PH	MH	AH	PH	MH
Farfan (1973)			6.92 (0.73)			8.76 (1.50)			8.25 (1.00)			9.59 (0.76)				
Nissan and Gilad (1984); Gilad and Nissan (1986)		7.6 (1.4)	6.5 (1.7)		8.9 (1.6)	6.7 (1.6)		10.3 (1.8)	7.2 (1.8)		12.0 (1.8)	7.7 (1.5)		14.1 (2.2)	7.5 (1.6)	
Twomey and Taylor (1985, 1987)	avg. M avg. F True. M True.F			11.6 10.6 9.2 7			11.4 11.4 10.3 8.2			10.6 9.1 10.6 8.3			9.5 8.7 11.7 8.8			8.7 7.8 10.9 8.4
Aharinejad et al. (1990)		7.57 (2.63)	8.06 (1.75)	9.96 (1.78)	8.22 (1.91)	8.17 (1.85)	10.33 (1.87)	8.63 (1.87)	8.63 (1.92)	10.97 (2.06)	9.07 (1.97)	9.01 (2.00)	11.61 (1.96)	9.41 (2.10)	9.39 (2.34)	12.20 (2.29)
Dabbs and Dabbs (1990)	w/LBP w/out LBP												12.0 (2.3) 11.4 (2.2)			11.6 (2.5) 11.3 (2.1)
Amonoo-Kuofi (1991)	10s, F	9.9 (1.5)	7.5 (1.7)		13.1 (1.2)	7.5 (1.8)		14.7 (1.0)	8.1 (1.0)		17.4 (2.8)	8.2 (1.9)		17.7 (2.5)	8.4 (1.2)	
	M	11.2 (1.8)	5.8 (0.7)		11.5 (1.7)	6.8 (1.6)		12.5 (1.7)	7.6 (1.4)		15.2 (2.0)	7.6 (1.5)		16.3 (2.1)	6.9 (1.3)	
	20s, F	9.4 (1.1)	4.8 (0.8)		10.6 (0.8)	5.6 (0.7)		13.6 (1.4)	6.5 (1.2)		14.8 (1.4)	8.7 (1.7)		17.9 (3.6)	7.4 (1.0)	
	M	11.7 (1.8)	5.4 (0.8)		13.1 (1.6)	6.5 (1.2)		14.6 (1.2)	7.4 (1.3)		18.4 (1.9)	8.1 (0.9)		17.8 (3.2)	7.4 (1.5)	
	30s, F	11.0 (1.6)	4.9 (0.9)		13.0 (2.1)	6.1 (1.2)		15.8 (1.7)	7.0 (1.6)		17.5 (1.7)	8.0 (1.4)		18.9 (2.4)	8.9 (1.5)	
	M	11.0 (1.0)	5.6 (1.1)		13.3 (1.6)	7.0 (1.1)		14.7 (1.9)	7.6 (1.0)		17.3 (1.8)	8.9 (1.0)		18.3 (2.2)	7.6 (1.0)	
	40s, F	10.7 (1.2)	6.1 (1.5)		14.4 (1.4)	6.9 (1.2)		17.0 (1.9)	8.2 (1.2)		19.6 (1.8)	9.2 (1.8)		22.4 (1.7)	8.7 (1.9)	
	M	10.9 (1.6)	6.2 (1.2)		13.1 (1.5)	8.0 (1.3)		16.4 (2.2)	8.3 (1.4)		21.6 (2.2)	10.8 (1.0)		23.1 (1.6)	9.0 (1.1)	
	50+, F	10.8 (1.4)	5.2 (0.9)		13.8 (1.9)	5.8 (1.0)		15.8 (1.6)	5.9 (1.5)		19.8 (2.1)	6.4 (1.6)		22.3 (2.1)	6.9 (1.1)	
	M	11.0 (1.0)	4.6 (1.2)		12.8 (0.4)	6.0 (1.0)		15.6 (0.7)	7.5 (0.6)		19.3 (1.7)	7.6 (1.0)		20.4 (2.4)	6.8 (0.9)	

AH (cm): anterior height; MH (cm): middle height; PH (cm): posterior height

Table 2.17: Height of lumbar intervertebral discs reported in the literature from 1992 to 2000

Authors	Notes	L1/L2			L2/L3			L3/L4			L4/L5			L5/S1		
		AH	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**
Aydinlioglu et al. (1999)	10s, F	11.5	5.0		10.7	6.0		14.5	6.0		16.5	7.5		15.5	5.5	
		(0.7)	(0.0)		(1.9)	(1.4)		(0.7)	(1.4)		(0.7)	(0.7)		(0.7)	(0.7)	
	M	12.7	7.3		11.4	8.0		16.7	9.7		18.0	10.3		13.3	6.7	
		(2.5)	(2.5)		(2.2)	(3.0)		(1.5)	(2.5)		(2.0)	(2.1)		(3.5)	(0.6)	
	20s, F	13.5	5.1		12.5	5.9		14.5	7.6		16.1	8.0		15.9	6.0	
		(0.7)	(1.4)		(2.3)	(1.9)		(2.7)	(1.9)		(3.7)	(2.5)		(3.8)	(1.7)	
	M	14.3	5.1		13.4	6.4		14.6	6.8		16.6	7.1		16.5	5.9	
		(3.0)	(1.4)		(1.8)	(1.1)		(2.4)	(1.2)		(2.8)	(1.3)		(3.6)	(1.6)	
	30s, F	14.5	5.0		13.1	6.1		15.4	6.9		16.5	7.6		15.6	5.8	
		(0.7)	(1.1)		(2.5)	(1.3)		(1.4)	(1.4)		(2.4)	(1.5)		(3.1)	(1.8)	
	M	16.7	4.9		13.3	6.2		14.9	7.3		16.3	7.4		16.5	6.3	
		(1.5)	(1.4)		(1.9)	(1.6)		(2.4)	(1.3)		(1.9)	(1.5)		(2.9)	(1.9)	
	40s, F	16.5	4.5		12.8	5.0		15.5	5.7		17.2	6.2		17.8	5.7	
		(0.7)	(1.4)		(3.3)	(1.3)		(4.2)	(1.2)		(4.7)	(1.9)		(3.6)	(1.5)	
	M	18.0	5.5		14.8	7.3		17.5	8.9		18.5	8.9		19.0	7.9	
		(2.0)	(1.2)		(2.6)	(2.1)		(3.7)	(2.5)		(3.9)	(2.4)		(3.6)	(1.1)	
	50+, F	15.5	5.2		13.6	6.3		15.3	6.8		16.1	7.3		16.8	7.3	
		(0.7)	(1.6)		(2.5)	(1.5)		(2.5)	(2.1)		(3.3)	(2.5)		(3.6)	(2.8)	
	M	13.3	5.4		13.7	6.5		16.9	8.0		19.1	9.3		21.6	8.1	
		(3.5)	(1.3)		(1.4)	(1.7)		(2.4)	(1.5)		(2.3)	(2.3)		(4.7)	(2.2)	
Zhou et al. (2000)	Total									11.6			11.3			10.7
										(1.8)			(2.1)			(2.1)
	F									11.0			10.6			10.3
										(1.6)			(2.0)			(2.1)
	M									12.4			12.2			11.2
										(1.7)			(2.0)			(2.0)

AH (cm): anterior height; MH (cm): middle height; PH (cm): posterior height

Table 2.18: Height of lumbar intervertebral discs reported in the literature from 2001 to present

Authors	Notes	L1/L2			L2/L3			L3/L4			L4/L5			L5/S1		
		AH	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**	**AH**	**PH**	**MH**
Al-Hadidi et al. (2001)	20s, F(12)			9.5 (0.5)			11.0 (0)			12.0 (1.0)			12.0 (0)			11.5 (0.5)
	M(6)			8.5 (0.9)			9.8 (1.1)			11.3 (1.1)			11.5 (2.1)			9.0 (2.1)
	30s, F(15)			10.5 (2.9)			10.8 (1.5)			12.6 (1.2)			12.6 (1.0)			12.0 (1.5)
	M(21)			10.1 (1.5)			11.3 (1.7)			13.1 (1.2)			11.4 (1.1)			12.1 (2.8)
	40s, F(18)			10.3 (1.9)			11.8 (1.8)			12.8 (2.1)			12.7 (3.2)			11.2 (3.0)
	M(39)			9.8 (1.3)			10.7 (1.1)			12.4 (1.3)			12.1 (1.9)			12.7 (2.1)
	50s, F(12)			9.8 (1.1)			11.8 (1.1)			12.2 (0.4)			11.7 (0.8)			12.5 (1.8)
	M(12)			10 (1.2)			11.8 (1.6)			13.3 (0.8)			13.8 (1.9)			12.0 (2.6)
	60s, F(15)			9 (1.6)			10.4 (2.0)			11.8 (2.4)			11.6 (1.6)			13.2 (2.9)
	M(12)			8.8 (1.5)			11.5 (1.5)			10.8 (3.0)			11.8 (4.6)			13.3 (4.7)
Campbell-Kyureghyan et al. (2005)	F + M			8.4 (1.3)			9.3 (1.3)			10.1 (1.3)			10.5 (1.5)			9.4 (1.4)
Mahato (2011)	Normal	9.53 (1.34)			10.31 (1.43)			10.58 (1.39)			11.59 (1.83)			10.33 (1.73)		
	Accessory	9.46 (1.71)			9.55 (2.13)			9.88 (1.57)			9.92 (1.96)			7.56 (1.51)		
	Fused	9.12 (1.16)			9.31 (2.25)			10.83 (3.62)			10.99 (1.56)			6.15 (1.72)		

AH (cm): anterior height; MH (cm): middle height; PH (cm): posterior height

2.6.3 Analytical findings in the literature

The analytical findings reported in the literature are summarized in a series of tables (Table 2.19 to 2.30), as well as the design of experiment and measurement protocol.

A number of studies have reported geometric dimensions as supplementary data to the mechanical tests that were the focus of their researches (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Porter et al., 1989) and biomechanical modeling (Drerup et al., 1999; Campbell-Kyureghyan et al., 2005). Morphologic studies, on the other hand, have revealed the influence of gender (Mosekilde, 1990; Aharinejad et al., 1990; Gilsanz et al., 1995; Aydinlioglu et al., 1999; Zhou et al., 2000; Al-Hadidi et al., 2001; van der Houwen et al., 2010; Karabekir et al., 2011; H. Chen et al., 2011), age (Twomey & Taylor, 1985, 1987; Mosekilde, 1990; Aharinejad et al., 1990; Amonoo-Kuofi, 1991) cephalocaudal changes (Nissan & Gilad, 1984; Gilad & Nissan, 1986; van Schaik et al., 1985; J. L. Berry et al., 1987; Twomey & Taylor, 1985, 1987; Colombini et al., 1989; Panjabi et al., 1992; Seidel et al., 2008; Kang et al., 2011; Mahato, 2011; Y. Wang et al., 2012), and ethnicity (Postacchini et al., 1983).

Even though no specific geometry data were reported, there have been a number of studies that investigated the morphometry of the spinal motion segments with respect to gender, age, and spinal level. Cheng et al. (1998) obtained lateral x-ray images of 198 healthy females and 142 healthy males over 50 years of age and measured the anterior, central, and posterior vertebral height of the non-fractured thoracolumbar vertebral bodies to investigate the relationships among these dimensions. It was noted that the anterior-to-posterior (H_a/H_p) ratios of males were significantly smaller than those of

females across the thoracolumbar region (from T4 to L4, 1.8% smaller on average). Similar trend were also reported for the central-to-posterior (H_c/H_p) ratios with a smaller average difference (0.7%). It was suggested that vertebral shape varies significantly with gender and spinal level and may provide valuable information for the morphological diagnosis of osteoporosis. Nieves et al. (2005) recruited 36 pairs of young female and male military cadets with matched age, body height and weight to investigate the influence of gender on the skeletal size and bone density using quantitative CT scans. It was reported that male cadets had significantly larger vertebral body widths and femoral dimensions. It was also reported that no gender effect was reported for disc heights. Sevinc, Barut, Is, Eryoruk, and Safak (2008) recruited 210 females and 156 males in a wider range of age and investigated the influence of age, gender, and their interactions on the morphometry of healthy lumbar spines (with no pathologic changes) using MR scans. It was reported that in the upper lumbar, female vertebral bodies had higher indices than males. The compression index (H_p/D) in female vertebrae decreased significantly with age across all lumbar levels, while the decrease in male vertebrae was significant only from L1 to L4. The biconcavity index (H_c/H_p) decreased significantly with age only in male lumbar vertebrae. In this study, age failed to show significance in wedge index (H_a/H_p) for both genders. Limthongkul, Karaikovic, Savage, and Markovic (2010), using a computerized program, measured the vertebral volume of the thoracolumbar spine of 20 females and 20 males with non-specific pain symptoms using CT scans and reported that volume of the vertebrae increased gradually from T1 to L4 and then decreased at L5. It was also noted that males had larger volume across the lumbar spine.

In general, it should be noted that the results reported from the analytical analyses are subjected to the shortcomings associated with small sample sizes. Secondly, with respect to the experimental design, although there are some similarities, these studies vary with respect to subject selection characteristics (e.g., gender, ethnicity, injury status, etc.), region of interest, and measurement modality. Regarding subjects profile, gender and health status are two major factors described in the methodology. A gender-balanced sample is highly desirable in experimental design. In terms of health status, there are several approaches applied in the literature, including: 1) obtaining cadavers with no pathological changes or bone abnormalities to the spine, 2) recruiting healthy subjects with no spinal pathology or surgery, 3) recruiting patients with no pathological changes to the region of interest, and 4) diagnosing the status of disc degeneration in unhealthy cadavers or symptomatic patients. Unfortunately, subject height, body weight, and other anthropometric characteristics have not been well documented in the literature, especially in cadaver studies using archived skeletons. In terms of the region of interest (ROI) and measurement modality, fresh cadavers and archived skeletons have been a major source that granted early researchers access to the lumbar segments. Among these early studies, vertebral bodies have received greater amount of research effort to characterize their geometry because their bony attributes withstand post-mortem alterations much more so than do soft tissues (e.g., intervertebral discs). In order to provide better understanding and characterization of the spine *in vivo*, medical imaging techniques, such as x-ray, computed tomography (CT), and magnetic resonance imaging (MRI) have been employed as reliable diagnostic methods for the anatomical structures of the spine and spinal

abnormalities. They also present reliable alternatives for researchers to investigate the geometric characteristics of the spinal structures.

In the following section, these issues are discussed in greater detail.

Table 2.19: Subject profile, region of interest, and measurement modality reported in the literature from 1960 to 1987

Authors	**Subject Profile**						**ROI**	**Measurement Modality***		
	n	**Gender**	**Age (years)**	**Ht (cm)**	**Wt (kg)**	**Health**				
Nachemson (1960)	14 19	F M	59.71 (16.92) 47.84 (17.47)	- -	- -	Macroscopic inspection performed for the assessment of the degree of degeneration into 4 groups	IVD	A	1	T
Farfan (1973)	-	-	-	-	-	-	IVD	A	2	S, T
Hansson et al. (1980)	21 15	F M	57.67 (11.08) 59.73 (15.35)	- -	- -	No known or suspected malignancies of the spine	IVD	A	-	T
Hutton and Adams (1982)	5 13	F M	52.00 (12.43) 38.31 (11.95)	- -	67.00 (17.22) 68.46 (13.99)	Degeneration status evaluated according to Galante	IVD	A	1	T
Postacchini et al. (1983)	63 Italian and 58 Indian	-	adult	-	-	-	VB	A	1	S, T
Nissan and Gilad (1984); Gilad and Nissan (1986)	157 cervical	M	26.8 (4.1)	174.7 (6.5)	72.4 (9.8)	Good health, no spinal deformities or known pathology	VB, IVD	B	1, 2	S
van Schaik et al. (1985)	123 lower lumbar	59 F + 64 M	41.4 (12.1)	-	-	Patient with low back pain or sciatica, no surgery or severe degenerative changes	VB	B	3	T
J. L. Berry et al. (1987)	30 Caucasian	M + F	50s, 60s, and 70s	-	-	No bone abnormality (e.g., tumors, fractures, or arthritis	VB	A	1	S, T
Twomey and Taylor (1985, 1987)	204	M + F	6 age groups	-	-	4-point classification of disc degeneration	VB, IVD	A	1	S

*Modality: (A. Cadaver, B. Scanned); (1. Caliper, 2. X-ray, 3. CT, 4. MRI, 5. Laser scanning, 6. Other); (S. Mid-sagittal, T. Transverse, F. Frontal)

Table 2.20: Subject profile, region of interest, and measurement modality reported in the literature from 1988 to 1990

Authors	Subject Profile						ROI	Measurement Modality*		
	n	Gender	Age (years)	Ht (cm)	Wt (kg)	Health				
Biggemann et al. (1988)	13 16	F M	49.94 (17.16) 49.15 (21.70)	- -	- -	No localized bony destruction, no radiographic defects	VB	A	3	T
Brinckmann et al. (1989)	22 31	F M	49.15 (21.70) 49.93 (17.16)	- -	- -	Degeneration status evaluated according to Galante	VB	A	3	T
Colombini et al. (1989)	32	16 F + 16 M	44 (7.3)/46 (8.2)	172.4 (5.4)	77.4 (6.8)	No disc alterations	IVD	B	3	T
Porter et al. (1989)	9	M	21.89 (4.78)	-	72.44 (5.85)	No gross evidence of trauma	IVD	A	6	T
Mosekilde (1990)	11 16 14	F M F M F M	28 (6) 30 (9) 66 (6) 64 (5) 82 (4) 80 (4)	162.7 (6.9) 174.6 (7.7) 162.3 (6.1) 175.3 (7.8) 157.4 (5.9) 169.2 (6.9)	55.6 (9.5) 73.8 (10.4) 60.4 (4.4) 71.9 (11.8) 55.7 (6.0) 65.4 (8.2)	No malignant diseases or fractures	VB	A	1	S, T
Aharinejad et al. (1990)	359 VBs and 215 IVDs	-	-	-	-	no pathology shown	VB, IVD	A, B	1, 3, 4	S, T
Dabbs and Dabbs (1990)		20 F + 31 M	20-50	-	-	no low back pain	IVD	B	2	S
		40 F + 46 M	20-50	-	-	structural in nature; no trauma, infection, neoplasm of the spine, inflammatory arthritis, or previous spinal surgery or other pathology; no anomalies in radiographs				

*Modality: (A. Cadaver, B. Scanned); (1. Caliper, 2. X-ray, 3. CT, 4. MRI, 5. Laser scanning, 6. Other); (S. Mid-sagittal, T. Transverse, F. Frontal)

Table 2.21: Subject profile, region of interest, and measurement modality reported in the literature from 1991 to 1999

Authors	Subject Profile						ROI	Measurement Modality*		
	n	Gender	Age (years)	Ht (cm)	Wt (kg)	Health				
Amonoo-Kuofi (1991)		50 F + 45 M	10s	-	-	Healthy, no surgery, no degenerative changes in radiographs, no history of trauma to the back, sciatica or ruptured discs	VB & IVDB		1, 2	S
		55 F + 70 M	20s	-	-					
		70 F + 75 M	30s	-	-					
		70 F + 65 M	40s	-	-					
		65 F + 50 M	50+	-	-					
Panjabi et al. (1992)		4 F + 8 M	46.3	167.8	67.8	No disc abnormality	VB	A	6	S, T
Gilsanz et al. (1994)	Caucasian	25 F	35.9 (6.9)	160.4 (9.5)	64.1 (18.4)	Physically active, no chronic pain	VB	B	3	S, T
		18 M	34.6 (6.7)	176.8 (7.3)	82.0 (14.6)					
Gilsanz et al. (1995)	Caucasian	32 F	72.7 (6.57)	159.9 (8.14)	59.1 (15.80)	Ambulatory, not taking any medication on a regular basis, without history of hip fracture or any chronic illness that could result in bone loss	VB	A	3	S
		32 F	72.9 (6.43)	157.1 (6.10)	58.8 (13.08)					
Aydinlioglu et al. (1999)	Turkish	10 F + 15 M	10s	-	-	No history of trauma, surgery, or abnormalities	IVD	B	1, 2	S
		15 F + 14 M	20s	-	-					
		16 F + 18 M	30s	-	-					
		30 F + 32 M	40s	-	-					
		22 F + 28 M	50s	-	-					
Drerup et al. (1999)	14	-	42.21 (9.77)	177.57 (7.34)	87.86 (33.37)	Operators of heavy earth-moving machinery	VB	B	3	T

*Modality: (A. Cadaver, B. Scanned); (1. Caliper, 2. X-ray, 3. CT, 4. MRI, 5. Laser scanning, 6. Other); (S. Mid-sagittal, T. Transverse, F. Frontal)

Table 2.22: Subject profile, region of interest, and measurement modality reported in the literature from 2000 to 2011

Authors	**Subject Profile**						**ROI**	**Measurement Modality***		
	n	**Gender**	**Age (years)**	**Ht (cm)**	**Wt (kg)**	**Health**				
Zhou et al. (2000)		71 F 55 M	50 (13.60) 49 (12.04)	- -	- -	No abnormalities, gross spinal pathology, no surgery	VB, IVD	B	3	S
Al-Hadidi et al. (2001)		66 F 87 M	47 (13.7) 43 (12.1)	- -	- -	No hisotry of back ailment with normal signal intensity	IVD	B	4	S
Turk and Celan (2004)	Patients	21 F + 19 M	44	-	-	Treated for lumbar symdrome				
	Random	65 M + 30 M	41	-	-	65 subjects with anamnesis of low back pain; 30 subjects never had low back pain	IVD	B	3	T
Campbell-Kyureghyan et al. (2005)	Model development	20 F 20 M 6 F + 8 M	25.0 (7.2) 26.4 (5.5) 24.4 (3.9)	165.5 (5.9) 175.9 (9.1) 172.4 (4.7)	57.9 (6.4) 79.8 (13.3) 66.0 (6.7)	No reported history of acivity limiting chronic back or leg injuries, nor any experience of low back pain at the time of the MRI scan	IVD	B	2, 4	T
	Validation	9 F + M	26.4	170.7 (7.1)	69.3 (16.1)					
Seidel et al. (2008)	53	-	33.26 (5.87)	179.92 (7.36)	82.66 (16.24)	-	VB	A	3	T
van der Houwen et al. (2010)	Patients	31 F + 46 M	49.8	-	-	Patient with varying spinal problems (e.g., hernias and fractures); only intact vertebrae below and above the problem areas measured; no implanted devices or visible deformations	VB	B	1, 3	S, T
Kang et al. (2011)	Koreans	15 F 35 M	41 39.8	161.2 170.6	53.4 70.5	No abnormal vertebrae, fractures, history of spinal surgery or scoliosis	VB	B	1, 2, 3	T, F

*Modality: (A. Cadaver, B. Scanned); (1. Caliper, 2. X-ray, 3. CT, 4. MRI, 5. Laser scanning, 6. Other); (S. Mid-sagittal, T. Transverse, F. Frontal)

Table 2.23: Subject profile, region of interest, and measurement modality reported in the literature from 2011 to present

Authors	**Subject Profile**						**ROI**	**Measurement Modality***		
	n	**Gender**	**Age (years)**	**Ht (cm)**	**Wt (kg)**	**Health**				
Karabekir et al. (2011)		10 F + 11 M	31-47	-	-	normal radiological evaluation, no disc herniation,no vertebral fractures, no congenital or acquired bone deformities, no tumors	VB	B	4	T
Mahato (2011)	50	-	32 (7.82)	-	-	Patients with low back pain, no disc herniation or spinal injuries, no congenital anomalies or spinal surgery, no osteoarthritis	VB	B	2	S, F
H. Chen et al. (2011)	83	-	43	-	-	No marked osteophyte formation, no significant vertebral degeneration or fractures	VB	A, B	3	S, F
Y. Wang et al. (2012)	149, Caucasian	M	under 64	-	-	No chronic illness or long hospitalization and death from cancer or infectious diseases	VB	A	1, 2, 5	T, F

*Modality: (A. Cadaver, B. Scanned); (1. Caliper, 2. X-ray, 3. CT, 4. MRI, 5. Laser scanning, 6. Other); (S. Mid-sagittal, T. Transverse, F. Frontal)

Table 2.24: Summary of measurement protocols and analytical findings reported in the literature from 1960 to 1983

Authors	**n**	**Preparation**	**Definitions of geometric dimensions**	**Analytical findings**
Nachemson (1960)	F, 8 L1/L2, 12 L2/L3, 9 L3/L4, 5 L4/L5 M, 15 L1/L2, 15 L2/L3, 15 L3/L4, 12 L4/L5	Discs were cut out with slices of adjacentVBs, 1 to 1.5 cm thick, cutting surface made parallel to each other, if possible also parallel to the endplate, rejections made when discs were damaged at post-mortem or when removing the lumbar vertebrae	1. CSA calculated with an Amsler planimeter, its ocular was moved round the edges of the surface, so that the roller R turned N times; 2. CSA = N×A×U, where A is the length of the moving arm and U is the circumference of the roller	N/A, as supplementary of the intradiscal pressure measurement
Farfan (1973)	4 L1/L2, 6 L2/L3, 6 L3/L4, 4 L4/L5	-	1. Major diameter (FD) as the maximum transverse diameter; 2. Minor diameter (APD) as the maximum anteroposterior diameter (**In the instance of pronounced re-entrant posterior surface, measured from a tangent to the two posterolateral angles**); 3. CSA = FD×APD×0.81 (Nachemson 1963 found 0.84)	1. A good approximation of the CSA from radiographs; 2. The shape of the disc cavity found to be similar to the shape of the disc itself; 3. dics cavity CSA at 25% of the disc CSA
Hansson et al. (1980)	F, 19 L1/L2, 16 L2/L3, 9 L3/L4 M, 14 L1/L2, 13 L2/L3, 7 L3/L4	VB with 3 mm of the adjacent discs covering each endplate	1. The borders of all cranial disces were colored and lightly pressed against a paper; 2. The CSA was cut from the paper and calculated	N/A, as supplementary of the intradiscal pressure measurement
Hutton and Adams (1982)	F, 1 L1/L2, 3 L2/L3, 2 L3/L4, 2 L4/L5 M, 2 L1/L2, 7 L2/L3, 4 L3/L4, 8 L4/L5, 4 L5/S1	Segments consisting of two VBs and one disc	1. CSA = Breadth (FD)×Depth (APD)×π/4	N/A, as supplementary of the intradiscal pressure measurement
Postacchini et al. (1983)	598	Archived skeletons	1. Midsagittal diameter (SD), transverse diameter (TD) of **cranial vertebral enplate** of the vertebral body; 2. Vertebral height of anterior wall	1. Italian skeletons had significant larger dimensions than Indian skeletons; 2. Lumbar vertebrae increased in size caudally

Table 2.25: Summary of measurement protocols and analytical findings reported in the literature from 1984 to 1987

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Nissan and Gilad (1984); Gilad and Nissan (1986)	157	lying on the side, 1.0 m between source and plate, special light box, caliper, and compass	1. 8-point in lateral image; 2. **Cranial and caual** midsagittal diameter (SD); 3. Anterior and posterior vertebral height (VH); 4. **Anterior and posterior** intervertebral disc height (DH)	1. Comprehensive description of cervical and lumbar vertebral bodies; 2. SD increased a little in the cervical region, remaining constant in the lumbar region at about twice the cervical size; 3. VH decreased in the upper cervical and increased towards the lower cervical and remained constant in the lumbar region; 4. The ratio disc height to cranial vertebral body height increased in lumbar region
van Schaik et al. (1985)	213	Transaxial CT, slices with 3 or 4.5 thickness, made parallel to the inferior endplate of each VB	1. Midsagittal diameter (MSD) as the length of midsagittal line from the anterior to the posterior border of the vertebral body; 2. Midtransverse diameter (MTD) as the the length of midtransverse line between the lateral borders perpendicular to the midsagittal line	1. Significant difference found between L3 and L4 vertebrae (1.2 mm), no difference between L4 and L5; 2. Significant difference found between L3 and L4 (1.3 mm), and between L4 and L5 (2.9 mm); 3.Significant difference in SD-to-FD ratio between L4 and L5; 4. Male segments significantly larger
J. L. Berry et al. (1987)	30 T2, T7, T12 and lumbar	Archived skeletons	1. Major vertebral body diameter at most superior level, at the midline, and at the most inferior (as MTD); 2 Minor diameter with same definition (as MSD); 3. Body height in anterior and posterior (as AVH and PVH)	1. Slight increase in major and minor diameters of lumbar vertebrae caudally; 2. AVH increased progressively from T2 to L5; 3. PVH slightly decreased across the lumbar region
Twomey and Taylor (1985, 1987)	204 lumbar columns	Deep-frozen, vertical cut with slices of average thickness of 2.04 mm at midline	1. Vertebral body concavity indices by dividing the "central" vertebral height by the AVH; 2. Average disc height calculated from the ADH, MDH, and PDH; 3. Disc convexity index calculated by MDH/(ADH + PDH) 4. "True" average DH caldulated by dividing the area of the disc in median section by its anteroposterior diameter	1. Larger APDs in males; 2. The middle lumbar discs had larger APDs than the L1/L2 and L5/S1; 3. APD increased with age, (F: 10%; M: 2%); 4. Increase in DH for both genders with increasing age; 5. Linear correlation between disc height and body height; 6. Increase in disc convexity indices.

Table 2.26: Summary of measurement protocols and analytical findings reported in the literature from 1988 to 1990

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Biggemann et al. (1988)	F, 5 L1/L2, 3 L3/L4, 2 L4/L5, 3 L5/S1; M, 2 L1/L2, 5 L2/L3, 4 L3/L4, 2 L4/L5, 3 L5/S1	Segments placed in a phantom simulating the spine within the human body	1. CSA measured by CT with digitized endplate contour; 2. The endplate were located in the lateral topograms and 2 mm thick slices were taken; 3. The pictures generated were magnified electronically to facilitate marking of endplate boundaries by an electronic cursor	N/A, as supplementary of the intradiscal pressure measurement
Brinckmann et al. (1989)	F, 6 L1/L2, 9 L2/L3, 4 L3/L4, 12 L4/L5; M, 6 L1/L2, 14 L2/L3, 3 L3/L4, 11 L4/L5	Segments placed in a phantom simulating the spine within the human body	1. CSA measured by both CT and photographic means with digitized endplate contour; 2. The endplate were located in the lateral topograms and 5 mm thick slices were taken; 3. The pictures generated were magnified electronically to facilitate marking of endplate boundaries by an electronic cursor	N/A, as supplementary of the intradiscal pressure measurement
Colombini et al. (1989)	16 L3/L4, 13 L4/L5, 11 L5/S1	Axial CT	1. Major and minor diameters of lumbar disc; 2. Cross-sectional area (CSA) calculated with the two diameters	1. The L4/L5 CSA was 5% greater than L3/L4, while the L5/S1 CSA was lower than L3/L4 and L4/L5 by about 5% and 10%, respectively; 2. Significant correlations found between CSA and some anthropometric characteristics (e.g., body weight and wrist diameter); 3. Regression models provided
Porter et al. (1989)	9 L2/L3, 9 L4/L5	Cut through in several planes	1. CSA measured by counting the squares of superimposed graph paper	N/A, as supplementary of the intradiscal pressure measurement
Mosekilde (1990)	82 L3 VBs	Deep-frozen	1. CSA calculated by dividing the volume (measured by water displacement) by the vertebral height (measured with a micrometer)	1. Significant age-related increase in CSA for males; 2. No significant correlation found between body height or weight and the CSA

Table 2.27: Summary of measurement protocols and analytical findings reported in the literature from 1990 to 1995

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Aharinejad et al. (1990)	segments obtained from cervical, thoracic, and lumbar region	Macerated bones, archived CT and MR scans	1. Median sagittal diameter (SD): through the middel of the transverse diameter; 2. Transverse diameter (TD) as the maximum breadth across the vertebral body; 3. AVH and PVH; 4. ADH, MDH, and PDH	1. SDs and TDs increased across the lumbar region craniocaudally; 2. AVHs greater than PVHs in the lumbar region; 3. DHs slightly increased across the lumbar region craniocaudally; 4. No difference between ADH and PDH, 25% more in MDH; 5. Gender had less pronounced effect in the lumbar region
Dabbs and Dabbs (1990)	86 L4/L5, 86 L5/S1 51 L4/L5, 51 L5/S1	Lateral radiographs	1. Two straight lines drawn along the cranial and caudal endplates from corner to corner and extended beyond the vertebral bodies; 2. ADH as the distance between two anterior corners; 3. PDH as the distance between two posterior corners; 4. DH= (ADH+PDH)/2	1. No significant difference in DHs between two groups
Amonoo-Kuofi (1991)	310 F, 305 M	Lateral recumbent position with the hips and knees flexed to 45 degree; X-ray beam centered on L3	1. Disc height: ADH and PDH; 2. Disc depth: Superior and Inferior depths	1. Age identified as a significant factor for the geometric dimensions of both disc and vertebral body heights
Panjabi et al. (1992)		Fresh autopsy spine specimens; measurements performed by custom-made software	1. 3D measurements; 2. Endplate widths; 3. Endplate depths; 4. Endplate areas (upper and lower) = $D \times W \times \pi/4$; 5. Posterior vertebral body height	1. Slight increase in widths from L1 to L5 of 14%; 2. Depths remained constant; W/D ratio increased for both upper and lower EP (12% for upper EP, 21% for lower EP; 3. CSA of upper EP increased from L1 to L5 (17% more), CSA of lower EP peaked at L3
Gilsanz et al. (1995)	16 L1, 26 L2, 23 L3, 27 L4 16 L1, 6 L2, 9 L3, 5 L4	Determined directly from CT images; measurements done only in VBs without fracture	1. Vertebral body height reported = (AVH + MVH + PVH)/3; 2. Vertebral CSA	1. No significant difference in vertebral body height between women with and without fracture; 2. CSA of unfractured vertebral bodies was found to be significant smaller in the 32 women with fractures, compared with their matched counterparts at L1, L2, and L4 level; 3. On average, the CSA of unfractured vertebrae was 7.7% smaller in women with fractures as compared with women without fractures

Table 2.28: Summary of measurement protocols and analytical findings reported in the literature from 1999 to 2004

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Aydinlioglu et al. (1999)	93 F + 107 M, Lumbar vertebrae	Lateral recumbent position with the hips and knees flexed to 45 degree; X-ray beam centered on L3	1. Disc height: ADH and PDH; 2. Disc depth: Superior and Inferior depths	1. DH increased with aging only in males and the disc depth in both genders
Drerup et al. (1999)	L3 VB	QCT section had 5-mm thickness and positioned through the caudal endplate of L3	-	N/A, as supplementary data for model development
Zhou et al. (2000)	L3/L4, L4/L5, L5/S1	Sequential 3-mm continuous cross-sectional images parallel to both upper and lower endplates	1. Upper and lower vertebral width (UVW and LVW) as the distance between the lateral borders of the upper and lower endplate; 2. Upper and lower vertebral depth (UVD and LVD) as the distance between the anterior and posterior borders (in fact, mid-sagittal diameter); 3. AVH as the distance between anterior margins of upper and lower endplates; 4. PVH as the distances between the posterior margins; 5. DH measured in the midline; 6. The circumference and outline of the lower endplate was defined from the CT images by dividing the circumference into 5-mm segments with the cursor, where CSA was displayed in the information box	1. The mean dimensions of the vertebral bodies for male spines were significantly larger than for the female spines; 2. The depth and width increased from L3 to L5; 3. AVH was the same for the L3 and L4, while PVH decreased significantly; 4. DH of L5/S1 was significantly less than L3/L4 and L4/L5
Al-Hadidi et al. (2001)	Lumbar VBs and IVDs	1.5 T, T1-weighted, TR = 500 ms, TE = 15 ms, 3-mm thickness slice, 5 slices of images parallel to the axial plane of the IVD, supine position	1. Anteroposterior depths of the superior and inferior endplates; 2. VH as the distance between the midpoint of two depths of the same vertebral body; 3. DH as the distance between the midpoint of two depths of the two adjacent vertebral bodies	1. Highly significant gender-independent cephalocaudal sequence; 2. DH increased significantly from L1/L2 to L2/L3 to L3/L4 (F, 17% and 25%; M, 17% and 29%); 3. At L4/L5 and L5/S1, the DH displayed age-dependent and gender-independent changes
Turk and Celan (2004)	L4/L5, L5/S1	-	Measurements made using "region of interest" method which can accurately determine the size of the surrounded area on the image of the disc cross-section	1. Significant difference found between measurement using ROI and estimation using Colombini's model; 2. New regression models provided; 3. Subjects with low back pain planits had significantly bigger CSA of disc when compared with those with positive anamnesis of low back pain

Table 2.29: Summary of measurement protocols and analytical findings reported in the literature from 2005 to 2011

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Campbell-Kyureghyan et al. (2005)	Lumbar VBs and IVDs	1. 0.3 T T1-weighted MRI, TR = 400 ms, TE = 10 ms; 2. Lateral radiographs	1. Height of each segment defined as the distance between the superior and inferior surface centroids, calculated from the digitized data	N/A, as supplementary data for model development
Seidel et al. (2008)	L3 to L5 vertebrae in frozen state	3D reconstruction of the VBs from CT scans necessary since not all slices of CT scans parallel to all endplates due to spinal curvature	1. With the reconstruction cutting planes aligned with each EP and then moved from the disc towards the vertebra to find the first single closed polygon; 2. The CSA of kidney-shaped EPs determined based on an envelope procedure that minimize the area within the polygun hull; 3. As control, L4 superior EP measured using ellipse-method	1. The superior EPs of L3 and L5 significantly different from the corresponding inferior ones; 2. The sizes of both EPs of L3 significantly different from the ones of L5; 3. The superior EP of L4 smaller than that of L5, the inferior EP of L4 bigger than that of L5; 4. Regression models tested
van der Houwen et al. (2010)	L1 to L5 VBs	1. CT scans with 0.75 mm reconstruction slice thickness; 2. Scans visualized and analyzed using software with reconstructed 10-coordinate on each endplate	1. Sagittal and transverse diameter of the enplate as rim-to-rim lengths (reported using median value)	1. A linear model found between the depths of the superior EP, the age and the location within the spinal column; 2. SD about constant at about 27-28 mm; 3. TD increased at L3/L4 level; 4. Both diameters on average larger for male than female
Kang et al. (2011)	complete thoracolumbar VBs	1. CT scans with 1-mm cut parallel to the superior vertebral endplate; 2. Lateral radiographs centered at L3	1. Vertebral body transverse diameter (CT-VBD) defined as the longest distance between the bilateral outer cortices; 2. X-VBD with similar definition in midline of vertebral body	1. CT-VBD increased from L1 to L5, with the largest at L5; 2. Similar findings for X-VBD
Karabekir et al. (2011)	Lumbar VBs	1. Consecutive 0.2 cm thick serial MRIs from sagittal T1 weighted with SE T1A (TR 500-700 ms; TE 10-30 ms); 2.one axial slice on MRI passing through both the upper part of the pedicle and the VB; 3. One axial slice passing through the lower part	1. AVH, PVH; 2. APD, TD; 3. no definition provided	1. Significant difference found between AVH and PVH for female at L3, L4 and L5, for male at L1, L3, L4 and L5; 2. No significant difference in APD and TD found between male and female

Table 2.30: Summary of measurement protocols and analytical findings reported in the literature from 2011 to present

Authors	n	Preparation	Definitions of geometric dimensions	Analytical findings
Mahato (2011)	Lumbar VBs	1. Patient in a erect position; 2. Data randomly selected from the database repository; 3. 50 anteroposterior and lateral images for patients without transitional anomalies; 30 images for patients with L5/S1 transitional states (unilateral or bilateral accessory articulations); 30 images for L5/S1 fusions	1. Disc height; 2. VBH; 3. VBW; 4. illustrated in radiographs	1. DH gradually increased from L1/L2 to L4/L5 and decreased to L5/S1; 2. VBH marginally greater on images of the normal spine, and smaller on the fused L5/S1 images; 3. VBW greater on the fused L5/S1 images, and smaller on the normal discs
H. Chen et al. (2011)	Lumbar VBs L1 to L3	1. CT scans selected retrospectively from the Picutre Archiving and Communication System (PACS); 2. 10 cadaver cut along the midsagittal planes; 3. 0.625 mm slice thickness	1. SD as the distance between anterior and posterior rims of the superior and inferior endplates on CT scans; TD as the distance between the left and right rims of the two endplates; 3.aSD as average SD of superior and inferior endplates	1. Age did not influence SD and TD significantly; 2. Female had significant smaller SD and TD than male (about 88%); 3. No significant difference in SD between superior and inferior endplates; 4. TD Superior endplates had significantly smaller TDs (91%)
Y. Wang et al. (2012)	266 lumbar VBs, 264 cranial and 336 caudal	1. Scanned using a 3D digitizer to acquire surface geometric measurements; 2. Both cranial and caudal endplates scanned with Polygon Editing Tool (PET)	1. APD measured in mid-sagittal plane; 2. TD as the maximal distance in the coronal plane; 3. CSA; 4. measured by software	1. The average APD relatively constant from L1/L2 to L4/L5; 2. The average TD increased gradually in craniocaudal direction

2.7 Research Void

After reviewing the literature, especially those reporting morphologic characteristics and geometric dimensions, this dissertation attempted to identify research voids that should be considered when summarizing and comparing the results and analytical findings of morphologic studies. The measurement of geometric dimensions involves three major considerations: 1) how to prepare specimens (cadaver or *in vivo*), 2) how to access the structure (cadaver or scanned image), and 3) how to define the dimensions, all of which are discussed in detail below.

2.7.1 How to prepare specimens (cadaver vs. *in vivo*)

As summarized in previous tables, seventeen (17) out of 35 studies performed geometric measurements with thoracolumbar spines from fresh cadavers or archived skeletons. Sixteen (16) out of 34 studies measured spine geometry *in vivo*. Two studies collected mixed samples with both cadavers and living subjects. With cadaver specimens, the major region of interest is the vertebral body or "vertebra", including the dimensions in the cranial, midline, and caudal planes. This could be explained by the capability of vertebral bodies to sustain post-mortem changes, which help preserve its morphologic characteristics measured by the bony landmarks identified (Farfan, 1973). In earlier studies investigating the morphologic characteristics, vertebrae were isolated from the spinal column, which provides more freedom to access the bony landmarks. Therefore, more geometric dimensions have been measured to characterize the relative relationship among these dimensions (J. L. Berry et al., 1987; Panjabi et al., 1992). On the other hand, some

cadaver studies investigating the mechanical properties of the lumbar motion segments across a single level or multiple levels, have also provided geometric dimensions (Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Porter et al., 1989). However, intervertebral discs and other soft tissues are highly susceptible to post-mortem changes (Adams et al., 2002). Meanwhile, spinal ligamentous tissues were scraped clean to characterize the sole mechanical properties of motion segment. Unfortunately, the removal of ligamentous tissues and other soft tissues could alter the morphologic characteristics, especially the disc height and cross-sectional area (Zhou et al., 2000). In addition, in mechanical tests, dissections have been performed to isolate the motion segments by cutting through the vertebral bodies or intervertebral discs, which possibly could introduce error in the measurements (Kunkel, Herkommer, Reinehr, Bockers, & Wilke, 2011). However, there is very limited understanding of how these procedures might influence actual spine geometry.

The *in vivo* human spine is loaded with compression introduced by the upper body weight and muscle contraction, which change the geometric dimensions of the intervertebral disc. In addition, the contribution of different spinal structures in load-bearing capacity are heavily influenced temporally (Adams et al., 1990), primarily through the decrease in water content over time and increase with sleep/rest in a supine or prone posture (Boos, Wallin, Gbedegbegnon, Aebi, & Boesch, 1993). Botsford et al. (1994) reported significant diurnal decrease of disc height and anteroposterior diameter after performing daily activities, which led to 21.1%, 18.7%, and 21.6% decreases of disc volume at the L3/L4, L4/L5, and L5/S1 level, respectively. LeBlanc, Evans, Schneider, Wendt, and Hedrick (1994) also reported significant adaptive changes of the CSAs in the

intervertebral discs during long-term weightless space flight. Kimura, Steinbach, Watenpaugh, and Hargens (2001) simulated the upper body weight of a group of 8 young subjects (1 female and 7 males) with a compression device compatible with MRI scanner and investigated the influence of compressive loading on the morphometry of lumbar spine. A significant difference was found between intervertebral angles before and during compression in the lower lumbar region. It was also noted that L4/L5 disc height reduced significantly during compression. Since the 1990s, geometric measurement *in vivo* has been performed in numerous studies investigating the morphologic characteristics with advanced imaging technology to access the internal structure of human spine.

In general, the bony component (e.g. vertebrae) and soft tissues (e.g., intervertebral discs and ligaments) provide the human spine the rigidity and flexibility to sustain compressive loads and to perform complex movements. Therefore, while cadaver studies provided very important information regarding spine geometry, measurements performed *in vivo* should improve our understanding and better characterize the morphometry of the living human spine.

2.7.2 How to access the structure

As discussed earlier, since isolated vertebrae provide better access to the structures, calipers provide a reliable means (0.05mm to 0.1mm accuracy) to measure the geometric dimensions in multiple anatomical planes (Postacchini et al., 1983; J. L. Berry et al., 1987; Panjabi et al., 1992). The dimensions measured in multiple planes provide valuable information to reconstruct three-dimensional aspect of the human vertebrae and improve the characterization of human spine geometry. Unfortunately, clinical procedures isolating

the vertebrae are highly likely to alter the spinal structures and may introduce error to the measurement of geometric dimensions of the intervertebral discs. Despite the fact that post-mortem changes and clinical procedures may alter the geometry of the intervertebral disc, research efforts have been made to measure the geometry of single-level motion segments (Nachemson, 1960; Hutton & Adams, 1982), and multiple-level segments (Twomey & Taylor, 1985, 1987). But direct measurements with calipers are limited to the dimensions between peripheral bony landmarks. On the other hand, medical imaging techniques (e.g., x-ray, CT, and MRI) have been employed in a number of studies owing to their superior accessibility to internal geometry and the capability of *in vivo* measurement .

X-ray

As summarized in previous tables (Table 2.19 to 2.23), radiographs of human spines have been a primary source for early investigators to access the lateral geometric characteristics, especially the vertebral body height (VB), disc height (DH), and anteroposterior (APD) and frontal diameter (FD) of the vertebral bodies and endplates. X-ray techniques have been widely used in clinical diagnosis of vertebral fractures and other pathological changes such as spondylitis or bone tumors (Tracy, Wright, & Hanigan, 1989; Krause, Drape, Maitrot, Woerly, & Tongio, 1991). Disc height (DH) is the primary dimension used to evaluate lateralized collapse, which is well accepted as good evidence of disc herniation (Krause et al., 1991). With respect to geometric dimensions, calipers are again the major instrument for measurements on plain radiographs (Nissan & Gilad, 1984; Gilad & Nissan, 1986; Amonoo-Kuofi, 1991; Kang et al., 2011).

Unfortunately, since radiographs are generated by a radiographic source projecting beams towards the spine onto the film, geometric dimensions measured are subjected to

varying magnification error depending on the spine-to-film and source-to-spine distance, ranging from 7.5% up to 30% (White III & Panjabi, 1990). Secondly, radiographs can only characterize the lateral (sagittal) and the frontal aspect of spinal geometry. It also has very limited capability to evaluate the morphometry of soft tissues, such as the intervertebral discs, in the transverse section.

Computed Tomography

Compared to radiography, computed tomography (CT) techniques produce superior tomographic sections of the spine and provide greater visualization of the anatomical characteristics, particularly the soft tissues (Teplick, 1992). Because of CT's superb imaging capability, it has become a primary diagnostic technique in clinical practice for demonstrating the majority of significant spinal abnormalities (e.g., spinal stenosis, spondyloysis, and disc herniation) (Krause et al., 1991; R. Schroeder, Pelsue, Park, Gasso, & Bruecker, 2011). It has also been used as a diagnostic technique to evaluate disc degeneration (Haughton, 1983) because of its capability to characterize the annulus fibrosus (Teplick, 1992). On the other hand, the CT sections can be obtained using x-ray beams angled parallel to each interspace. Therefore, the scanned images can be made through the intervertebral discs, the vertebral endplates, and the vertebral bodies at each spinal level (Teplick, 1992), providing a very valuable transverse section of the spine (Schnebel, Kingston, Watkins, & Dillin, 1989). The tilted transverse CT slices reconstruct the entire peripheral margin of the vertebral body and intervertebral disc with no disturbance, which become a very useful modality to investigate the morphometry of the lumbar spine and reported geometric dimensions measured with sophisticated computerized program, as summarized in previous tables (Table 2.19 to 2.23).

Unfortunately, in general, a CT scanner has a limited capability to tilt the slicing section, typically a maximum of 20 degrees (Teplick, 1992), which may be insufficient to accommodate the intervertebral angles reported in lumbar curvature *lordosis* (Aspden, 1989; Cheng et al., 1998; Y. L. Chen, 1999; Been, Li, Hunter, & Kalichman, 2011). Hence, it may not be well suited to reconstruct the lower lumbar spine, especially at L4/L5 and L5/S1 level, resulting in possible errors and distortions (Colombini et al., 1989).

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a rapidly developing clinical diagnostic method and provides the most complete noninvasive evaluation of a greater number of spinal abnormalities as compared to CT (Tracy et al., 1989; Yu et al., 1991), owing to its multi-planar capabilities and superior soft tissue contrast (Gundry & Fritts, 1997). MRI can provide excellent resolution and contrast among all bony structures and soft tissues in sagittal, transverse, and frontal tomographic sections, since most anatomical structures have different signal intensities depending on acquisition sequence techniques (e.g., T1 weighted and T2 weighted) (Teplick, 1992). Compared to CT, MR techniques allow greater discrimination between the nucleus, annulus, and anterior and posterior longitudinal complex when adapted sequences are used (Krause et al., 1991; Teplick, 1992; Gundry & Fritts, 1997). For example, the intervertebral disc has a moderately low signal when T1 weighted, where signal is even lower in the peripheral aspect, compared to T2 weighted where signal is low in the periphery and high in central portion representing the nucleus pulposus and inner annulus fibrosus (Teplick, 1992). Secondly, owing to it superior capability to differentiate the spinal structures by signal intensity using adapted scanning sequences (Gundry & Fritts, 1997), MRI has great value in the evaluation of disc

degeneration (Modic & Herfkens, 1990; Sether et al., 1990; Parkkola & Kormano, 1992; Gruber & Hanley, 1998; Luoma, Vehmas, Riihimäki, & Raininko, 2001; Takatalo et al., 2009) and the development of grading systems to classify disc degeneration status (Pfirrmann, Metzdorf, Zanetti, Hodler, & Boos, 2001). In addition, along with the advances in hardware design of high field magnets (Fries et al., 2008) and more sophisticated and sensitive coils (Noury et al., 2008), improvements have also been made in scanning sequences (Blumenkrantz et al., 2006; C. Wang, Witschey, Elliott, Borthakur, & Reddy, 2010; Stelzeneder et al., 2011; Hoppe et al., 2012; Zobel et al., 2012) and post-scanning software (Rosset, Spadola, & Ratib, 2004; Alomari, Corso, Chaudhary, & Dhillon, 2010).

Unfortunately, only a few studies in the literature have utilized MRI as the primary imaging modality to investigate morphologic characteristics of the lumbar motion segments (Al-Hadidi et al., 2001; Karabekir et al., 2011), despite the great resolution and excellent contrast of the morphologic landmarks.

2.7.3 How to define the dimensions

As summarized in previous tables (Table 2.24 to 2.30), linear dimensions, such as disc height (DH), vertebral body height (VB) in sagittal section and the diameters in transverse section, have been the most measured and reported morphologic characteristics in the literature. Only a few studies, however, have reported their measurement data for two-dimensional geometry such as the cross-sectional area and the three-dimensional geometry such as the vertebral body volume. On the other hand, the methods used to define certain geometric dimensions vary a lot in the literature, depending on the techniques employed.

Linear dimensions

According to the review, most studies share similar method to identify the anterior and posterior corners of bony spinal structures in the sagittal section and bilateral ones in the frontal section to define the heights, anteroposterior diameter, and frontal diameter (Nissan & Gilad, 1984; Gilad & Nissan, 1986; J. L. Berry et al., 1987; Aharinejad et al., 1990; Dabbs & Dabbs, 1990; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999; Zhou et al., 2000; Al-Hadidi et al., 2001; Mahato, 2011). As illustrated in Figure 2.12, linear vertical distance between two anterior/posterior corners define the anterior/posterior heights, while linear horizontal distances between anterior and posterior corners define diameters in the sagittal section as the same definition applied in the frontal section.

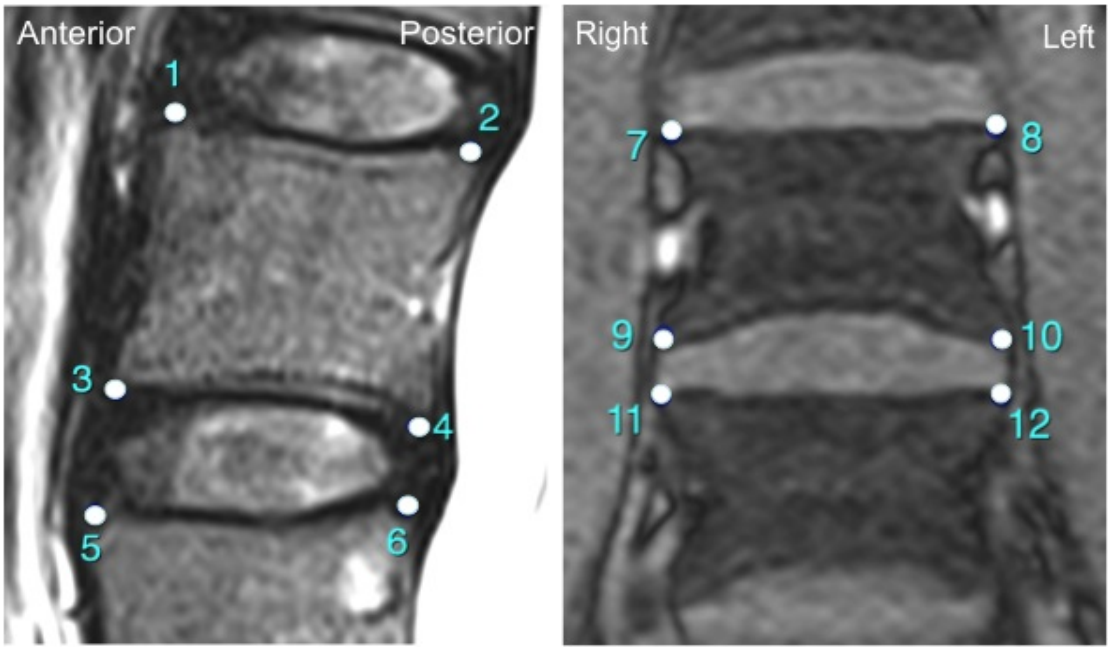
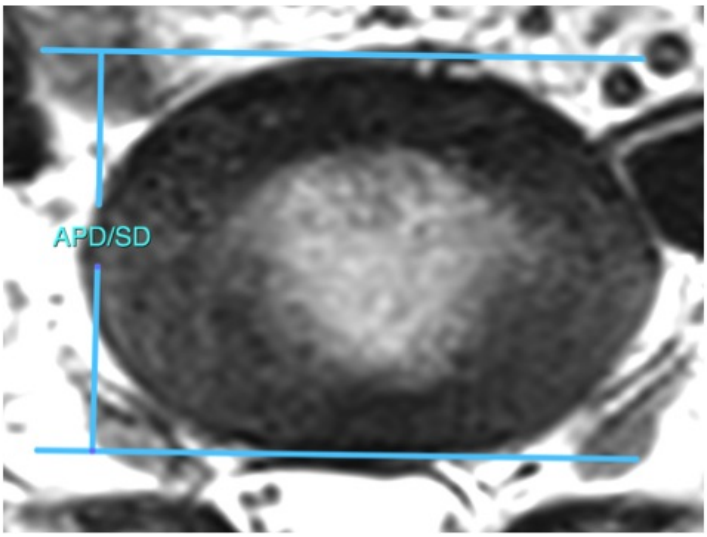


Figure 2.12: Illustrations of bony landmarks identified in **(left) sagittal** and **(right) frontal section**

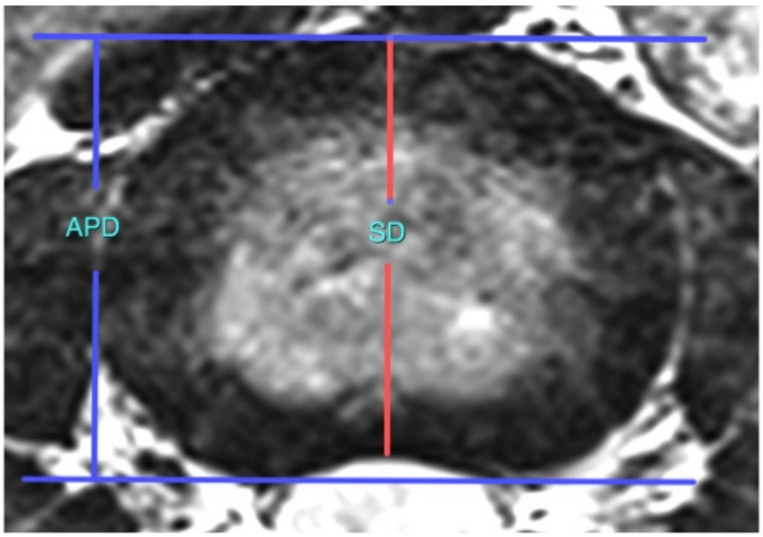
With advanced imaging techniques, recent evidence has unveiled that vertebral bodies may have two distinct peripheral bony edges (Tomomitsu, Murase, Sone, &

Fukunaga, 2005), which may be explained by the existence of a ring apophysis (Raj, 2008) and the concave shape of the vertebral endplates (Lakshmanan et al., 2012). Unfortunately, to date, there is no clear understanding whether such distinction has significant influence on the study characterizing spinal geometry. Secondly, in many cases, the lines drawn to measure the disc height may not be perpendicular to the midline of the disc (Frobin, Brinckmann, Biggemann, Tillotson, & Burton, 1997). Frobin et al. (1997) proposed a new definition for measurement of disc height as the sum of the perpendicular distance between two anterior corners and the midline, serving as the "ventral disc height". Unfortunately, since only a few studies have employed this definition (Shao, Rompe, & Schiltenwolf, 2002), there is very limited understanding about its validity. On the contrary, disc heights measured with the traditional definition have been referenced by a great number of finite element analyses (Robin et al., 1994; Martinez et al., 1997; Natarajan & Andersson, 1999; Noailly et al., 2007; Niemeyer et al., 2012).

Another discrepancy noted in the literature review is the selection of and agreement on which geometric dimensions should be used to characterize the transverse section of the spinal structures. Some researchers selected the anteroposterior diameter as the linear distance between the antero-most and postero-most landmarks (Farfan, 1973; Brinckmann et al., 1989), while other researchers selected mid-sagittal diameter (Postacchini et al., 1983; van Schaik et al., 1985; Aharinejad et al., 1990; Zhou et al., 2000; Y. Wang et al., 2012). For oval-shaped discs, the two diameters should provide the same measurement, while differences should be noted for kidney-shaped discs (Figure 2.13).



(a) Diameter in transverse section for oval-shaped discs (L5/S1 from a 32-years-old female)



(b) Diameter in transverse section for kidney-shaped discs (L2/L3 from a 32-years-old female)

Figure 2.13: Illustrations of anteroposterior diameter and mis-sagittal diameter in the transverse section for accommodating the intervertebal discs in different shape (**a. oval-shaped** and **b. "kidney-shaped"**).

Cross-sectional area

Compared to linear dimensions, cross-sectional area (CSA), as an important geometric dimension, has only been measured and reported in a few studies as summarized in previous tables. Nachemson (1960) calculated the CSA with readings obtained from an Amsler planimeter moving around the edges of the surface. Hansson et al. (1980) stamped the cadaveric vertebrae onto a piece of paper, traced the border of the surface, and then calculated the CSA. Porter et al. (1989) measured the CSA by counting the squares of superimposed graph paper. Mosekilde (1990) calculated the CSA by dividing the subwater displacement volume by the vertebral height. With advanced imaging techniques and sophisticated software, a scanned image of a transverse section can be digitized and then used to measure the CSA (Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008; Y. Wang et al., 2012).

On the other hand, an ellipsoid approximation method has been employed by a number of researchers attempting to simplify the characterization of the morphometry of the spinal structures in transverse sections (Farfan, 1973; Hutton & Adams, 1982; Brinckmann et al., 1989; Colombini et al., 1989; Panjabi et al., 1992; Seidel et al., 2008). The ellipsoid method calculates the CSA using two diameters measured in transverse section as the major and minor axis of an ellipse (Formula 2.1).

$$CSA = \frac{MajorAxis \times MinorAxis \times \pi}{4} \tag{2.1}$$

Frontal diameter, measured as the distance between the most bilateral edges, has been regarded as the input for the major axis (Farfan, 1973). However, there is

disagreement on which diameter represents the minor axis. Several studies have noted the necessity to accommodate the different shape of the lumbar motion segments (Farfan, 1973), since the intervertebral discs across the lumbar spine (from L1/L2 to L4/L5 levels) are concave posteriorly to obtain greater area of annulus which offers better mechanical capacity to withstand forward bending movement (Bogduk, 2005). As shown in Figure 2.14, the selection of a sagittal diameter may explain the underestimation of the actual CSA of the lumbar intervertebral disc from L1/L2 to L4/L5 levels using ellipsoid approximation method (Seidel et al., 2008).

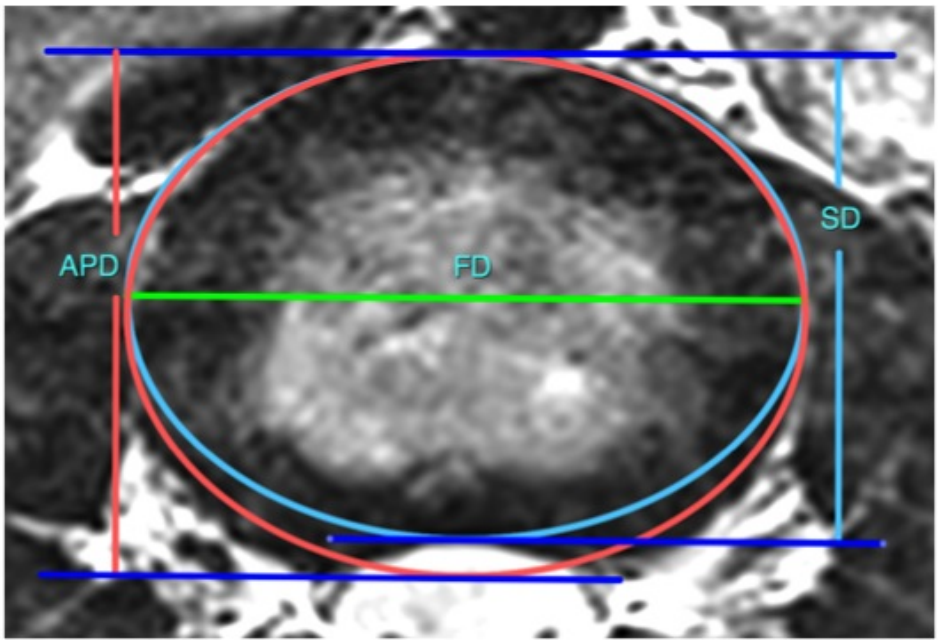


Figure 2.14: Illustrations of different ellipsoid approximation methods calculating the cross-sectional area (CSA) of the intervertebal disc

2.7.4 Influence of other factors

As mentioned in previous discussions, personal factors such as gender and age have been found to be associated with spinal geometry by a number of studies in the literature.

However, only a few of studies have investigated the influence of other personal factors such as height, body weight, and other anthropometric characteristics (Gilsanz et al., 1994; Colombini et al., 1989; Nieves et al., 2005; Seidel et al., 2008).

Colombini et al. (1989) investigated the correlation between multiple anthropometric measures and the cross-sectional area of the lumbar intervertebral discs, including height, body weight, diameters of the wrist, elbow, ankle and knee. Some sophisticated measures have also been calculated, including the average square thickness of bony structures (AST) and bony structure weight (SW). AST and SW was first proposed by Matiegka (1921) to characterize the development of the whole skeleton, referring to the thickness of the bone of the extremities (wrist, elbow, knee, and ankle) and the estimated weight of the skeleton (Formula 2.2 and 2.3).

$$AST = \left(\frac{W_{wrist} + W_{elbow} + W_{knee} + W_{ankle}}{4}\right)^2 \tag{2.2}$$

W: wrist diameter; E: elbow diameter; K: knee diameter; A: ankle diameter

$$SW = AST \times Heightt \times 1.1 \tag{2.3}$$

Because of the promising strong correlation between the anthropometric measures and the specific spinal geometry, several studies have attempted to develop regression models of the human spine morphometry, particularly at the lumbar spine (Colombini et al., 1989; Turk & Celan, 2004; Shao et al., 2002), as shown in Table 2.31. Colombini et al. (1989) found that bony structure weight (SW) and wrist diameter were better estimator of

the cross-sectional area (CSA) of the lower lumbar intervertebral discs, rather than body weight. Unfortunately, only 16 male and female subjects were involved in the study and the reported data were subjected to the effect of ellipsoid approximation method. Turk and Celan (2004) recruited a relatively large sample and found that the regression model reported by Colombini et al. (1989) significantly overestimated the actual CSA of the disc measured on CT scans. Turk and Celan (2004) proposed another model by applying the same concept of the average square thickness of bony structures (AST), but modified the formula by dropping the insignificant factor (ankle diameter) (Formula 2.4).

$$AST_{Turk} = \left(\frac{W_{wrist} + W_{elbow} + W_{knee}}{3}\right)^2 \tag{2.4}$$

Seidel et al. (2008) reported that the models proposed by both studies failed to predict the cross-sectional area of the vertebral endplates, for which one would speculate well correlated with the overall bony structure. With respect to the sagittal dimensions, Shao et al. (2002) measured over 1200 plain lateral radiographs of male and female spines and suggested using age as the single estimator to predict the height of the lumbar intervertebral discs.

Table 2.31: Regression models estimating lumbar CSAs

Author(s)	Parameter	Regression Equation	R^2	S.E.	p value
Colombini et al. (1989)	Bony structure weight (SW) (g)	$CSA_{L3/L4}$ = 0.95 + 0.002× SW	0.70		<0.001
		$CSA_{L4/L5}$ = 2.7 + 0.0019× SW	0.62	4.05 (1.40)	<0.001
		$CSA_{L5/S1}$ = 2.57 + 0.0017× SW	0.67	2.97 (1.32)	<0.001
	Wrist diameter (WD) (cm)	$CSA_{L3/L4}$ = -10.33 + 5.44× WD	0.49		<0.001
		$CSA_{L4/L5}$ = -14.26 + 6.39× WD	0.56		<0.001
		$CSA_{L5/S1}$ = -13.35 + 5.88× WD	0.62		<0.001
	Body weight (WT) (kg)	$CSA_{L3/L4}$ = 8.35 + 0.142× WT	0.42		<0.001
		$CSA_{L4/L5}$ = 3.52 + 0.22× WT	0.58		<0.001
		$CSA_{L5/S1}$ = 4.85 + 0.17× WT	0.42		<0.001
Turk and Celan (2004)	Modified AST	$CSA_{L4/L5}$ = 2.11 + 0.29× AST_{Turk}			<0.001
		$CSA_{L5/S1}$ = 3.55 + 0.25× AST_{Turk}			<0.001
Shao et al. (2002)	Age, Male	DH_T12/L1 = 0.519 + 0.004903× Age	0.25		<0.001
		DH_L1/L2 = 0.680 + 0.006201× Age	0.31		<0.001
		DH_L2/L3 = 0.832 + 0.006687× Age	0.31		<0.001
		DH_L3/L4 = 1.105 + 0.005455× Age	0.19		<0.001
		DH_L4/L5 = 1.076 + 0.006952× Age	0.24		<0.001
		DH_L5/S1 = 0.973 + 0.008630× Age	0.30		<0.001
	Age, Female	DH_T12/L1 = 0.433 + 0.004840× Age	0.34		<0.001
		DH_L1/L2 = 0.627 + 0.004771× Age	0.27		<0.001
		DH_L2/L3 = 0.817 + 0.004982× Age	0.24		<0.001
		DH_L3/L4 = 0.985 + 0.005052× Age	0.21		<0.001
		DH_L4/L5 = 1.051 + 0.005979× Age	0.24		<0.001
		DH_L5/S1 = 0.926 + 0.008170× Age	0.30		<0.001

2.7.5 Summary

A number of studies to date have sought to investigate the geometric and morphometric characteristics of the human lumbar spine. Unfortunately, the geometric data reported in the literature indicated large variations and a wide range of data, possibly due to the different measurement protocols and varying subject demographics. Even though, a majority of geometric data have been reported by researchers that actually measured the structure either on cadaveric specimens or with imaging techniques, there has been promising evidence indicating that some geometric dimensions may be estimated without the cumbersome clinical preparation or costly medical imaging procedures, using statistical models.

Chapter 3

MORPHOMETRY OF LUMBAR LUMBAR INTERVERTEBRAL DISC AND VERTEBRAL ENDPLATES: ANALYSES OF MRI-DERIVED MEASUREMENTS IN TRANSVERSE SECTION

The manuscript in the following pages is in preparation for submission to a peer-reviewed academic journal

Morphometry of Lower Lumbar Intervertebral Discs and Vertebral Endplates: Analyses of MRI-derived Measurements in Transverse Section

3.1 Introduction

The intervertebral disc (IVD) connects vertebral bodies together, forming the main joints of the spinal column and providing spine the mechanical properties necessary to perform complex movements, such as flexion and rotation (S. J. Ferguson & Steffen, 2003; Raj, 2008). The biomechanical properties of the IVD are largely determined by its structural integrity in terms of the mode and magnitude of loading transmitted from one segment to another (Adams & Hutton, 1981; Adams et al., 1980). In the literature, geometric dimensions of spinal motion segment in transverse section such as cross-sectional area (CSA) and vertebral endplate width and depth have been found to influence the biomechanical properties of the disc, e.g., ultimate compressive strength and axial displacement (Brinckmann et al., 1989; Edmondston et al., 1994; Robin et al., 1994; Niemeyer et al., 2012). Bone mineral content (BMC) has been identified as the best predictor for the ultimate compressive strength of the human lumbar motion segment (Brinckmann et al., 1989; Genaidy et al., 1993; Gallagher et al., 2007). Cross-sectional area of the load-bearing surface is a critical component to determine the BMC possessed by a lumbar motion segment. Using animal cadavers, some researchers have suggested that the ultimate compressive strength of a spinal motion segment can be predicted by employing endplate area alone (Parkinson et al., 2005). Briggs et al. (2004) has concluded in their review that the dimensions of the spinal motion segment are correlated with the incidence of osteoporosis, strongly predicting the risk of vertebral fracture.

The importance of disc geometry is also acknowledged in studies developing comprehensive biomechanical and mathematical models depicting lumbar spinal motions (Jager & Luttmann, 1989; Panjabi et al., 1992; Natarajan & Andersson, 1999; Natarajan et al., 2008; Iyer et al., 2010). To investigate the potential risk of work-related musculoskeletal disorders (MSDs), morphological data have been used to develop geometric representations of the human spine (Fisher, 1967; Sicard & Gagnon, 1993; Nussbaum & Chaffin, 1996; Y. L. Chen, 1999), which then have been employed as critical inputs in mathematical models to characterize the biomechanical behaviors of the human spine in different postures and under forceful loadings (Chaffin, 1969; Campbell-Kyureghyan et al., 2005). Accurate descriptions of spinal geometry could also potentially benefit the development of spinal implants, and surgical instrumentation and procedures, such as for disc arthoplasty (J. L. Berry et al., 1987; Hall et al., 1998; van der Houwen et al., 2010; S. Wang et al., 2012). Recently, numerous complex finite element models (FEM) have been developed to simulate the internal loading conditions of the human spine and investigate the influence of spinal motions, postures, and forceful loadings on the spinal structures with respect to potential tissue damages and pathological alterations (Nerurkar et al., 2010; Chan et al., 2011). FE models require specific geometric data of the elements to characterize their mechanical behavior and the influences of spinal motions and forceful loadings on spinal structures using models for a single-level motion segment (Natarajan et al., 1994; Martinez et al., 1997; Natarajan et al., 2008; Y. Schroeder, Huyghe, van Donkelaar, & Ito, 2010) and models for multi-level motion segments (Zander, Rohlmann, Calisse, & Bergmann, 2001; Noailly et al., 2005, 2007; Schmidt et al., 2007; Rohlmann et

al., 2008; Arjmand, Gagnon, Plamondon, Schirazi-Adl, & Larivière, 2009; Rohlmann et al., 2009; Kuo et al., 2010; K. S. Han, Zander, Taylor, & Rohlmann, 2011).

In the literature, geometric dimensions of the lumbar motion segment in the transverse section have been reported primarily through morphometric investigations of spinal structures (Farfan, 1973; Postacchini et al., 1983; Nissan & Gilad, 1984; Gilad & Nissan, 1986; van Schaik et al., 1985; J. L. Berry et al., 1987; Colombini et al., 1989; Mosekilde, 1990; Aharinejad et al., 1990; Amonoo-Kuofi, 1991; Panjabi et al., 1992; Gilsanz et al., 1995; Aydinlioglu et al., 1999; Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008; van der Houwen et al., 2010; H. Chen et al., 2011; Kang et al., 2011; Karabekir et al., 2011; Mahato, 2011; Y. Wang et al., 2012), as well as through some studies investigating the ultimate compressive strength of the spinal motion segments in terms of cross-sectional areas (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Porter et al., 1989; Mosekilde, 1990; Drerup et al., 1999).

Unfortunately, the geometric data reported in the literature are still very scarce, and subjected to the effects of small sample size, resulting in large variations among the reported data, which may contribute to the sometimes inconsistent biomechanical responses of finite element models (Niemeyer et al., 2012). Secondly, the lack of a standardized experimental protocol to measure the structures of interest with uniform denotations and reference landmarks also contributes to the variable results. Previous studies have also differed in the modality of measurement, varying from direct cadaveric measurement (Nachemson, 1960; Hutton & Adams, 1982; Postacchini et al., 1983; J. L. Berry et al., 1987; Panjabi et al., 1992; Aharinejad et al., 1990; Mosekilde, 1990) to image-derived measurements, including radiographs (Farfan, 1973; Nissan & Gilad, 1984;

Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999), computed tomography (CT) scans (van Schaik et al., 1985; Biggemann et al., 1988; Brinckmann et al., 1989; Colombini et al., 1989; Gilsanz et al., 1995; Drerup et al., 1999; Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008; van der Houwen et al., 2010; Kang et al., 2011; Mahato, 2011; Y. Wang et al., 2012), and magnetic resonance imaging (MRI) scans (Karabekir et al., 2011). Thirdly, in the literature, the majority of geometric dimensions in the transverse section frequently reported are linear measurements such as the anteroposterior diameter (APD) and frontal diameter (FD) of the vertebral endplates (EPs) and the intervertebral discs (IVDs), while extremely limited geometric data have been reported regarding the cross-sectional area (CSA). Unfortunately, the majority of CSA data reported in the literature are estimates of ellipsoid method using linear dimensions as major and minor axes (Hutton & Adams, 1982; Brinckmann et al., 1989; Colombini et al., 1989), which inevitably introduce systematic errors to the results (Seidel et al., 2008). In addition, despite the fact being the most common site of pathological alteration and low back pain (Andersson, 1998), the geometry of the lumbosacral (L5/S1) disc is extremely lacking in the literature, especially the cross-sectional area (CSA), which may due to the lack of capability to accommodate the effect of lumbar curvature *lordosis*.

Magnetic resonance imaging (MRI) techniquesprovides the most complete noninvasive clinical diagnoses and evaluation of a greater number of spinal abnormalities as compared to CT (Tracy et al., 1989; Yu et al., 1991), owing to its multi-planar capabilities and superior soft tissue contrast (Gundry & Fritts, 1997). MRI can provide excellent resolution and contrast among all bony structures and soft tissues in sagittal, transverse, and frontal tomographic sections, since most anatomical structures have different signal intensities

depending on acquisition sequence techniques (e.g., T1 weighted and T2 weighted) (Teplick, 1992). Compared to CT, MR techniques allow greater discrimination between the nucleus, annulus, and anterior and posterior longitudinal complexes when adapted sequences are used (Krause et al., 1991; Teplick, 1992; Gundry & Fritts, 1997). Secondly, owing to its superior capability to differentiate spinal structures by signal intensity using adapted scanning sequences (Gundry & Fritts, 1997), MRI has great value in the evaluation of disc degeneration (Modic & Herfkens, 1990; Sether et al., 1990; Parkkola & Kormano, 1992; Gruber & Hanley, 1998; Luoma et al., 2001; Takatalo et al., 2009) and the development of grading systems to classify disc degeneration status (Pfirrmann et al., 2001). In addition, along with advances in the hardware design of high field magnets (Fries et al., 2008) and more sophisticated and sensitive coils (Noury et al., 2008), improvements have also been made in scanning sequences (Blumenkrantz et al., 2006; C. Wang et al., 2010; Stelzeneder et al., 2011; Hoppe et al., 2012; Zobel et al., 2012) and post-scanning software (Rosset et al., 2004; Alomari et al., 2010). So far, only a few studies in the literature have utilized MRI as the primary imaging modality to investigate morphologic characteristics of the lumbar motion segments (Al-Hadidi et al., 2001; Karabekir et al., 2011), despite the great resolution and excellent contrast of the morphologic landmarks and the capability to provide oblique "slicing" sections to accommodate the orientation of each intervertebral disc, especially at the lumbosacral (L5/S1) level.

The purposes of this study were 3-fold: 1) to perform geometric measurements of the lower lumbar intervertebral discs and the adjacent endplates from the L3/L4 to L5/S1 level with respect to the transverse section using archived MR scans; 2) to perform morphometric analysis regarding the geometric dimensions of the lower lumbar spine, and

3) to compare morphometric data to previous studies and address some limitations found in the literature.

3.2 Material and methods

3.2.1 Acquisition of MR scans

Digitally archived T2-weighted medical MR scans of the lower lumbar spine from L3/L4 to L5/S1 level performed at University Hospital (University of Utah, Salt Lake City, Utah, USA) were retrieved from the picture archiving and communication system (PACS). Lumbar scans were performed on a 1.5 Tesla open-bore MRI scanner (MAGNETOM Avanto, Siemens AG, Erlangen, Germany), where all subjects were in a head-first-supine position. MR scans of subjects between the ages of 20 and 40 years were reviewed by an expert to exclude subjects with 1) evidence of morphological alterations in lumbar or thoracic spine (e.g., crushed vertebral body, trauma); and 2) any known pathology likely to alter the geometric characteristics (e.g., scoliosis, tumor). This expert has ample experience (BS in Physical Therapy and Ph.D in Anatomy) analyzing MR scans of the human spine with respect to the anatomical characteristics. The MRI files were also anonymized (name, patient ID, date of birth, etc.) before being released for this study. Approval of the research protocol and experimental design was obtained by the Institutional Review Boards (IRBs) at both participating institutions (University of Utah and Auburn University, see Appendix A). In total, 109 subjects (55 females and 54 males) were included in this study. Demographic data, such as gender, age, body height and weight was also recorded in the PACS embedded in the scans. Body mass index (BMI) was

calculated using subject's body height and weight, and then classified into four body composition levels: 1) **underweight**, less than 18.5 kg/m^2; 2) **normal**, between 18.5 kg/m^2 and 25.0 kg/m^2; 3) **overweight**, between 25.1 kg/m^2 and 29.9 kg/m^2; and 4) **obese**, greater than 30.0 kg/m^2. Since subject height is not required information for a MRI scan, 30 subjects (14 females and 16 males) were missing height data. Table 3.1 summarizes the detailed descriptive statistics for the subjects' demographic data.

Table 3.1: Demographic data of anthropometric characteristics*

		N	Mean	SD	Min	Max	t	df	Sig.
Age (years)	Female	55	30.1	5.8	21	39	-0.786	107	0.432
	Male	54	30.6	5.4	21	39			
	Total	109	30.4	5.6	21	39			
Ht (cm)	Female	41	165.72	9.46	142.20	195.60	-10.412	77	***0.000****
	Male	38	178.33	9.32	157.50	200.70			
	Total	79	171.79	11.29	142.20	200.70			
Wt (kg)	Female	55	74.65	19.71	45.36	131.54	-5.770	107	***0.000****
	Male	54	87.43	20.57	58.06	178.71			
	Total	109	80.98	21.05	45.36	178.71			
BMI (kg/m^2)	Female	41	26.68	7.20	19.05	45.37	-0.800	77	0.424
	Male	38	27.03	5.61	19.19	51.99			
	Total	79	26.85	6.44	19.05	51.99			

*Independent student's t tests

The average age was 30.1 (5.8) years for females and 30.6 (5.4) years for males (note that values in parentheses represent the standard deviation). The average body height and weight was 165.72 (9.46) cm and 74.65 (19.71) kg for females and 178.33 (9.32) cm and 87.43 (20.57) kg for males. Female subjects were significantly lighter (p=0.000) and shorter (p=0.000) than males. The average BMI was 26.68 (7.20) kg/m^2 for females and 27.03 (5.61) kg/m^2 for males (Table 3.1), both of which fell in the "overweight" category. Based on the BMI classification, 0.9% of subjects were "underweight", 33% of them were "normal", 20.2% of them were "overweight", and 25.6% of them were "obese" (Table 3.2).

Table 3.2: BMI classification of subjects

BMI	Gender	N	%
Underweight	Female	0	0.0
	Male	1	0.9
	Total	1	0.9
Normal	Female	22	20.2
	Male	14	12.8
	Total	36	33.0
Overweight	Female	8	7.3
	Male	14	12.8
	Total	22	20.2
Obese	Female	11	10.1
	Male	9	8.3
	Total	20	18.3

3.2.2 Measurement of intervertebral disc geometry

The transverse MR scans were analyzed using OsiriX® (v.4.0, Pixmeo, Geneva, Switzerland), an open source image analysis software package for the Apple Mac OS (Microsoft Corp, Redmond, Washington), which has been used in a wide variety of clinical diagnoses and scientific research studies (Rosset et al., 2004; Yamauchi et al., 2010). The landmarks and for geometric measurements were manually identified and traced using a computer workstation equipped with high resolution display monitor (27-inch, 2560× 1440 resolution, 60 Hertz, Apple Inc., Cupertino, CA). The geometric dimensions were displayed in corresponding dialog boxes.

MRI-derived measurements

At each lower lumbar level, there were three anatomical structures of interest: 1) the intervertebral disc (IVD) (Figure 3.1(B)), 2) vertebral endplate cranial to the IVD (CrEP) (Figure 3.1(A)), and 3) vertebral endplate caudal to the IVD (CaEP) (Figure 3.1(C)).

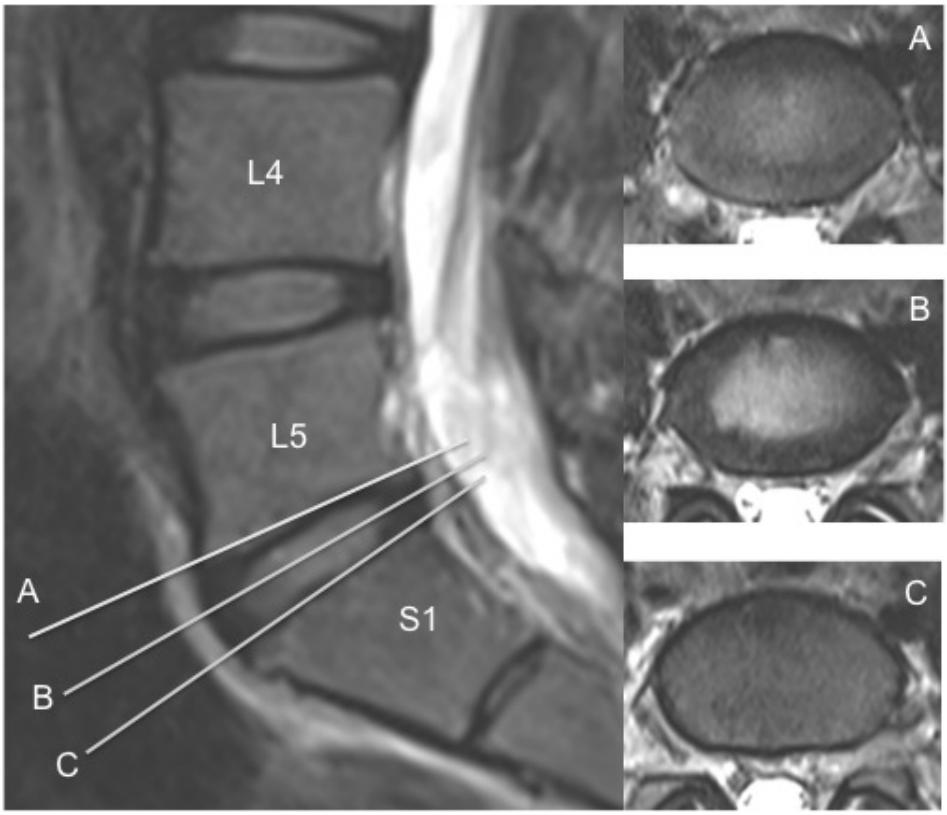


Figure 3.1: Anatomical structures of interest

In the transverse section, four geometric dimensions were measured for each structure, including anteroposterior diameter (APD), mid-sagittal diameter (SD), frontal diameter (FD), and cross-sectional area (CSA). The measurements were performed only in "tilted" slices, since the oblique view of the structure produced minimum error and distortion.

The descriptions of the detailed measurement are illustrated in Figure 3.2. The denotations and definitions of these measurements are listed in Table 3.3.

Table 3.3: Definitions of geometric dimensions measured

Dimensions	Definitions
Cross-sectional area (CSA)	cross-sectional area determined by tracing the actual periphery of the intervertebral disc
Anteroposterior diameter (APD)	linear distance between the anterior-most and posterior-most transverse contour extends of the intervertebral disc
Frontal diameter (FD)	linear distance between the right and left lateral-most transverse contour extends of the intervertebral disc
Mid-sagittal diameter (SD)	linear distance between the mid-sagittal extends of the intervertebral disc

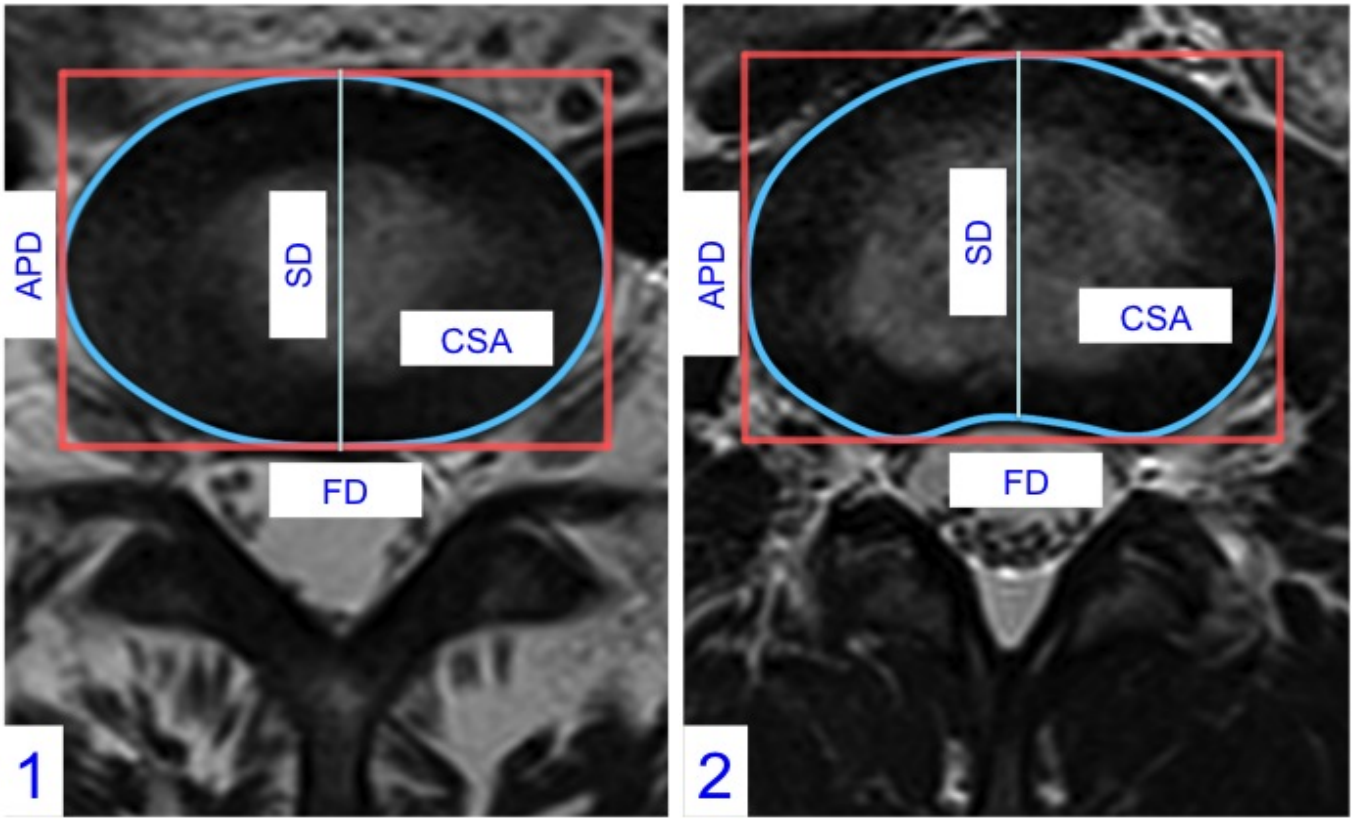


Figure 3.2: Illustrations of geometric dimensions in the transverse section (Note the different APD measurements for **1. oval-shaped** (frequently found in the L5/S1 level) and **2. "kidney-shaped"** (frequently found in the L3/L4 and L4/L5 levels))

To evaluate the difference between two ellipsoid approximation methods, cross-sectional areas (CSAs) were calculated using Formula 3.1 and 3.2, both of which have been frequently referenced in the literture (Farfan, 1973; Seidel et al., 2008).

$$CSA = \frac{APD \times FD \times \pi}{4} \tag{3.1}$$

$$CSA = \frac{APD \times SD \times \pi}{4} \tag{3.2}$$

In total, 327 IVDs and 606 endplates were measured. There were missing measurements of the vertebral endplates due to the lack of oblique slicing plane, particularly at the L5/S1 level. Table 3.4 presents the number of spinal structures measured at each lower lumbar spine level.

Table 3.4: Number of spinal structures measured across the lower lumbar region

	L3/L4			L4/L5			L5/S1		
	CrEP	IVD	CaEP	CrEP	IVD	CaEP	CrEP	IVD	CaEP
Female	55	55	55	55	55	55	42	55	42
Male	54	54	54	54	54	54	43	54	43
Total	109	109	109	109	109	109	85	109	85

Morphometric index

Ovality ratio (OR) were calculated for each structure of interest (intervertebral discs and adjacent vertebral endplates), using Formula 3.3 (Farfan, 1973).

$$OR = \frac{IVD\_FD}{IVD\_APD} \tag{3.3}$$

Disc degeneration

All discs were assessed for health status according to the grading system developed by Pfirrmann et al. (2001), which has well-accepted validity for evaluating the status of disc degeneration (Pappou, Cammisa, & Girardi, 2007; Takatalo et al., 2009; D. S. Schultz, Rodriguez, Hansma, & Lotz, 2009; Rodriguez et al., 2012). Figure 3.3 illustrates examples of MR scans showing each degeneration grade. The grade of degeneration was analyzed on mid-sagittal MR scans using a T2-weighted spin-echo imaging sequence. Table 3.5 listed the detailed description of each degeneration grade.

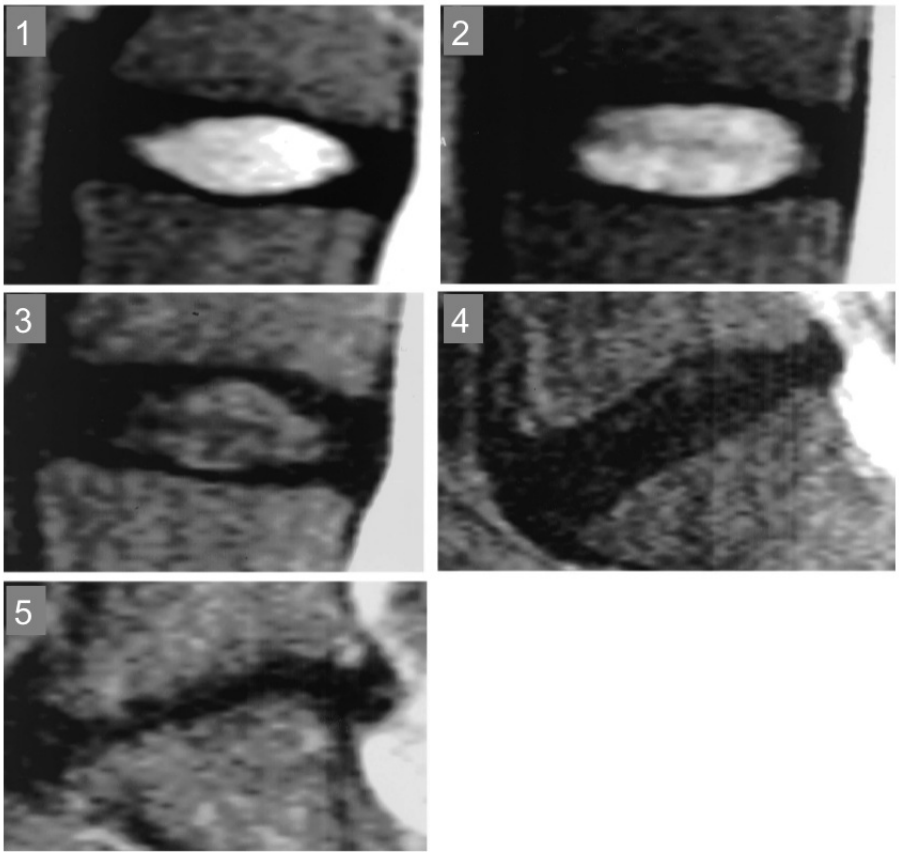


Figure 3.3: **Grade 1-5**, The numbered pictures represent examples of disc in corresponding degeneration grade. (reproduced from Pfirrmann et al. 2001)

Table 3.5: Classification of disc degeneration*

Grade	Structure	Nucleus/Annulus Distinction	Signal Intensity	Intervertebral Disc Height
I	Homogeneous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
II	Inhomogeneous, with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
III	Inhomogeneous, gray	Unclear	Intermediate	Normal to slightly decreased
IV	Inhomogeneous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased
V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space

∗ Table reproduced from Pfirrmann et al. 2001

In this study, with respect to spinal geometry, discs in Grade I and Grade II were grouped as "healthy", discs in Grade III and IV were regarded as "moderately degenerated", and Grade V were regarded as "severely degenerated". According to Table 3.5, discs in Grade V have collapsed disc space, which would alter their geometric characteristics. For the purposes of this study, data regarding Grade V discs and their adjacent endplates were excluded from the final analyses. Table 3.6 summarizes overall degeneration status of the 327 discs measured in this study. Table 3.7 summarized the all subject demographic data after the removal of Grade V discs.

Intra- and inter-observer reliability

A subset of 40 MR scans (20 females and 20 males) was randomly selected to evaluate measurement reliability. Two observers performed the geometric measurements independently. Each observer took measurements twice with a one-month interval between. The order of observations at each measurement time was also randomized. To measure the reliability with respect to how much agreement was achieved between two rounds of

Table 3.6: Overall disc degeneration status

		Normal		Moderate		Severe
		Grade I	Grade II	Grade III	Grade IV	Grade V
L3/L4	Female	1	30	21	3	0
	Male	2	28	16	6	2
	Total	3	58	37	9	2
L4/L5	Female	4	20	23	8	0
	Male	2	22	16	10	4
	Total	6	42	39	18	4
L5/S1	Female	3	22	18	12	0
	Male	4	20	11	16	3
	Total	7	42	29	28	3

Table 3.7: Demographic data for all subjects included in the final analyses*

			N	Mean	SD	t	df	Sig.
L3/L4	Age (years)	Female	55	30.1	5.8	-0.381	105	0.704
		Male	52	30.5	5.3			
	Ht (cm)	Female	41	165.72	9.46	-5.960	77	***0.000****
		Male	38	178.33	9.32			
	Wt (kg)	Female	55	74.65	19.71	-3.178	105	***0.002****
		Male	52	87.12	20.89			
	BMI (kg/m^2)	Female	41	26.68	7.20	-0.458	75	0.648
		Male	36	27.36	5.53			
L4/L5	Age (years)	Female	55	30.1	5.8	0.064	103	0.949
		Male	50	30.0	5.1			
	Ht (cm)	Female	41	165.72	9.46	-5.792	76	***0.000****
		Male	37	178.00	9.23			
	Wt (kg)	Female	55	74.65	19.71	-3.093	103	***0.003****
		Male	50	86.71	20.21			
	BMI (kg/m^2)	Female	41	26.68	7.20	-0.286	74	0.776
		Male	35	27.11	5.39			
L5/S1	Age (years)	Female	55	30.1	5.8	-0.425	104	0.672
		Male	51	30.6	5.3			
	Ht (cm)	Female	41	165.72	9.46	-5.691	74	***0.000****
		Male	35	177.58	8.54			
	Wt (kg)	Female	55	74.65	19.71	-3.116	104	***0.002****
		Male	51	86.70	20.09			
	BMI (kg/m^2)	Female	41	26.68	7.20	-0.388	72	0.699
		Male	33	27.27	5.51			

*Independent student's t tests

measurement (intra-observer) and between the two observers (inter-observer), two common statistical methods were used, including the intra-class correlation coefficient (ICC) and Pearson's correlation coefficient. In the first method, a two-way mixed absolute agreement model was selected since 1) the two rounds of measurement were taken by two observers, the error may be attributed to both observers and the subject image, and 2) the systematic differences among levels of observations were considered relevant (Shrout & Fleiss, 1979). The interpretation of results in both methods is described in Table 3.8, which is in accordance with other studies in the literature (Portney & Watkins, 2000; Mayerhoefer et al., 2012; Stelzeneder et al., 2011; Weiler et al., 2012).

Table 3.8: Interpretation of reliability of measurements

	ICC	Pearson's
Excellent	>0.900	>0.810
Good	0.800 - 0.899	0.610 - 0.809
Moderate		0.410 - 0.609
Fair	0.700 - 0.799	0.210 - 0.409
Poor	<0.699	<0.209

Statistical analyses

Split Plot Factorial (SPF) Design (2×3 ANOVA) were used to determine the effect of gender, spinal level, and the interactions of these two on the geometric dimensions measured in the transverse section. **Tukey's post-hocs tests** were performed, using honestly significant difference (HSD) (Montgomery, 2005), to determine the trend of changes in the spinal morphometry across the three lower lumbar spinal levels (L3/L4, L4/L5, and L5/S1).

HSD = $q(a,\ df) \times \sqrt{MS_{Within}/n}$; where **q** is the studentized range statistic, **a** is the number of treatments, and **df** is the number of degree of freedom associated with MS_{Within} at α=0.05), MS_{Within} is mean square term within subjects, and **n** is the number of subjects.

Independent Student's T-tests were used to analyze the main effect of gender on the spinal morphometry across the three lower lumbar levels. **Paired sample t tests** were also used to compare geometric dimensions regarding the structures of interest which have been assumed to be related to each other, for example the two adjacent endplates in a single-level lumbar motion segment (CrEP vs CaEP), or the two endplates associated with one lumbar vertebra (L3/L4 CaEP vs L4/L5 CrEP and L4/L5 CaEP vs L5/S1 CrEP). For all statistical analyses, a significant level of P<0.050 was used.

3.3 Results

3.3.1 Repeatability tests

Table 3.9 listes the results of intra- and inter-observer reliability tests. In terms of intra-class correlation coefficient (ICC), the present study yielded "excellent" inter-observer and "excellent" intra-observer reliability (ICC>0.900) in all geometric measurements in the transverse section. In terms of Pearson's correlation coefficient, the present study also yielded "excellent" intra- and inter-observer reliability (Pearson's>0.810) in all seven measurements.

Table 3.9: Reliability of measurements

	Intra-observer				Inter-observer	
	Observer I		Observer II		Observer I & II	
	ICC	Pearson's	ICC	Pearson's	ICC	Pearson's
Cross-sectional area (CSA)	0.996	0.997	0.990	0.996	0.971	0.978
Frontal diameter (FD)	0.984	0.986	0.984	0.988	0.953	0.955
Anteroposterior diameter (APD)	0.993	0.994	0.984	0.988	0.970	0.971
Mid-sagittal diameter (SD)	0.914	0.904	0.906	0.909	0.938	0.940

3.3.2 Descriptive statistics

Table 3.10 presents the descriptive statistics for both genders and the overall sample for all the geometric dimensions measured on MR scans, including the mean, standard deviation and range of data. All figures illustrate means and 95% confidence intervals (CIs) with respect to each geometric dimension measured on MR scans.

Table 3.10: Descriptive statistics of geometric dimensions measured on MR scans

		L3/L4					L4/L5					L5/S1				
Geometry	Gender	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
IVD_CSA (cm^2)	Female	55	14.76	1.90	11.48	20.82	55	14.63	1.80	10.63	18.36	55	13.52	1.91	10.21	17.95
	Male	52	17.71	1.96	13.59	22.51	50	18.08	2.02	13.78	22.80	51	17.06	2.34	13.15	22.98
	Total	107	16.19	2.43	11.48	22.51	105	16.27	2.57	10.63	22.80	106	15.23	2.76	10.21	22.98
IVD_APD (cm)	Female	55	3.70	0.26	3.12	4.42	55	3.68	0.23	3.21	4.16	55	3.53	0.23	3.01	4.00
	Male	52	4.03	0.24	3.47	4.61	50	4.06	0.26	3.56	4.68	51	4.01	0.32	3.47	4.76
	Total	107	3.86	0.30	3.12	4.61	105	3.86	0.31	3.21	4.68	106	3.76	0.36	3.01	4.76
IVD_FD (cm)	Female	55	4.97	0.32	4.39	5.92	55	5.03	0.32	4.22	5.67	55	4.93	0.39	4.13	5.96
	Male	52	5.48	0.36	4.65	6.22	50	5.59	0.32	4.89	6.24	51	5.50	0.40	4.84	6.22
	Total	107	5.22	0.42	4.39	6.22	105	5.29	0.43	4.22	6.24	106	5.21	0.49	4.13	6.22
CrEP_CSA (cm^2)	Female	55	12.59	1.68	9.77	17.74	55	12.49	1.53	9.90	15.95	42	11.71	1.50	9.25	15.11
	Male	52	15.19	1.73	11.52	19.14	50	15.13	1.74	11.74	19.88	41	14.47	2.00	11.32	20.45
	Total	107	13.85	2.14	9.77	19.14	105	13.75	2.10	9.90	19.88	83	13.08	2.23	9.25	20.45
CrEP_APD (cm)	Female	55	3.43	0.22	2.98	3.91	55	3.41	0.21	3.07	3.97	42	3.32	0.19	2.90	3.77
	Male	52	3.77	0.22	3.28	4.33	50	3.76	0.25	3.37	4.57	41	3.72	0.27	3.28	4.61
	Total	107	3.59	0.28	2.98	4.33	105	3.58	0.29	3.07	4.57	83	3.52	0.31	2.90	4.61
CrEP_FD (cm)	Female	55	4.54	0.33	3.95	5.11	55	4.58	0.35	3.91	5.35	42	4.61	0.33	3.82	5.18
	Male	52	5.03	0.35	4.27	5.80	50	5.03	0.32	4.17	5.63	41	5.05	0.39	4.13	5.82
	Total	107	4.78	0.41	3.95	5.80	105	4.79	0.41	3.91	5.63	83	4.83	0.42	3.82	5.82
CaEP_CSA (cm^2)	Female	55	14.04	1.75	10.36	20.00	55	13.95	1.56	10.46	17.77	42	13.35	1.78	10.21	17.60
	Male	52	16.29	1.86	11.61	19.94	50	16.47	1.95	12.37	21.04	41	15.93	2.25	12.26	22.46
	Total	107	15.13	2.12	10.36	20.00	105	15.15	2.16	10.46	21.04	83	14.63	2.39	10.21	22.46
CaEP_APD (cm)	Female	55	3.61	0.23	3.12	4.22	55	3.50	0.21	3.12	4.03	42	3.41	0.24	2.95	4.01
	Male	52	3.84	0.23	3.22	4.41	50	3.76	0.23	3.23	4.47	41	3.74	0.31	3.15	4.64
	Total	107	3.72	0.26	3.12	4.41	105	3.63	0.25	3.12	4.47	83	3.57	0.32	2.95	4.64
CaEP_FD (cm)	Female	55	4.85	0.32	4.10	5.48	55	5.01	0.31	4.28	5.67	42	4.96	0.39	4.19	5.92
	Male	52	5.26	0.33	4.52	5.90	50	5.44	0.36	4.71	6.21	41	5.42	0.41	4.86	6.31
	Total	107	5.05	0.38	4.10	5.90	105	5.21	0.40	4.28	6.21	83	5.19	0.46	4.19	6.31
CrEP_SD	Female	55	3.01	0.21	2.64	3.59	55	3.09	0.19	2.72	3.58	55	3.26	0.20	2.85	3.81
	Male	52	3.49	0.21	2.99	4.09	50	3.55	0.23	3.11	4.27	51	3.71	0.22	3.28	4.25
	Total	107	3.24	0.32	2.64	4.09	105	3.31	0.31	2.72	4.27	106	3.48	0.31	2.85	4.25
CaEP_SD	Female	55	3.08	0.23	2.60	3.62	55	3.11	0.18	2.77	3.65	55	3.32	0.20	2.82	3.78
	Male	52	3.47	0.22	2.96	4.00	50	3.52	0.24	3.11	4.22	51	3.73	0.24	3.15	4.43
	Total	107	3.27	0.30	2.60	4.00	105	3.31	0.29	2.77	4.22	106	3.52	0.32	2.82	4.43
IVD_SD	Female	55	3.22	0.24	2.77	3.77	55	3.30	0.22	2.84	3.88	55	3.46	0.26	2.83	4.03
	Male	52	3.73	0.21	3.32	4.23	50	3.80	0.26	3.23	4.43	51	4.00	0.32	3.46	4.70
	Total	107	3.47	0.34	2.77	4.23	105	3.54	0.34	2.84	4.43	106	3.72	0.40	2.83	4.70

Cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) (IVD_CSA)

Statistics from SPF ANOVA (Table 3.11) indicated that the main effects for both gender (p=0.000) and spinal level (p=0.000) significantly influenced the IVD_CSA, but the main effect of their interaction was not significant (p=0.088).

Table 3.11: ANOVA summary table for the main and interaction effects of gender and spinal level on IVD_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	755.347	755.347	84.03	***0.000****
Subject(Gender)	99	889.892	8.989	9.98	
Within Subjects					
Spinal Level	2	77.302	37.773	41.96	***0.000****
Gender*Spinal Level	2	4.439	2.219	2.47	0.088
Spinal Level*Subject(Gender)	198	178.259	0.900		
Total	302	1905.239			

Independent t tests (Table 3.12) revealed that the average male intervertebral discs (IVDs) were significantly larger than female ones in IVD_CSAs across all three lower lumbar levels (p=0.000) with a 20% increase at the L3/L4 level, a 24% increase at the L4/L5 level, and a 26% increase at the L5/S1 level. Post-hocs analyses (Table 3.13) revealed that the difference in CSAs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, CSAs of the L5/S1 IVDs were 6% and 7% smaller than the L3/L4 and L4/L5 IVDs, respectively. Figure 3.4 illustrates the IVD_CSAs for both genders at each lower lumbar spinal level.

Table 3.12: Influence of gender on the IVD_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	7.918	105	***0.000****	2.955	20%
L4/L5	9.232	103	***0.000****	3.443	24%
L5/S1	8.569	104	***0.000****	3.539	26%

Table 3.13: Pairwise comparisons of the IVD_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.12	0.312	N. S.	
L5/S1	L3/L4	-1.006	0.312	***Significant****	-6%
	L4/L5	-1.127	0.312	***Significant****	-7%

N. S.: not significant; Δ%= (I-J)/J× 100%

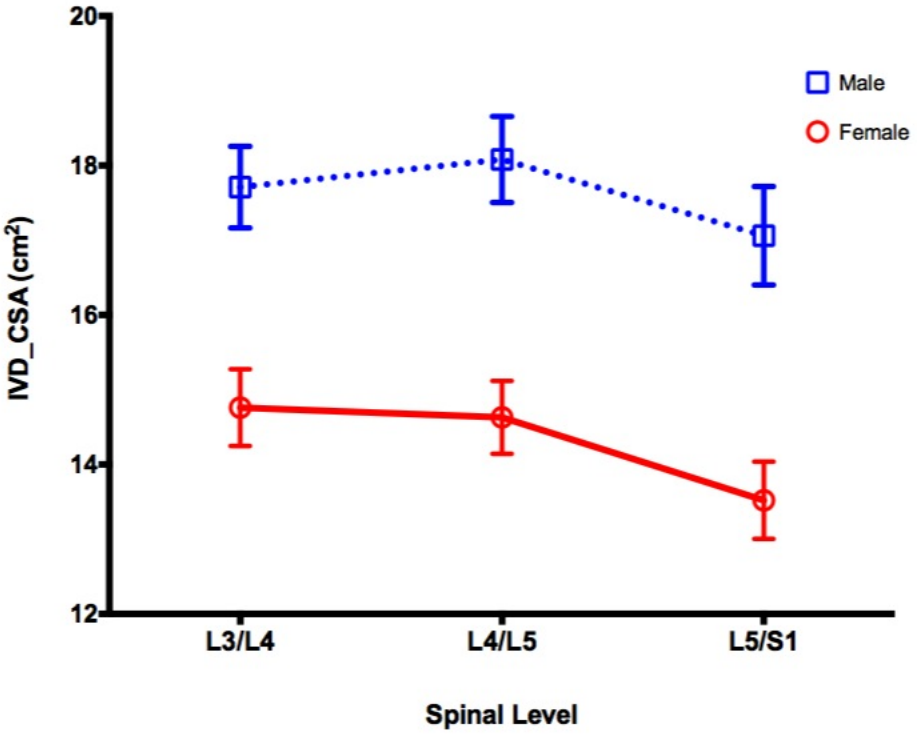


Figure 3.4: IVD_CSAs for both genders at each lower lumbar level

Cross-sectional areas (CSAs) of the cranial vertebral endplates (CrEP_CSA)

Statistics from SPF ANOVA (Table 3.14) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CrEP_CSA, but the main effect of their interaction was not significant (p=0.505).

Table 3.14: ANOVA summary table for the main and interaction effects of gender and spinal level on CrEP_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	319.112	319.112	50.2	***0.000****
Subject(Gender)	77	489.507	6.357	9.92	
Within Subjects					
Spinal Level	2	36.494	17.852	27.85	***0.000****
Gender*Spinal Level	2	0.880	0.440	0.69	0.505
Spinal Level*Subject(Gender)	154	98.709	0.641		
Total	236	944.702			

Independent t tests (Table 3.15) revealed that the average male intervertebral discs (IVDs) were significantly larger than the female ones in CrEP_CSAs across all three lower lumbar levels (p=0.000) with a 17% increase at the L3/L4 and L4/L5 levels, and a 19% increase at the L5/S1 level. Post-hocs analyses (Table 3.16) revealed that the difference in CrEP_CSAs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, CrEP_CSAs of the L5/S1 IVDs were 6% smaller than the L3/L4 and L4/L5 IVDs each. Figure 3.5 illustrates the CrEP_CSAs for both genders at each lower lumbar spinal level.

Table 3.15: Influence of gender on the CrEP_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	7.876	105	***0.000****	2.596	17%
L4/L5	8.247	103	***0.000****	2.639	17%
L5/S1	7.141	81	***0.000****	2.761	19%

Table 3.16: Pairwise comparisons of the CrEP_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	-0.049	0.298	N. S.	
L5/S1	L3/L4	-0.856	0.298	***Significant****	-6%
	L4/L5	-0.807	0.298	***Significant****	-6%

N. S.: not significant; Δ%= (I-J)/J× 100%

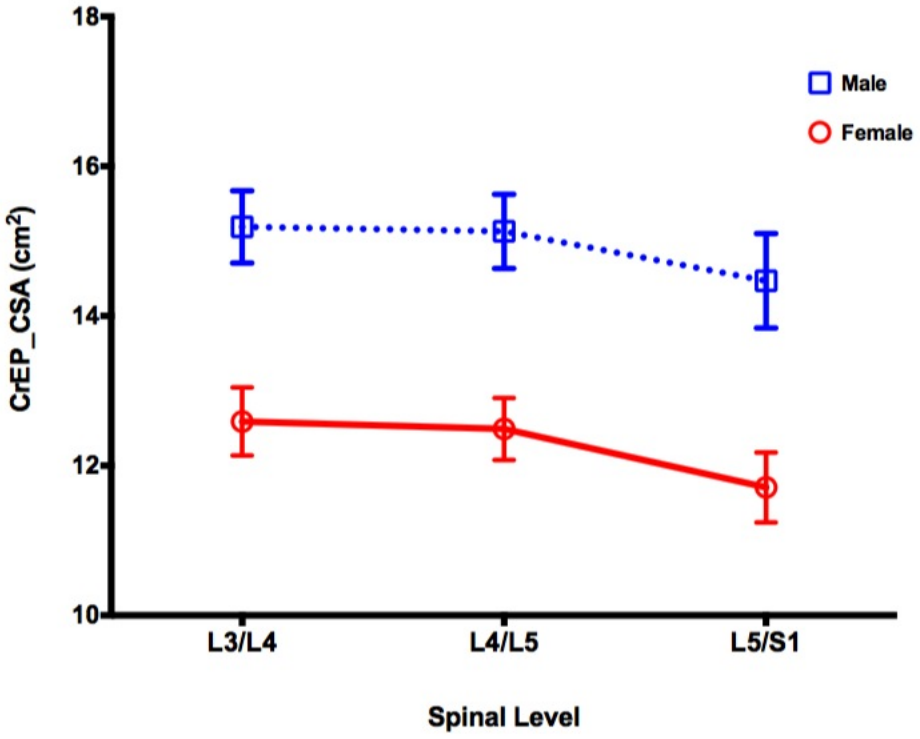


Figure 3.5: CrEP_CSAs for both genders at each lower lumbar spinal level

Cross-sectional areas (CSAs) of the caudal vertebral endplates (CaEP_CSA)

Statistics from SPF ANOVA (Table 3.17) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CaEP_CSA, but the main effect of their interaction was not significant (p=0.123).

Table 3.17: ANOVA summary table for the main and interaction effects of gender and spinal level on CaEP_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	251.316	251.316	33.24	***0.000****
Subject(Gender)	77	582.204	7.561	7.99	
Within Subjects					
Spinal Level	2	23.133	11.09	11.72	***0.000****
Gender*Spinal Level	2	4.021	2.011	2.12	0.123
Spinal Level*Subject(Gender)	154	145.721	0.946		
Total	236	1006.394			

Independent t tests (Table 3.18) revealed that the average male intervertebral discs (IVDs) were significantly larger than the female ones in CaEP_CSAs across all three lower lumbar levels (p=0.000) with a 16% increase at the L3/L4 level and a 18% increase at the L4/L5 level, and a 19% increase at the L5/S1 level. Post-hocs analyses (Table 3.19) revealed that the difference in CaEP_CSAs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, CaEP_CSAs of the L5/S1 IVDs were 4% and 5% smaller than the L3/L4 and L4/L5 IVDs, respectively. Figure 3.6 illustrates the CaEP_CSAs for both genders at each lower lumbar spinal level.

Table 3.18: Influence of gender on the CaEP_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	6.467	105	***0.000****	2.253	16%
L4/L5	7.365	103	***0.000****	2.527	18%
L5/S1	5.813	81	***0.000****	2.582	19%

Table 3.19: Pairwise comparisons of the CaEP_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.107	0.362	N. S.	
L5/S1	L3/L4	-0.603	0.362	***Significant****	-4%
	L4/L5	-0.710	0.362	***Significant****	-5%

N. S.: not significant; Δ%= (I-J)/J× 100%

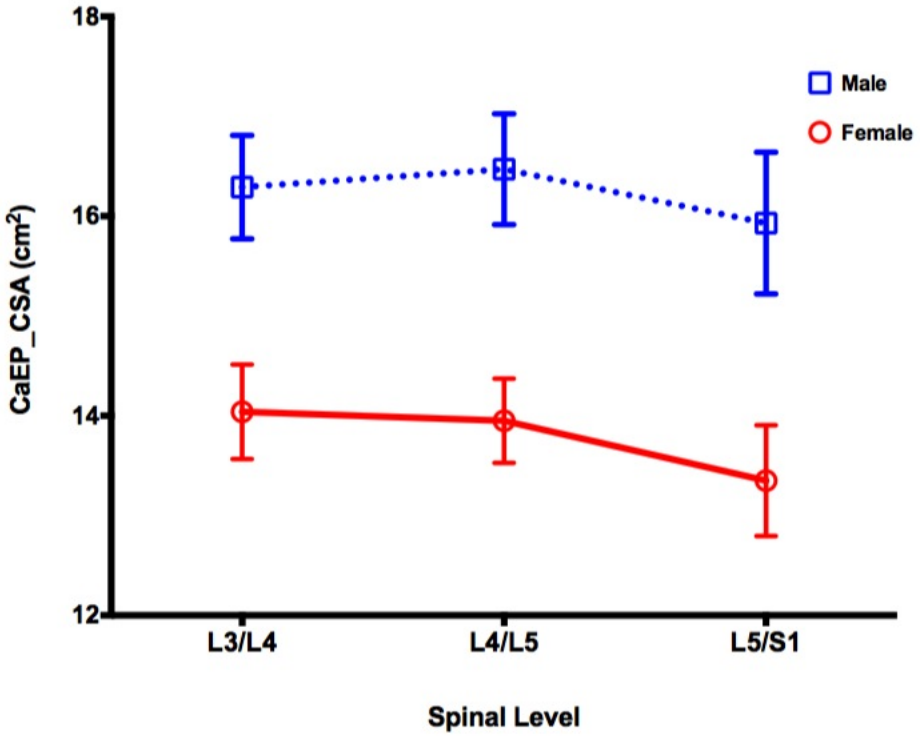


Figure 3.6: CaEP_CSAs for both genders at each lower lumbar spinal level

Craniocaudal differences in the cross-sectional areas (CSAs)

Figure 3.7 illustrates the cross-sectional areas measured for each anatomical structure of interest. Paired sample t tests were used to compare the size of these structures rather than independent t tests, since for each subject, these dimensions may be related to each other in some way (e.g., the same spinal level or vertebral body).

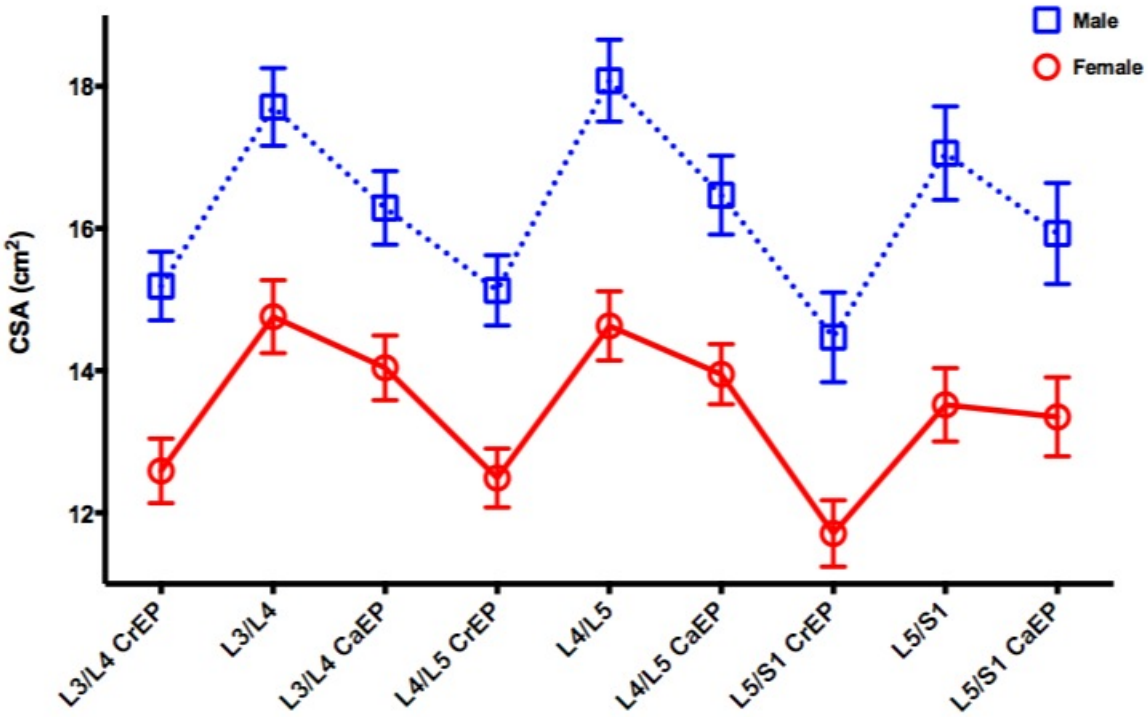


Figure 3.7: Complete distribution profiles of CSAs across the three lower lumbar levels

Single level lumbar motion segments

Paired sample t tests (Table 3.20) indicated that IVDs had significantly larger cross-sectional area than the adjacent cranial and caudal endplates in both male ($p=0.000$) and female subjects ($p<0.05$). The two vertebral endplates also differed significantly in cross-sectional areas, where the increase from CrEP to CaEP was more pronounced in female subjects ($p=0.000$, average 12%) than in males ($p=0.000$, average 9%).

Table 3.20: Differences in CSAs between the intervertebral discs and the adjacent vertebral endplates

			t	df	Sig.	Mean	SD	Δ%
Ca_EP - Cr_EP	Female	L3/L4	9.601	54	***0.000****	1.446	1.117	11%
		L4/L5	9.896	54	***0.000****	1.454	1.090	12%
		L5/S1	7.307	41	***0.000****	1.637	1.452	14%
	Male	L3/L4	6.231	51	***0.000****	1.103	1.276	7%
		L4/L5	6.501	49	***0.000****	1.341	1.459	9%
		L5/S1	7.412	40	***0.000****	1.458	1.259	10%
IVD - Cr_EP	Female	L3/L4	15.564	54	***0.000****	2.167	1.032	17%
		L4/L5	16.950	54	***0.000****	2.143	0.938	17%
		L5/S1	10.969	41	***0.000****	2.012	1.189	17%
	Male	L3/L4	16.548	51	***0.000****	2.526	1.101	17%
		L4/L5	16.402	49	***0.000****	2.948	1.271	19%
		L5/S1	14.035	40	***0.000****	2.533	1.156	17%
IVD - Ca_EP	Female	L3/L4	6.518	54	***0.000****	0.721	0.820	5%
		L4/L5	5.779	54	***0.000****	0.689	0.885	5%
		L5/S1	3.110	41	***0.003****	0.375	0.782	3%
	Male	L3/L4	9.533	51	***0.000****	1.423	1.076	9%
		L4/L5	8.338	49	***0.000****	1.606	1.362	10%
		L5/S1	5.663	40	***0.000****	1.075	1.215	7%

Lower lumbar vertebrae

Paired sample t tests (Table 3.21) indicated that for both female and male L5 vertebrae, the cranial endplates had significantly larger cross-sectional areas (CSAs) than corresponding caudal endplates (p=0.000). Only female L4 vertebrae exhibited the same significant difference between the two endplates (p=0.000). The difference in male L4 vertebrae was approaching the significance level (p=0.090).

significant decreases in the endplate cross-sectional areas from the cranial to the caudal aspect of the L5 vertebrae for both male and female subjects (p=0.000), while only female L4 vertebrae exhibited a significant decrease in the cross-sectional areas from the cranial to the caudal aspect (p=0.000).

Table 3.21: Craniocaudal differences in EP_CSAs with respect to L4 and L5 lumbar vertebral body

		t	df	Sig.	Mean	SD	Δ%
Female	L4	-9.636	54	***0.000****	-1.544	1.188	-11%
	L5	-14.537	41	***0.000****	-2.468	1.100	-11%
Male	L4	-1.729	49	0.090	-0.773	3.161	
	L5	-9.643	37	***0.000****	-2.030	1.298	-12%

3.3.3 Influence of ellipsoid approximation

Paired sample t tests (Table 3.22) were used to investigate the difference between actual measured cross-sectional area and an ellipsoid approximation. Using Formula 3.1 (ellipsoid approximation, anteroposterior diameter (APD) as the minor axis), significantly underestimates (average 2% less) cross-sectional areas (CSAs) of all intervertebral discs (IVDs) and vertebral endplates (EPs) ($p<0.050$), except for the L5/S1 IVDs for which the CrEP_CSA and IVD_CSA were significantly overestimated ($p=0.000$). Only the CaEP_CSAs of L5/S1 IVDs were not significantly different ($p=0.886$). Ellipsoid approximations using Formula 3.2 (mid-sagittal diameter (SD) as the minor axis) exhibited similar overestimation for the CrEP_CSA ($p=0.005$) and IVD_CSA ($p=0.004$) for the L5/S1 IVDs, and also the significant but greater underestimation (average 10% less) ($p=0.000$). Again, only the CaEP_CSAs of L5/S1 IVDs were not significantly different ($p=0.646$).

Absolute errors, calculated between the actual measured dimensions and the ellipsoid approximations also confirmed the estimates using anteroposterior diameter (APD) as the minor axis exhibited much less error (2% difference) that estimates using mid-sagittal diameter (SD) (9% difference).

Table 3.22: Comparison of cross-sectional areas measured on MR scans and calculated with ellipsoid approximations

$CSA_{F3.1}$=APD×FD×π/4

			Paired Sample T Tests				Absolute Error				
			Mean	SD	Sig.	Diff. (%)	Mean	SD	Min	Max	Diff. (%)
$CSA_{F3.1}$ - CSA_{MRI}	L3/L4	CrEP	-0.291	0.426	***0.000****	-2%	0.330	0.397	0.006	3.461	2%
		IVD	-0.287	0.312	***0.000****	-2%	0.340	0.252	0.013	1.710	2%
		CaEP	-0.320	0.387	***0.000****	-2%	0.395	0.310	0.001	1.866	3%
	L4/L5	CrEP	-0.214	0.432	***0.000****	-2%	0.341	0.340	0.005	2.520	2%
		IVD	-0.124	0.374	***0.001****	-1%	0.312	0.239	0.006	1.110	2%
		CaEP	-0.240	0.401	***0.000****	-2%	0.353	0.306	0.001	1.878	2%
	L5/S1	CrEP	0.340	0.419	***0.000****	3%	0.426	0.329	0.006	1.545	3%
		IVD	0.236	0.474	***0.000****	2%	0.422	0.318	0.018	1.514	3%
		CaEP	0.005	0.327	0.886		0.263	0.192	0.002	0.964	2%

$CSA_{F3.1}$=SD×FD×π/4

			Paired Sample T Tests				Absolute Error				
			Mean	SD	Sig.	Diff. (%)	Mean	SD	Min	Max	Diff. (%)
$CSA_{F3.2}$ - CSA_{MRI}	L3/L4	CrEP	-1.617	0.710	***0.000****	-12%	1.617	0.710	0.057	5.835	12%
		IVD	-1.888	0.709	***0.000****	-12%	1.888	0.709	0.497	4.708	12%
		CaEP	-2.111	0.738	***0.000****	-14%	2.111	0.738	0.321	4.448	14%
	L4/L5	CrEP	-1.229	0.665	***0.000****	-9%	0.353	0.306	0.001	1.878	3%
		IVD	-1.481	0.660	***0.000****	-9%	1.481	0.660	0.087	3.139	9%
		CaEP	-1.542	0.849	***0.000****	-10%	1.594	0.746	0.034	4.474	11%
	L5/S1	CrEP	0.295	0.931	***0.005****	2%	0.709	0.667	0.020	4.710	5%
		IVD	0.220	0.780	***0.004****	1%	0.604	0.537	0.001	3.750	4%
		CaEP	0.049	0.976	0.646		0.685	0.694	0.001	5.33	5%

3.3.4 Diameters in the transverse section

Anteroposterior diameter of the intervertebral disc (IVD_APD)

Statistics from SPF ANOVA (Table 3.23) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the IVD_APD. The main effect of their interaction was also found significant (p=0.017). Figure 3.8 illustrates the effect of gender, spinal level, and the interaction between the two on the IVD_APD.

Table 3.23: ANOVA summary table for the main and interaction effects of gender and spinal level on IVD_APD

Source	DF	SS	MS	F	P
Between Subjects					
Gender	1	10.465	10.465	73.67	***0.000****
Subject(Gender)	99	14.063	0.142	6.44	
Within Subjects					
Spinal Level	2	0.898	0.414	18.76	***0.000****
Gender*Spinal Level	2	0.184	0.092	4.17	***0.017****
Spinal Level*Subject(Gender)	198	4.366	0.022		
Total	302	29.977			

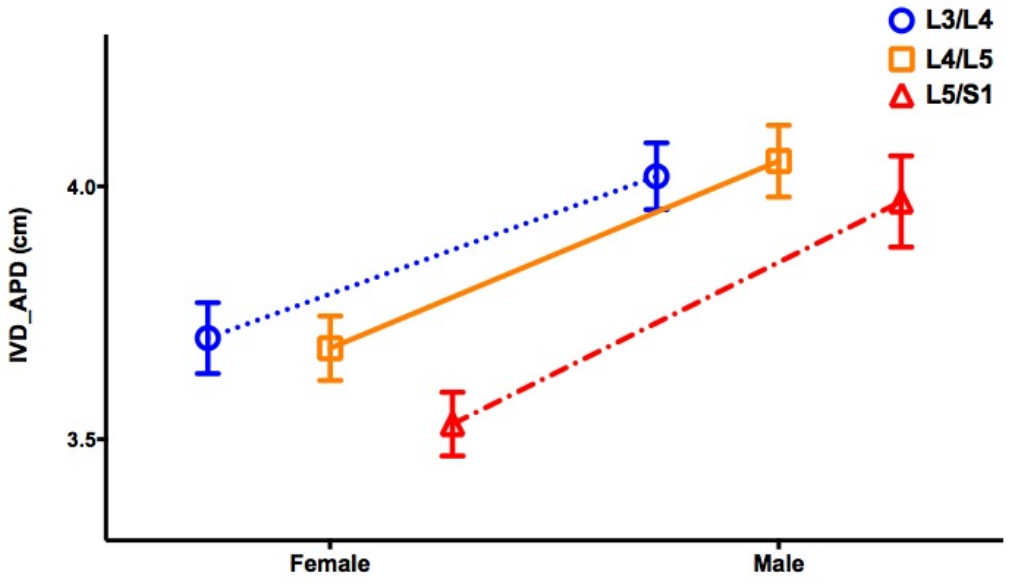


Figure 3.8: IVD_APDs for both genders at each lower lumbar level

Frontal diameter of the intervertebral disc (IVD_FD)

Statistics from SPF ANOVA (Table 3.24) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the IVD_FD, but the main effect of their interaction was not significant (p=0.308).

Table 3.24: ANOVA summary table for the main and interaction effects of gender and spinal level on IVD_FD

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	21.367	21.367	75.17	***0.000****
Subject(Gender)	99	28.144	0.284	8.11	
Within Subjects					
Spinal Level	2	0.654	0.337	9.62	***0.000****
Gender*Spinal Level	2	0.083	0.041	1.18	0.308
Spinal Level*Subject(Gender)	198	6.939	0.035		
Total	302	57.189			

Independent t tests (Table 3.25) revealed that the average male intervertebral discs were significantly larger than female ones in IVD_FDs across all three lower lumbar levels (p=0.000) with a 10% increase at the L3/L4 level, an 11% increase at the L4/L5 level, and a 12% increase at the L5/S1 level. Post-hocs analyses (Table 3.26) revealed that the difference in IVD_FDs between the L4/L5 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L5/S1 IVDs. There were a 2% increase from the L3/L4 to the L4/L5 level and a 2% decrease from the L4/L5 to the L5/S1 level. Figure 3.9 illustrates the IVD_FDs for both genders at each lower lumbar spinal level.

Table 3.25: Influence of gender on the IVD_FD

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	7.755	105	***0.000****	0.509	10%
L4/L5	9.045	103	***0.000****	0.564	11%
L5/S1	7.480	104	***0.000****	0.574	12%

Table 3.26: Pairwise comparisons of the IVD_FD across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.087	0.062	***Significant****	2%
L5/S1	L3/L4	-0.020	0.062	N. S.	
	L4/L5	-0.107	0.062	***Significant****	-2%

N. S.: not significant; Δ%= (I-J)/J× 100%

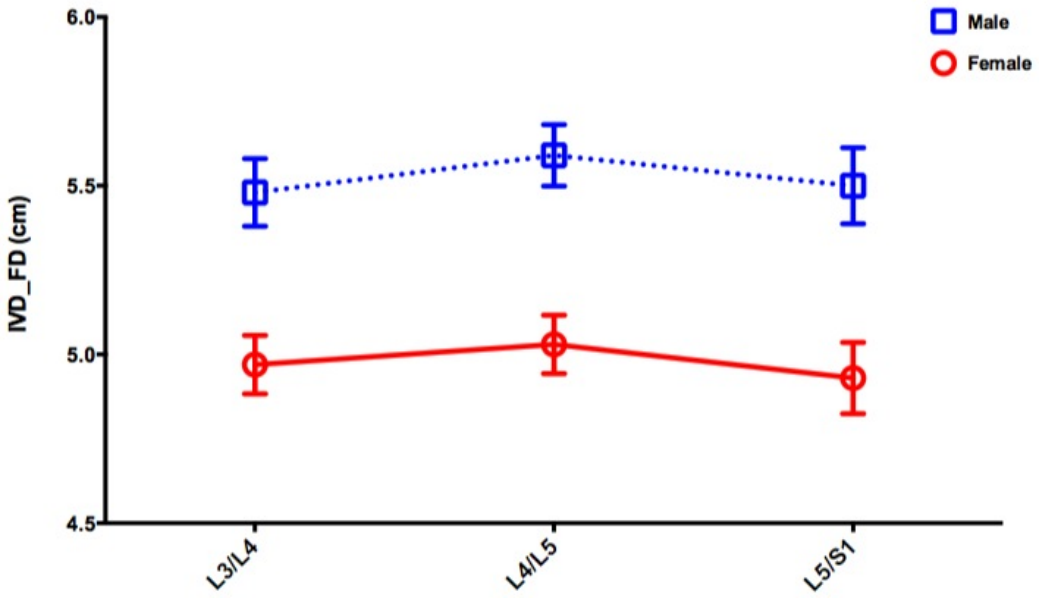


Figure 3.9: IVD_FDs for both genders at each lower lumbar level

Anteroposterior diameter of the cranial endplate (CrEP_APD)

Statistics from SPF ANOVA (Table 3.27) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CrEP_APD, but the main effect of their interaction was not significant (p=0.079).

Table 3.27: ANOVA summary table for the main and interaction effects of gender and spinal level on CrEP_APD

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	6.438	6.438	53.92	***0.000****
Subject(Gender)	77	9.193	0.119	9.42	
Within Subjects					
Spinal Level	2	0.302	0.142	11.21	***0.000****
Gender*Spinal Level	2	0.065	0.033	2.58	0.079
Spinal Level*Subject(Gender)	154	1.952	0.013		
Total	236	17.951			

Independent t tests (Table 3.28) revealed that the average male intervertebral discs were significantly larger than female ones in CrEP_APDs across all three lower lumbar levels (p=0.000) with a 10% increase at the L3/L4 and L4/L5 levels, respectively, and a 12% increase at the L5/S1 level. Post-hocs analyses (Table 3.29) revealed that the difference in CrEP_APDs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, CrEP_APDs of the L5/S1 IVDs were 2% smaller than the L3/L4 and L4/L5 IVDs each. Figure 3.10 illustrates the CrEP_APDs for both genders at each lower lumbar spinal level.

Table 3.28: Influence of gender on the CrEP_APD

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	8.018	105	***0.000****	0.341	10%
L4/L5	7.796	103	***0.000****	0.346	10%
L5/S1	7.709	81	***0.000****	0.398	12%

Table 3.29: Pairwise comparisons of the CrEP_APD across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	-0.014	0.042	N. S.	
L5/S1	L3/L4	-0.082	0.042	***Significant****	-2%
	L4/L5	-0.068	0.042	***Significant****	-2%

N. S.: not significant; Δ%= (I-J)/J× 100%

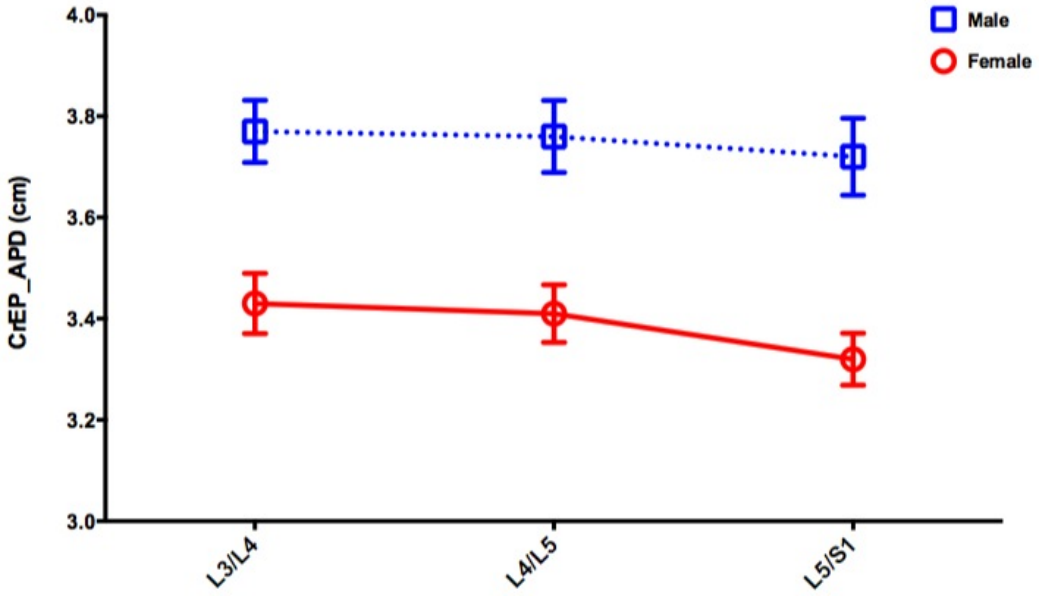


Figure 3.10: CrEP_APDs for both genders at each lower lumbar level

Frontal diameter of the cranial endplate (CrEP_FD)

Statistics from SPF ANOVA (Table 3.30) indicated that only the main effect of gender (p=0.000) significantly influenced the CrEP_FD, while spinal level had no significant main effect (p=0.755) nor did the interaction between these two factors (p=0.785).

Table 3.30: ANOVA summary table for the main and interaction effects of gender and spinal level on CrEP_FD

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	8.613	8.613	33.28	***0.000****
Subject(Gender)	77	19.930	0.259	7.82	
Within Subjects					
Spinal Level	2	0.021	0.009	0.28	0.755
Gender*Spinal Level	2	0.016	0.008	0.24	0.785
Spinal Level*Subject(Gender)	154	5.095	0.033		
Total	236	33.675			

Independent t tests (Table 3.31) revealed that the average male intervertebral discs were significantly larger than female ones in CrEP_FDs across all three lower lumbar levels (p=0.000) with an 11% increase at the L3/L4, a 10% increase at the L4/L5 level, and a 9% increase at the L5/S1 level. Post-hocs analyses (Table 3.32) also revealed that all differences in CrEP_FDs across the three lower lumbar spinal levels were less than the Tukey's HSD value and, therefore, were not statistically significant. Figure 3.11 illustrates the CrEP_FDs for both genders at each lower lumbar spinal level.

Table 3.31: Influence of gender on the CrEP_FD

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	7.495	105	***0.000****	0.488	11%
L4/L5	6.858	103	***0.000****	0.452	10%
L5/S1	5.447	81	***0.000****	0.433	9%

Table 3.32: Pairwise comparisons of the CrEP_FD across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.016	0.068	N. S.	
L5/S1	L3/L4	0.022	0.068	N. S.	
	L4/L5	0.006	0.068	N. S.	

N. S.: not significant; Δ%= (I-J)/J× 100%

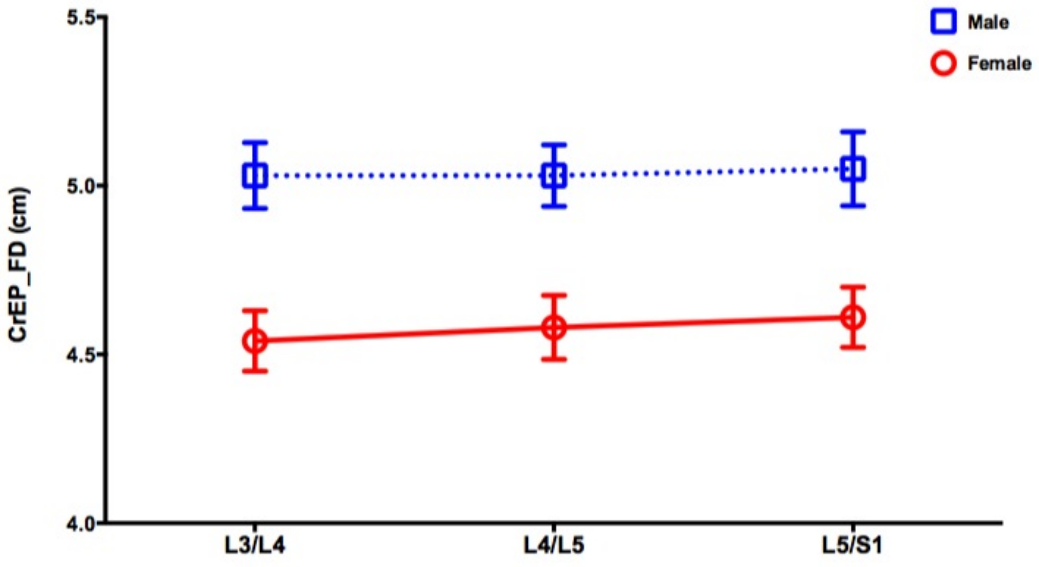


Figure 3.11: CrEP_FDs for both genders at each lower lumbar level

Anteroposterior diameter of the caudal endplate (CaEP_APD)

Statistics from SPF ANOVA (Table 3.33) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CaEP_APD. The main effect of their interaction was also significant (p=0.044). Figure 3.12 illustrates the effect of gender, spinal level, and the interaction between the two on the CaEP_APD.

Table 3.33: ANOVA summary table for the main and interaction effects of gender and spinal level on CaEP_APD

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	3.308	3.308	26.94	***0.000****
Subject(Gender)	77	9.454	0.123	5.37	
Within Subjects					
Spinal Level	2	1.204	0.574	25.11	***0.000****
Gender*Spinal Level	2	0.1454	0.073	3.18	***0.044****
Spinal Level*Subject(Gender)	154	3.520	0.023		
Total	236	17.632			

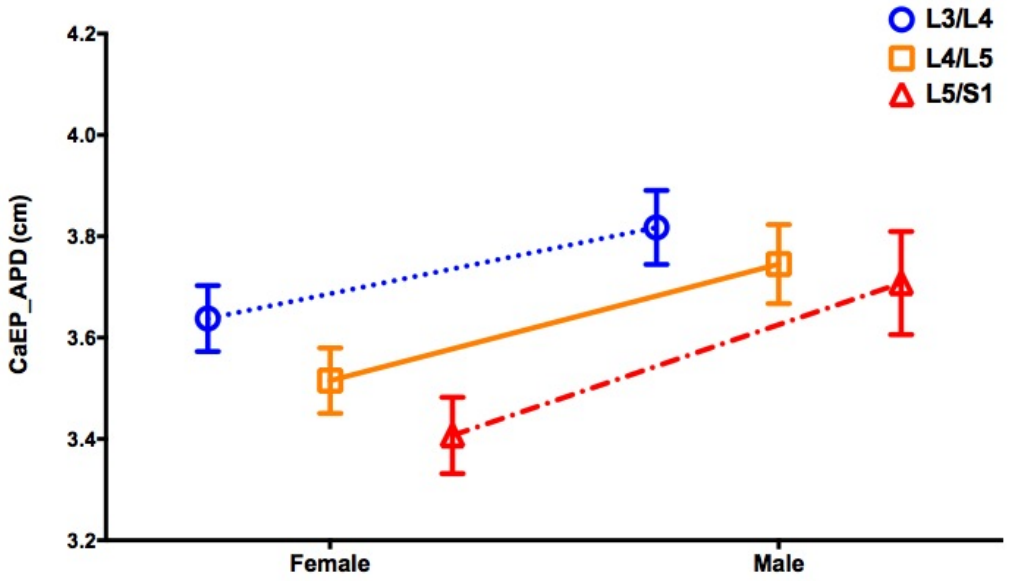


Figure 3.12: CaEP_APDs for both genders at each lower lumbar level

Frontal diameter of the caudal endplate (CaEP_FD)

Statistics from SPF ANOVA (Table 3.34) indicated that the main effects of both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CaEP_FD, but the main effect of their interaction was not significant (p=0.181).

Table 3.34: ANOVA summary table for the main and interaction effects of gender and spinal level on CaEP_FD

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	7.227	7.227	27.72	***0.000****
Subject(Gender)	77	20.077	0.261	5.88	
Within Subjects					
Spinal Level	2	1.242	0.629	14.2	***0.000****
Gender*Spinal Level	2	0.153	0.077	1.73	0.181
Spinal Level*Subject(Gender)	154	6.824	0.044		
Total	236	35.523			

Independent t tests (Table 3.35) revealed that the average male intervertebral discs were significantly larger than female ones in CaEP_FDs across all three lower lumbar levels (p=0.000) with an 8% increase at the L3/L4 level and 9% increases at both L4/L5 and L5/S1 levels. Post-hocs analyses (Table 3.36) revealed that the difference in CaEP_FDs between the L4/L5 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L3/L4 IVDs. No significant difference was found between the L4/L5 and L4/L5 IVDs. On average, CaEP_FDs of the L4/L5 IVDs were 3% larger than the L3/L4 IVDs, while CaEP_FDs of the L5/S1 IVDs were 2% larger than the L3/L4 IVDs. Figure 3.13 illustrates the CaEP_FDs for both genders at each lower lumbar spinal level.

Table 3.35: Influence of gender on the CaEP_FD

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	6.530	105	***0.000****	0.411	8%
L4/L5	6.578	103	***0.000****	0.432	9%
L5/S1	5.143	81	***0.000****	0.454	9%

Table 3.36: Pairwise comparisons of the CaEP_FD across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.175	0.078	***Significant****	3%
L5/S1	L3/L4	0.113	0.078	***Significant****	2%
	L4/L5	-0.062	0.078	N. S.	

N. S.: not significant; Δ%= (I-J)/J× 100%

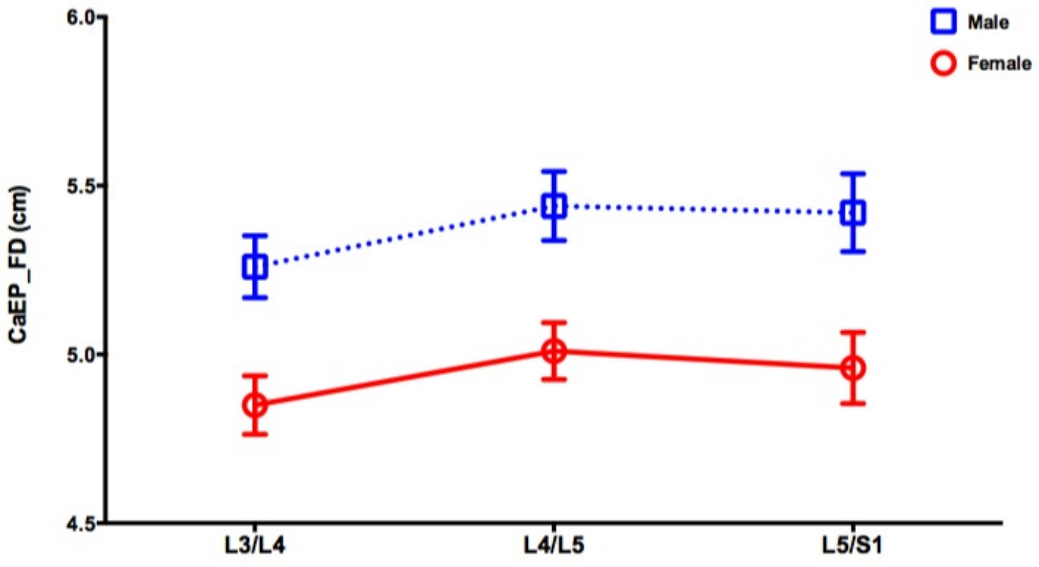


Figure 3.13: CaEP_FDs for both genders at each lower lumbar level

3.3.5 Morphometric index

Statistics from SPF ANOVA (Table 3.37) indicated that the main effect of spinal level (p=0.000) significantly influenced the ovality ratios of the intervertebral discs (IVD_ORs), the cranial endplates (CrEP_ORs), and the caudal endplates (CaEP_ORs). The main effects of gender and the interaction between the gender and the spinal level were not significant.

Table 3.37: ANOVA summary table for the main and interaction effects of gender and spinal level on the ovality ratios (ORs)

Ovality Ratios of the Intervertebral Discs (IVD_ORs)

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	0.002	0.002	0.15	0.700
Subject(Gender)	99	1.321	0.013	3.69	
Within Subjects					
Spinal Level	2	0.067	0.031	8.62	***0.000****
Gender*Spinal Level	2	0.016	0.008	2.25	0.108
Spinal Level*Subject(Gender)	198	0.715	0.004		
Total	302	2.121			

Ovality Ratios of the Cranial Endplates (CrEP_ORs)

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	0.017	0.017	1.44	0.234
Subject(Gender)	77	0.893	0.012	3.75	
Within Subjects					
Spinal Level	2	0.068	0.032	10.28	***0.000****
Gender*Spinal Level	2	0.017	0.009	2.79	0.064
Spinal Level*Subject(Gender)	154	0.476	0.003		
Total	236	1.471			

Ovality Ratios of the Caudal Endplates (CaEP_ORs)

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	0.013	0.013	0.12	0.727
Subject(Gender)	77	0.839	0.011	2.61	
Within Subjects					
Spinal Level	2	0.467	0.230	55.12	***0.000****
Gender*Spinal Level	2	0.003	0.002	0.41	0.661
Spinal Level*Subject(Gender)	154	0.642	0.004		
Total	236	1.954			

Post-hocs analyses (Table 3.38) revealed that the CrEP_ORs at the L5/S1 level were significantly larger than the ratios at the L3/L4 (by 3%) and L4/L5 levels (2%), while no significant difference was found between the CrEP_ORs at the L3/L4 and L4/L5 levels. The only significant difference in IVD_ORs was found between the L4/L5 and L5/S1 levels with a 3% increase, on average. CaEP_ORs at the L4/L5 and L5/S1 levels were significantly larger than the L3/L4 level, with a 6% and a 7% increase, on average. No significant difference was found between the L4/L5 CrEP_ORs and the L5/S1 CrEP_ORs.

Table 3.38: Pairwise comparisons of the ORs across the three lower lumbar spinal levels

	Spinal Level		Post-hocs tests (Tukey HSD)			Δ%
	(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	
CrEP_ORs	L4/L5	L3/L4	0.010	0.021	N. S.	
	L5/S1	L3/L4	0.039	0.021	***Significant****	3%
		L4/L5	0.029	0.021	***Significant****	2%
IVD_ORs	L4/L5	L3/L4	0.020	0.020	N. S.	
	L5/S1	L3/L4	0.037	0.020	***Significant****	3%
		L4/L5	0.017	0.020	N. S.	
CaEP_ORs	L4/L5	L3/L4	0.086	0.024	***Significant****	6%
	L5/S1	L3/L4	0.100	0.024	***Significant****	7%
		L4/L5	0.014	0.024	N. S.	

3.4 Discussion

3.4.1 Essence of the morphometry of the spinal motion segments

The morphometry of the human spine has numerous potential applications, providing biomechanical models mathematical representations of the spinal geometry to evaluate the risks of work-related musculoskeletal disorders (WMSDs) associated with postures and forceful motions (Chaffin, 1969, 1988). It also provides critical inputs of geometric data for finite element models to better grasp the mechanical behavior of the spine and offer better

explanations to spinal pathologies linked to mechanical factors (Noailly et al., 2007). Previously, the geometric dimensions of the spinal motion segments have been measured and reported primarily in morphometric studies for selected spinal regions, including the cervical spine (Nissan & Gilad, 1984; Gilad & Nissan, 1986), the thoracic spine (Goh, Price, Song, Davis, & Singer, 2000; Kunkel et al., 2011), the thoracolumbar spine (Nissan & Gilad, 1984; Gilad & Nissan, 1986; J. L. Berry et al., 1987; Aharinejad et al., 1990; Kunkel, Schmidt, & Wilke, 2010; van der Houwen et al., 2010; H. Chen et al., 2011; Kang et al., 2011; Karabekir et al., 2011), and the lumbar spine (Farfan, 1973; Postacchini et al., 1983; van Schaik et al., 1985; Colombini et al., 1989; Panjabi et al., 1992; Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008). In the literature, geometric data have also been reported occasionally as supplementary data associated with mechanical tests investigating the ultimate compressive strength of spinal motion segments, particularly in lumbar region (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Porter et al., 1989; Mosekilde, 1990; Drerup et al., 1999). The review of morphometric studies in the literature also indicated that previous studies differed tremendously in the modality of geometric measurement with respect to the material (cadaver vs. *in vivo*), the measurement protocol (caliper vs. image-based), and the dimensional attributes (linear vs. planar).

Materials

With cadaveric specimens, particularly the isolated vertebrae, the majority of measurement performed in the transverse section have been at the vertebral endplate (Postacchini et al., 1983; J. L. Berry et al., 1987; Biggemann et al., 1988; Brinckmann et

al., 1989; Panjabi et al., 1992; Seidel et al., 2008), which has a greater capability to to sustain post-mortem changes as a part of the bony vertebral body (Adams et al., 2002) and preserve its geometric dimensions as identified by the bony landmarks (J. L. Berry et al., 1987). Even though some cadaver studies investigating the mechanical properties of the lumbar motion segments across a single level or multiple levels, have also provided geometric dimensions (Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Porter et al., 1989), intervertebral discs and other soft tissues are highly susceptible to post-mortem changes (Adams et al., 2002). Meanwhile, spinal ligamentous tissues were "scraped clean" to characterize the sole mechanical properties of motion segment. Unfortunately, the removal of ligamentous tissues and other soft tissues can alter the morphologic characteristics, especially the disc height and cross-sectional area (Zhou et al., 2000). In addition, in some mechanical tests, dissections have been performed to isolate the motion segments by cutting through the vertebral bodies or intervertebral discs, which possibly could introduce error in the measurements (Kunkel et al., 2011) and so far there is very limited understanding of how these procedures might influence actual spine geometry. Therefore, the geometric dimensions obtained with cadavers may not be a good representation of a living individual, whose spine is constantly loaded with compression introduced by the upper body weight and muscle contraction. In addition, the contribution of different spinal structures in load-bearing capacity are heavily influenced temporally (Adams et al., 1990), primarily through the decrease in water content over time and increase with sleep/rest in a supine or prone posture (Boos et al., 1993). LeBlanc et al. (1994) also reported significant adaptive changes of the cross-sectional area of the intervertebral discs during long-term weightless space flight. In general, the bony

components (e.g. vertebrae) and soft tissues (e.g., intervertebral discs and ligaments) together provide the human spine the rigidity and flexibility to sustain compressive loads and to perform complex spinal motions. Therefore, *in vivo* morphometry of the spinal motion segments should provide better geometric description and improve our understanding of the intrinsic characteristics of the human spine as an intact structure. The rapid development of medical imaging technology has already made it feasible to perform *in vivo* morphometric investigations with a large sample size.

Measurement protocol

Direct measurement with calipers

Calipers have been an accurate means (0.05mm to 0.1mm accuracy) to measure the geometric dimensions of the cadaveric lumbar vertebrae (Postacchini et al., 1983; J. L. Berry et al., 1987; Panjabi et al., 1992; Kang et al., 2011) and intervertebral discs (Nachemson, 1960; Hutton & Adams, 1982; van der Houwen et al., 2010). With isolated vertebrae, the dimensions can be measured in multi-planar fashion which provides valuable information to reconstruct the three-dimensional aspects of human vertebrae and improve understanding of human spinal geometry (J. L. Berry et al., 1987; Panjabi et al., 1992). Unfortunately, clinical procedures isolating the vertebrae are highly likely to prevent any accurate measurement regarding the morphometry of the intervertebral discs. Unfortunately, direct measurements with calipers usually are limited to the dimensions between peripheral bony landmarks, although some researcher has attempted to measure the cross-sectional area of the isolated intervertebral disc with a specifically designed instrument (Nachemson, 1960). In general, even though calipers are an instrument for

precision measurement (van der Houwen et al., 2010), their reliability in terms of inter- and intra-observer agreement is questionable since their use depends on visual feedback. Therefore, while the instrument may be precise, the method is not accurate. In addition, inter- and intra-observer reliability have not generally been reported along with the results in the literature.

X-ray

Radiographs (x-rays) of the lower lumbar spine have been a primary source for early investigators to access the lateral geometric characteristics, especially anteroposterior (APD) and frontal diameter (FD) of the vertebrae and vertebral endplates (Nissan & Gilad, 1984; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999). X-ray techniques have been widely used in clinical diagnosis of vertebral fractures and other pathological changes such as spondylitis or bone tumors (Tracy et al., 1989; Krause et al., 1991). Therefore, historical radiographs have become a good reference source for morphometric studies (Amonoo-Kuofi, 1991; Y. Wang et al., 2012). For geometric dimensions from plain radiographs, calipers are the major measurement instrument for measurements (Nissan & Gilad, 1984; Gilad & Nissan, 1986; Amonoo-Kuofi, 1991; Kang et al., 2011).

Unfortunately, since radiographs are generated by a radiological source projecting radiation beams towards the spine onto film, the geometric dimensions measured on radiographs are subjected to varying magnification errors depending on the spine-to-film and source-to-spine distances, ranging from 7.5% up to 30% (White III & Panjabi, 1990). However, some studies reported good agreement of measurements between radiographs and CT scans (Kang et al., 2011; Y. Wang et al., 2012) and between radiographs and MR scans (Tomomitsu et al., 2005). Secondly, the exposure to radiologic sources may pose potential

health risks to subjects. Thirdly, radiographs can only describe the lateral (sagittal) and the frontal aspect of spinal geometry. It also has very limited capability to describe the morphometry of the intervertebral discs, particularly in the transverse section.

Computed Tomography

Compared to radiography, computed tomography (CT) techniques produce superior tomographic sections of the spine and provide greater visualization of the anatomical characteristics, particularly the soft tissues (Teplick, 1992). Because of CT's superb imaging capability, it has become a primary diagnostic technique in clinical practice for demonstrating the majority of significant spinal abnormalities (e.g., spinal stenosis, spondyloysis, and disc herniation) (Krause et al., 1991; R. Schroeder et al., 2011). It has also been used as a diagnostic technique to evaluate disc degeneration (Haughton, 1983) because of its capability to characterize the annulus fibrosus (Teplick, 1992). On the other hand, CT sections can be obtained using x-ray beams angled parallel to each interspace. Therefore, the scanned images can be made through the intervertebral discs, the vertebral endplates, and the vertebral bodies at each spinal level (van Schaik et al., 1985; Teplick, 1992), providing a very valuable transverse section of the spine (Schnebel et al., 1989). The tilted transverse CT slices reconstruct the entire peripheral margin of the vertebral body and intervertebral disc with no disturbance, which become a very useful modality to investigate the morphometry of the lumbar spine and reported geometric dimensions measured with sophisticated computerized program (van Schaik et al., 1985; Biggemann et al., 1988; Brinckmann et al., 1989; Colombini et al., 1989; Drerup et al., 1999; Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008; van der Houwen et al., 2010; Y. Wang et al., 2012).

Unfortunately, in general, a CT scanner has a limited capability to tilt the slicing section, typically a maximum of 20 degrees (Teplick, 1992), which may be insufficient to accommodate the intervertebral angles reported in lumbar curvature *lordosis* (Aspden, 1989; Cheng et al., 1998; Y. L. Chen, 1999; Been et al., 2011). Hence, it may not be well suited to reconstruct the lower lumbar spine, especially at L4/L5 and L5/S1 level, resulting in possible errors and distortions (Colombini et al., 1989).

Magnetic Resonance Imaging

As discussed earlier, magnetic resonance imaging (MRI) technique is an excellent alternative to improve the morphometric studies of the lower lumbar spine, providing multi-planar access to the structures and capability to evaluate the health of the disc. For the past decade, it has rapidly become a reliable clinical diagnostic method and a great amount of historical MR scans has been generated. These historical MR scans have great potential to facilitate morphometric researches of the spinal motion segments, particularly at the lower lumbar spine and improve our understanding of the characteristics of the human spine. The present study is among the first to attempt to describe the morphometry of the lumbar motion segments in the transverse section along only a few other studies (Karabekir et al., 2011).

Dimensional attributes

Linear vs. Planar

The review of literature indicated that linear dimensions, such as the frontal diameter and anteroposterior diameter, are the most measured and reported morphometric characteristics in the transverse section (Farfan, 1973; Postacchini et al., 1983; Nissan &

Gilad, 1984; Gilad & Nissan, 1986; van Schaik et al., 1985; J. L. Berry et al., 1987; Aharinejad et al., 1990; Amonoo-Kuofi, 1991; Panjabi et al., 1992; Aydinlioglu et al., 1999; Zhou et al., 2000; van der Houwen et al., 2010; H. Chen et al., 2011; Y. Wang et al., 2012). It was also revealed that there has been disagreement regarding the selection of which linear dimension should be used to describe the transverse section of the motion segments (shown in Figure 3.2 and Figure 3.14). Some researchers have selected the anteroposterior diameter as the linear distance between the antero-most and postero-most landmarks (Farfan, 1973; Brinckmann et al., 1989; Panjabi et al., 1992), while other researchers have selected the mid-sagittal diameter (Postacchini et al., 1983; van Schaik et al., 1985; J. L. Berry et al., 1987; Aharinejad et al., 1990; Zhou et al., 2000; van der Houwen et al., 2010; Y. Wang et al., 2012). The remaining studies only provided a general term (e.g., depth) and did not provide further descriptions for how such measures were taken (Hutton & Adams, 1982; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999). Two of these studies used lateral plain radiographs (Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999), the "depth" could be referring to the anteroposterior distance since the projection of the lateral aspect of vertebra would accommodate the "kidney-shaped" disc. However, this is speculative since depth was not clearly defined. For approximately oval-shaped discs, the two diameters should provide relatively the same measurement, while the difference should be addressed for kidney-shaped discs. The posteriorly concave-shaped discs have a greater area of annulus fibrosus which offers better mechanical capacity to withstand spinal movements (Bogduk, 2005).

Compared to linear dimensions, cross-sectional area (CSA) as an important geometric dimension, has only been measured and reported in a few studies (Nachemson, 1960;

Farfan, 1973; Hansson et al., 1980; Hutton & Adams, 1982; Biggemann et al., 1988; Brinckmann et al., 1989; Colombini et al., 1989; Turk & Celan, 2004; Y. Wang et al., 2012). Nachemson (1960) calculated the CSA with readings obtained from an Amsler planimeter moving around the edges of the surface. Hansson et al. (1980) "stamped" the cadaveric vertebrae onto a piece of paper, traced the border of the surface, and then calculated the area. Porter et al. (1989) measured the area by counting the squares of superimposed graph paper. Mosekilde (1990) calculated the CSA of lumbar vertebrae by dividing the subwater displacement volume by the vertebral height. With advanced imaging techniques and sophisticated software, a scanned image of a transverse section can be digitized and then used to measure the CSA with intrinsic software (Zhou et al., 2000; Turk & Celan, 2004; Seidel et al., 2008; Y. Wang et al., 2012), however no further information was reported regarding the validity of such software. On the other hand, a number of studies have employed the ellipsoid approximation method (Formula 3.1 and 3.2) which calculates an area using the frontal and anteroposterior (or mid-sagittal) diameters as the major and minor axis of an ellipse (Farfan, 1973; Hutton & Adams, 1982; Brinckmann et al., 1989; Colombini et al., 1989; Panjabi et al., 1992), as illustrated in Figure 3.14.

Intervertebral disc vs. Vertebral endplate

The majority of geometric dimensions reported in the literature have been measured for the vertebral endplates (Postacchini et al., 1983; Nissan & Gilad, 1984; Gilad & Nissan, 1986; van Schaik et al., 1985; J. L. Berry et al., 1987; Biggemann et al., 1988; Brinckmann et al., 1989; Aharinejad et al., 1990; Amonoo-Kuofi, 1991; Panjabi et al., 1992; Aydinlioglu et al., 1999; Drerup et al., 1999; Zhou et al., 2000; Seidel et al., 2008; van der Houwen et al., 2010; H. Chen et al., 2011; Y. Wang et al., 2012), compared to the intervertebral discs

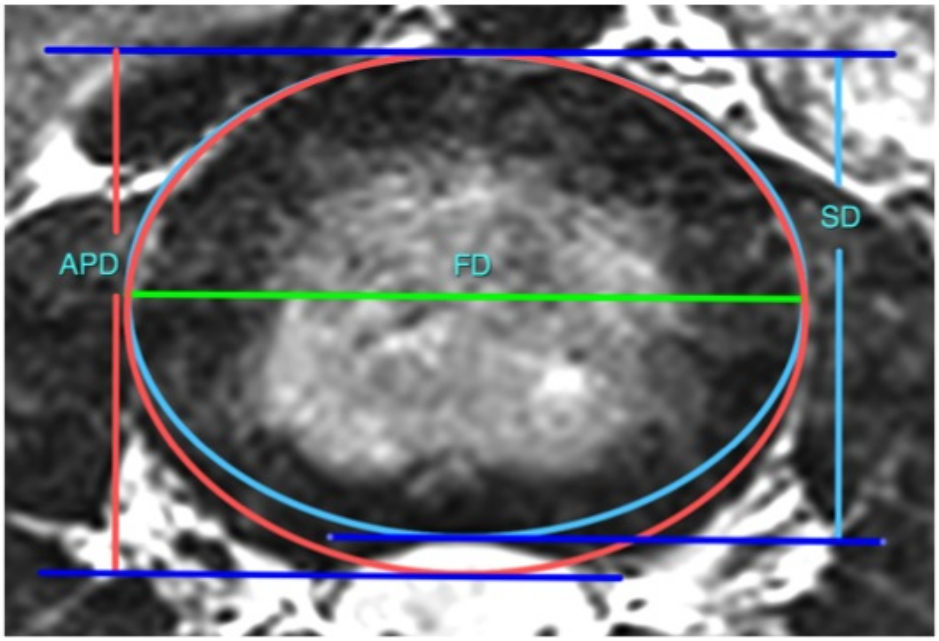


Figure 3.14: Illustrations of different ellipsoid approximation methods calculating the cross-sectional area (CSA) of the intervertebal disc

which have only been described by a relatively small number of studies (Nachemson, 1960; Farfan, 1973; Hansson et al., 1980; Hutton & Adams, 1982; Colombini et al., 1989; Porter et al., 1989; Turk & Celan, 2004). It could be explained by the fact that earlier studies used more cadavers and more radiographs of spines on which the vertebral endplates can be more easily identified. Secondly, several studies have suggested that the vertebral endplate may be the most critical component in the transverse section with respect to the a motion segment's load-bearing capability (Biggemann et al., 1988; Brinckmann et al., 1989). In addition, more evidence has indicated a distinct disc degeneration phenotype driven by the vertebral endplate (Adams & Dolan, 2012), in which the morphometric characteristics may be associated with the process (Hall et al., 1998; Rodriguez et al., 2012; Lakshmanan et al., 2012; He et al., 2012; Stern, Njagulj, Likar, Pernuš, & Vrtovec, 2013).

3.4.2 Research findings

In the present study, the morphometry of human lower lumbar intervertebral discs and vertebral endplates in the transverse section was described in detail using a large sample of archived medical MR scans. Geometric dimensions were measured using a software that has superior capability to process MR scans (DICOM format) (Rosset et al., 2004; Yamauchi et al., 2010) and has been employed by a number of studies investigating the anatomical characteristics of the human spine (Peoples et al., 2008) and paraspinal musculature (Bishop, Horn, Lott, Arpan, & George, 2011; Fortin & Battié, 2012) and assisting the clinical diagnosis of spinal pathologies (Karlo et al., 2010; Henderson, Kulik, Richarme, Theumann, & Schizas, 2012). The present study may be the first attempt to apply such image processing method to comprehensively measure and analyze the morphometry of an individual's lower lumbar motion segments with respect to the load-bearing surfaces. Therefore, each geometric dimension measured was explicitly defined and illustrated with clear figures demonstrating each landmark referenced, which helped this study yield "excellent" intra- and inter-observer measurement reliabilities, suggesting great potential for future morphometric studies. Using MR scans and advanced software, the present study was able to describe the actual geometry of the lumbar intervertebral discs, particularly at the lumbosacral joint, rather than using an simple ellipsoid approximation (Farfan, 1973; Brinckmann et al., 1989; Colombini et al., 1989; Panjabi et al., 1992), which compromises the accuracy of the results as found by the present study and other researchers (Seidel et al., 2008).

The present study aimed to provide accurate morphometry of the multi-level spinal motion segments across the lower lumbar spine, describing both the linear and planar aspects of the spinal geometry regarding both the intervertebral discs (IVDs) and vertebral endplates (EPs), which has been lacking in the literature. For the lumbar IVDs, the previous geometric data, found in the literature (as shown in Table 3.39), have been mainly focusing on the planar aspects of the IVDs (Nachemson, 1960; Farfan, 1973; Hansson et al., 1980; Hutton & Adams, 1982; Colombini et al., 1989; Porter et al., 1989; Turk & Celan, 2004), while only Farfan (1973) reported the diameters of the discs. For the lumbar EPs, the previous morphometric characteristics (as shown in Table 3.40 and 3.41) have been described for the planar aspects of the two adjacent EPs (Brinckmann et al., 1989; Panjabi et al., 1992; Seidel et al., 2008; Y. Wang et al., 2012) or the cranial EPs only (Drerup et al., 1999; Zhou et al., 2000), and for the linear aspect of the two adjacent EPs (Nissan & Gilad, 1984; J. L. Berry et al., 1987; Panjabi et al., 1992; Zhou et al., 2000; van der Houwen et al., 2010; Y. Wang et al., 2012), the cranial EPs only (van Schaik et al., 1985; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999), or the caudal EPs only (Postacchini et al., 1983; Aharinejad et al., 1990). Other than the present study, only Panjabi et al. (1992) and Y. Wang et al. (2012) have attempted to describe both linear and planar aspects, however neither study described the caudal EP of the lumbosacral discs.

Table 3.39: Geometric data regarding the lower lumbar intervertebral disc in the literature

Authors	Subjects	Age	Ht	Wt	**Cross-sectional Area (cm^2)**				
					L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Nachemson (1960)	14 Female	59.71	-	-	13.32 (1.22)	14.72 (1.47)	15.39 (1.54)	16.10 (1.80)	
(Caliper, Cadaver)	19 Male	47.84	-	-	17.85 (2.6)	18.21 (2.32)	19.61 (2.53)	18.52 (1.27)	
Farfan (1973) (**Ellipsoid**)	-	-	-	-	16.59 (5.67)	17.15 (4.87)	16.33 (2.25)	18.55 (1.85)	
Hansson et al. (1980)	21 Female	57.67	-	-	16.08 (2.77)	17.14 (2.55)	18.05 (3.06)		
(Cadaver, Graph Paper)	15 Male	59.73	-	-	17.02 (2.57)	18.77 (2.81)	20.86 (3.72)		
Hutton and Adams (1982)	5 Female	52.00	-	67.00	11.1	15.83 (2.25)	12.80 (1.00)	15.20 (1.00)	
(**Ellipsoid**, Cadaver)	13 Male	38.31	-	68.46	15.65 (1.77)	18.20 (3.96)	17.00 (1.92)	18.92 (3.76)	
Colombini et al. (1989) (**Ellipsoid**, CT, *In vivo*, Healthy)	16 (F or M)	45.00	172.40	77.40			19.88 (3.51)	21.43 (3.89)	18.88 (3.18)
Porter et al. (1989) (Actual,Cadaver)	9 Male	21.89	-	72.40		16.82 (1.34)		18.50 (1.74)	
(Turk & Celan, 2004)	21F + 19M	44	-	-				17.96 (2.40)	16.88 (2.06)
(CT, Patient/LBP/Healthy)	65 Male	41	-	-				18.59 (1.38)	17.40 (1.17)
	30 Male							20.79 (1.95)	19.26 (1.65)
Tang 2013a	55 Female	30.11	165.72	74.65			14.76 (1.90)	14.63 (1.80)	13.52 (1.91)
(MRI, *In vivo*, Patient)	52 Male	30.59	178.33	87.43			17.71 (1.96)	18.08 (2.02)	17.06 (2.34)
	107 F + M	30.35	171.79	80.98			16.19 (2.43)	16.27 (2.57)	15.23 (2.76)

					Anteroposterior Diameter (cm)				
					L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Farfan (1973)	-	-	-	-	3.81 (0.80)	3.81 (0.60)	3.60 (0.30)	3.87 (0.13)	
	55 Female	30.11	165.72	74.65			3.70 (0.26)	3.68 (0.23)	3.53 (0.23)
Tang 2013a	52 Male	30.59	178.33	87.43			4.03 (0.24)	4.06 (0.26)	4.00 (0.32)
	107 F + M	30.35	171.79	80.98			3.86 (0.30)	3.86 (0.31)	3.76 (0.36)

					Frontal Diameter (cm)				
					L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Farfan (1973)					5.27 (0.70)	5.46 (0.77)	5.59 (0.43)	5.90 (0.43)	
	55 Female	30.11	165.72	74.65			4.97 (0.32)	5.03 (0.32)	4.93 (0.39)
Tang 2013a	52 Male	30.59	178.33	87.43			5.48 (0.36)	5.59 (0.32)	5.50 (0.40)
	107 F + M	30.35	171.79	80.98			5.22 (0.42)	5.29 (0.43)	5.21 (0.49)

Table 3.40: Geometric data regarding the lower lumbar cranial endplate in the literature

Authors	Subjects	Age	Ht	Wt	Cross-sectional Area (cm^2) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Brinckmann et al. (1989)	22 F	49.15	-	-	12.53 (1.60)	14.22 (1.75)	13.72 (1.96)	15.21 (2.20)	
(CT, Cadaver, **Ellipsoid**)	31 M	49.93	-	-	15.75 (3.20)	17.44 (3.85)	18.43 (5.77)	18.16 (2.22)	
Panjabi et al. (1992) (Cadaver, **Ellipsoid**)	4F + 8M	46.3	167.8	67.8	11.17 (0.49)	11.97 (0.51)	12.90 (0.64)	12.73 (0.52)	12.18 (0.59)
Drerup et al. (1999) (CT, *In vivo*)	14 Male	42.21	177.57	87.86			16.00 (1.36)		
Zhou et al. (2000)	71 Female	50	-	-			13.86 (1.88)		
(CT, *In vivo*, Patient)	55 Male	49	-	-			15.98 (0.66)		
	F + M	50	-	-			14.92 (1.74)		
Seidel et al. (2008) (CT, Cadaver)	53	33.26	179.92	82.66			16.00 (1.81)	15.84 (1.82)	15.06 (1.90)
Y. Wang et al. (2012) (Cadaver, Caliper/X-ray/Laser Scan, Patient)	149 Male	under 64	-	-	14.40 (2.10)	14.90 (2.40)	15.80 (2.4)	16.10 (2.50)	15.10 (2.80)
Tang 2013a	55 Female	30.11	165.72	74.65			12.59 (1.68)	12.49 (1.53)	11.71 (1.50)
(MRI, *In vivo*, Patient)	52 Male	30.59	178.33	87.43			15.19 (1.73)	15.13 (1.74)	14.47 (2.00)
	107 F + M	30.35	171.79	80.98			13.85 (2.14)	13.75 (2.10)	13.08 (2.23)

					Anteroposterior Diameter (cm) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Nissan and Gilad (1984) (Caliper,X-ray, Healthy)	157 Male	26.80	174.70	72.40	3.41 (0.29)	3.47 (0.30)	3.46 (0.28)	3.49 (0.28)	3.39 (0.27)
van Schaik et al. (1985)	59 Female	-	-	-			3.26	3.33	3.42
(CT, Patient, Mid-sagittal)	64 Male	-	-	-			3.51	3.72	3.73
	F + M	41.40	-	-			3.40 (0.25)	3.52 (0.30)	3.59 (0.29)
J. L. Berry et al. (1987) (Caliper, Cadaver, Caucasian)	30 F + M	50 to 79	-	-	3.23 (0.35)	3.34 (0.34)	3.42 (0.33)	3.56 (0.31)	3.45 (0.30)
Amonoo-Kuofi (1991)	310 Female	10 to 64	-	-			3.92	4.01	3.84
(X-ray, Healthy)	305 Male						4.20	4.31	4.15
Panjabi et al. (1992)	4F + 8M	46.3	167.8	67.8	3.53 (0.13)	3.49 (0.07)	3.48 (0.12)	3.39 (0.09)	3.32 (0.92)
Aydinlioglu et al. (1999)	97 Female	10 to 59	-	-			4.31	4.37	4.30
(X-ray, Healthy, Average)	103 Male						4.77	4.88	4.75
Zhou et al. (2000)	71 Female	50	-	-			3.37 (0.31)	3.44 (0.28)	3.43 (0.33)
	55 Male	49	-	-			3.74 (0.31)	3.86 (0.34)	3.83 (0.38)
	F + M						3.53 (0.36)	3.62 (0.37)	3.60 (0.40)
van der Houwen et al. (2010)	31 Female	49.8	-	-	2.53	2.6	2.54	2.81	2.51
(Caliper, CT, Patient, Mid-sagittal)	46 Male				2.97	2.9	3.04	3.06	2.74
H. Chen et al. (2011)	40 Female	43	-	-	2.54 (0.27)	2.60 (0.28)			
(CT, Patient, Mid-sagittal)	43 Male				2.94 (0.24)	2.93 (0.26)			
Y. Wang et al. (2012)	149 Male	under 64	-	-	3.57 (0.23)	3.57 (0.31)	3.58 (0.28)	3.55 (0.29)	3.38 (0.35)
	55 Female	30.11	165.72	74.65			3.43 (0.22)	3.41 (0.21)	3.32 (0.19)
Tang 2013a	52 Male	30.59	178.33	87.43			3.77 (0.22)	3.76 (0.25)	3.72 (0.27)
	107 F + M	30.35	171.79	80.98			3.59 (0.28)	3.58 (0.29)	3.52 (0.31)

					Frontal Diameter (cm) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
van Schaik et al. (1985)	59 Female	-	-	-			4.12	4.26	4.51
	64 Male	-	-	-			4.58	4.75	5.01
	F + M	41.40	-	-			4.37 (0.41)	4.50 (0.38)	4.79 (0.45)
J. L. Berry et al. (1987)	30 F + M	50 to 79	-	-	4.91 (0.37)	5.48 (0.48)	5.38 (0.37)	5.09 (0.46)	5.27 (0.43)
Panjabi et al. (1992)	4F + 8M	46.3	167.8	67.8	4.33 (0.08)	4.55 (0.11)	4.80 (0.12)	4.95 (0.14)	4.94 (0.14)
Zhou et al. (2000)	71 Female	50	-	-			4.93 (0.41)	5.04 (0.42)	5.04 (0.49)
	55 Male	49	-	-			5.48 (0.36)	5.51 (0.41)	5.67 (0.53)
	F + M	50	-	-			5.17 (0.48)	5.25 (0.47)	5.31 (0.60)
van der Houwen et al. (2010)	31 Female	49.8	-	-	2.97	3.27	3.79	4.11	4.18
	46 Male				3.97	4.11	4.06	4.89	4.66
H. Chen et al. (2011)	40 Female	43	-	-	3.77 (0.31)	3.83 (0.32)			
	43 Male				4.27 (0.35)	4.45 (0.40)			
Y. Wang et al. (2012)	149 Male	under 64	-	-	4.70 (0.35)	4.80 (0.31)	5.13 (0.37)	5.30 (0.41)	5.12 (0.45)
	55 Female	30.11	165.72	74.65			4.54 (0.33)	4.58 (0.35)	4.61 (0.33)
Tang 2013a	52 Male	30.59	178.33	87.43			5.03 (0.35)	5.03 (0.32)	5.05 (0.39)
	107 F + M	30.35	171.79	80.98			4.78 (0.41)	4.79 (0.41)	4.83 (0.42)

Table 3.41: Geometric data regarding the lower lumbar caudal endplate in the literature

Authors	Subjects	Age	Ht	Wt	Cross-sectional Area (cm^2) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Brinckmann et al. (1989)	22 F	49.15	-	-	13.23 (1.75)	15.00 (1.56)	14.40 (1.45)	15.73 (2.48)	
(CT, Cadaver, **Ellipsoid**)	31 M	49.93	-	-	16.15 (3.35)	18.03 (3.59)	19.83 (6.85)	18.89 (2.30)	
Panjabi et al. (1992) (Cadaver, **Ellipsoid**)	4F + 8M	46.3	167.8	67.8	11.36 (0.62)	11.95 (0.55)	12.39 (0.58)	12.37 (0.58)	
Seidel et al. (2008) (CT, Cadaver)	53	33.26	179.92	82.66		15.61 (1.76)	15.79 (1.98)	16.06 (2.00)	
Y. Wang et al. (2012) (Cadaver, Caliper/X-ray/Laser Scan, Patient)	149 Male	under 64	-	-	15.40 (2.30)	15.60 (2.10)	16.70 (2.4)	15.80 (3.00)	
Tang 2013a	55 Female	30.11	165.72	74.65			14.04 (1.75)	13.95 (1.56)	13.35 (1.78)
(MRI, *In vivo*, Patient)	52 Male	30.59	178.33	87.43			16.29 (1.86)	16.47 (1.95)	15.93 (2.25)
	107 F + M	30.35	171.79	80.98			15.13 (2.12)	15.15 (2.16)	14.63 (2.39)

					Anteroposterior Diameter (cm) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Postacchini et al. (1983)	63 Italian	Adult	-	-	3.1 (0.3)	3.0 (0.3)	3.2 (0.3)	3.3 (0.3)	
(Caliper, Cadaver, Mid-sagittal)	58 Indian				2.7 (0.2)	2.8 (0.2)	2.9 (0.2)	2.9 (0.2)	
Nissan and Gilad (1984) (Caliper,X-ray, Healthy)	157 Male	26.80	174.70	72.40	3.44 (0.28)	3.47 (0.27)	3.43 (0.27)	3.42 (0.27)	
J. L. Berry et al. (1987) (Caliper, Cadaver, Caucasian)	30 F + M	50 to 79	-	-	3.33 (0.37)	3.39 (0.33)	3.49 (0.34)	3.51 (0.28)	
Aharinejad et al. (1990) (Cadaver/CT/MRI, Mid-sagittal)	574 segments	-	-	-	3.11 (0.25)	3.46 (0.42)	3.80 (0.66)	3.76 (0.46)	
Panjabi et al. (1992) (Cadaver, **Ellipsoid**)	4F + 8M	46.3	167.8	67.8	3.46 (0.11)	3.52 (0.11)	3.55 (0.09)	3.47 (0.12)	
Zhou et al. (2000)	71 Female	50	-	-		3.08 (0.31)	3.32 (0.33)	3.43 (0.35)	
(CT, *In vivo*, Patient)	55 Male	49	-	-		3.41 (0.26)	3.64 (0.32)	3.76 (0.31)	
	F + M	50	-	-		3.23 (0.33)	3.46 (0.36)	3.57 (0.37)	
van der Houwen et al. (2010)	31 Female	49.8	-	-	2.71	2.63	2.61	2.77	
(Caliper, CT, Patient, Mid-sagittal)	46 Male				2.89	2.97	2.89	2.76	
H. Chen et al. (2011)	40 Female	43	-	-	2.60 (0.24)	2.56 (0.31)			
(CT, Patient, Mid-sagittal)	43 Male				2.92 (0.26)	2.91 (0.27)			
Y. Wang et al. (2012)	149 Male	under 64	-	-	3.62 (0.28)	3.56 (0.28)	3.61 (0.28)	3.47 (0.32)	
Tang 2013a	55 Female	30.11	165.72	74.65			3.61 (0.23)	3.50 (0.21)	3.41 (0.24)
	52 Male	30.59	178.33	87.43			3.84 (0.23)	3.76 (0.23)	3.74 (0.31)
	107 F + M	30.35	171.79	80.98			3.72 (0.26)	3.63 (0.25)	3.57 (0.32)

					Frontal Diameter (cm) L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Postacchini et al. (1983)	63 Italian	Adult	-	-	4.3 (0.5)	4.4 (0.4)	4.7 (0.4)	4.9 (0.4)	
	58 Indian				3.7 (0.3)	4.0 (0.3)	4.1 (0.4)	4.3 (0.4)	
J. L. Berry et al. (1987)	30 F + M	50 to 79	-	-	4.77 (0.47)	4.96 (0.32)	5.12 (0.56)	5.34 (0.44)	
Aharinejad et al. (1990)	574 segments	-	-	-	4.16 (0.43)	4.77 (0.59)	5.25 (1.05)	5.45 (0.60)	
Panjabi et al. (1992)	4F + 8M	46.3	167.8	67.8	4.26 (0.07)	4.41 (0.09)	4.66 (0.12)	4.73 (0.12)	
Zhou et al. (2000)	71 Female	50	-	-		4.09 (0.36)	4.67 (0.47)	5.04 (0.44)	
	55 Male	49	-	-		4.61 (0.32)	5.08 (0.37)	5.45 (0.49)	
	F + M					4.32 (0.43)	4.85 (0.47)	5.22 (0.51)	
van der Houwen et al. (2010)	31 Female	49.8	-	-	3.3	3.47	3.77	3.81	
	46 Male				3.81	4.02	4.24	4.39	
Kang et al. (2011)	15 Female	41	161.2	53.4	3.73 (0.26)	4.07 (0.27)	4.38 (0.33)	4.97 (0.46)	
(Caliper/X-ray/CT, Healthy, Korean)	35 Male	39.8	170.6	70.5	4.38 (0.30)	4.63 (0.34)	4.81 (0.34)	5.48 (0.43)	
H. Chen et al. (2011)	40 Female	43	-	-	3.60 (0.28)	3.72 (0.34)			
	43 Male				4.14 (0.40)	4.24 (0.38)			
Y. Wang et al. (2012)	149 Male	under 64	-	-	5.03 (0.36)	5.15 (0.34)	5.36 (0.37)	5.23 (0.47)	
Tang 2013a	55 Female	30.11	165.72	74.65			4.85 (0.32)	5.01 (0.31)	4.96 (0.39)
	52 Male	30.59	178.33	87.43			5.26 (0.33)	5.44 (0.36)	5.42 (0.41)
	107 F + M	30.35	171.79	80.98			5.05 (0.38)	5.21 (0.40)	5.19 (0.46)

On the other hand, the value of these geometric data depends on the demographics of samples and the accuracy of measurements. With a relatively large sample size, the present study found that the range of geometric dimensions measured was substantial. Depending on the experimental design, investigations with a small sample size may not provide adequate representation of the overall spinal morphometry (Zhou et al., 2000), which unfortunately reduces the ability to directly compare geometric data among studies. Therefore, the review of previous morphometric studies may provide a general understanding of the spinal geometry such as the range of data. In addition, when geometric data were reported regarding multi-level spinal morphometry, cephalocaudal changes could be interpreted and compared across the similar studies, since the changes were relative to a single spinal column which could act as a control for itself.

It has been reported that ellipsoid approximation methods may underestimate the cross-sectional areas (CSAs) of the vertebral endplates (EPs) by 9% on average (Seidel et al., 2008) when mid-sagittal diameter was referenced as the minor axis. The present study corroborated that such methods significantly underestimated the CSAs of the L3/L4 and L4/L5 lumbar motion segments by 11% on average, but overestimated the CSAs of the L5/S1 IVDs and the adjacent cranial EPs by 2% on average. In addition, there is another approach using the anteroposterior diameter as the minor axis (Farfan, 1973; Brinckmann et al., 1989; Panjabi et al., 1992), which introduced the same pattern of systematic error that overestimated the CSAs at the lumbosacral level and underestimated the CSAs at the other two levels but with much less difference (2% on average) found in the present study.

Intervertebral discs

As shown in Table 3.39, the geometric dimensions of the intervertebral discs have been described for selected lower lumbar levels in a few cadaveric studies with relatively small sample sizes (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Porter et al., 1989), all of which only measured the cross-sectional area (CSA). Others measured the CSA *in vivo* by sampling spinal segments from L4/L5 to L5/S1 levels (Turk & Celan, 2004) or from L3/L4 to L5/S1 levels (Colombini et al., 1989) of segment with CT scans. Other than the present study, the only reference to the linear aspects of the spinal geometry was reported by Farfan (1973), which unfortunately did not disclose any subject demographics or measurement protocol. The present study was also the first to describe the lumbosacral disc with respect to the CSA and the diameters (anteroposterior and frontal diameters). Meanwhile, since the intervertebral discs with severe degeneration were excluded from the present study, the remaining intervertebral discs should be a relatively good representation of the general population.

Cross-sectional area

The present study identified that gender had a significant influence on the cross-sectional area (CSA) of the lower lumbar intervertebral disc. The review of literature reporting geometric data split for gender also revealed that male IVDs were consistently larger than the female ones (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982). However, since significant differences were reported in the subject height and weight, the influence of gender might be confounded with these factors. Colombini et al. (1989) found that body weight had better correlation with the CSA than body height did, despite that both had relatively lower correlation coefficients than other anthropometric

characteristics such as the wrist diameter. Unfortunately, even though their subjects presented a good range of heights (164 cm to 180 cm) and weights (70 kg to 91 kg), only 16 subjects were included in their study which may not be adequate to reveal any relationships with CSA. Additionally, Colombini et al. (1989) used the ellipsoid approximation method to calculate the CSA, which could introduce systematic error and compromise the findings. With a relatively large sample (40 subjects), Turk and Celan (2004) reported greater correlation coefficients of body height and weight to the CSA actually measured on CT scans.

The present study found that lumbosacral discs (L5/S1 IVDs) had significantly smaller cross-sectional areas (CSAs) than the L4/L5 IVDs by 7% and L3/L4 IVDs by 6%, corroborating Colombini et al. (1989). The present study found no significant difference between the L3/L4 and L4/L5 IVDs, contradicting Colombini et al. (1989) who reported a 5% increase. The geometric data reported by Turk and Celan (2004) exhibited a similar trend with L5/S1 IVDs smaller in CSA than the L4/L5 ones. Despite the fact that the present study did not report any significant difference in CSA between the L3/L4 and L4/L5 IVDs, the geometric data reported by Farfan (1973) and Hutton and Adams (1982) indicated large discrepancies, unfortunately both studies conducted no statistical analysis to further investigate possible relationships.

Compared to the literature (Figure 3.15), the present sample of subjects typically had smaller cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) as a group or as gender-specific groups. The present study had a relatively large sample (55 females and 52 males) with younger age (30 years on average), compared to the previous studies which used a relatively small sample of cadavers (Nachemson, 1960; Hansson et al.,

1980; Hutton & Adams, 1982; Porter et al., 1989), which were highly susceptible to post-mortem changes (e.g., lost of water content) (White III & Panjabi, 1990; Zhou et al., 2000) and the possible influence of preservation process which usually involves storage in freezing condition (Nachemson, 1960) or injection of preservation fluids (Brinckmann, 1986), and may not reflect the same geometric characteristics as healthy intervertebral discs *in vivo*. Secondly, it was noted that larger CSAs were more likely to be found in older IVDs (Nachemson, 1960; Hansson et al., 1980) compared to the younger ones (Porter et al., 1989), suggesting that aging process may be associated with the size of the intervertebral disc. It was noted that the present study reported similar CSAs for male IVDs to the geometric data reported by Turk and Celan (2004) regarding male patients with low back pain. Despite the difference of 10-years in average subject age, both studies measured the CSA regarding the actual shape of the IVDs. However, the geometric data reported by the present study was considerably smaller than that reported by Colombini et al. (1989), in which *in vivo* measurements were performed on CT scans, despite the fact that the both studies reported similar subject demographics regarding the body height (171.79 cm *vs.* 172.40 cm) and weight (80.98 kg *vs.* 77.40 kg). It should be noted that the difference could be even larger for the L3/L4 and L4/L5 IVDs since their data were calculated using an ellipsoid approximation method. However, it was noted that Colombini et al. (1989) only had 16 subjects and reported relatively large standard deviations for each CSA calculated, which indicates the effects of small sample size and perhaps less representative subjects. In addition, another possible explanation could be the determination of health status regarding the intervertebral discs themselves. Since Colombini et al. (1989) only mentioned the exclusion criteria vaguely as "no disc alterations" assessed on axial CT scans, one could

speculate that they may not have been able to determine the severity of disc degenerations properly with respect to the morphometric characteristics of the intradiscal space. In the present study, severely degenerated IVDs were excluded from the analyses.

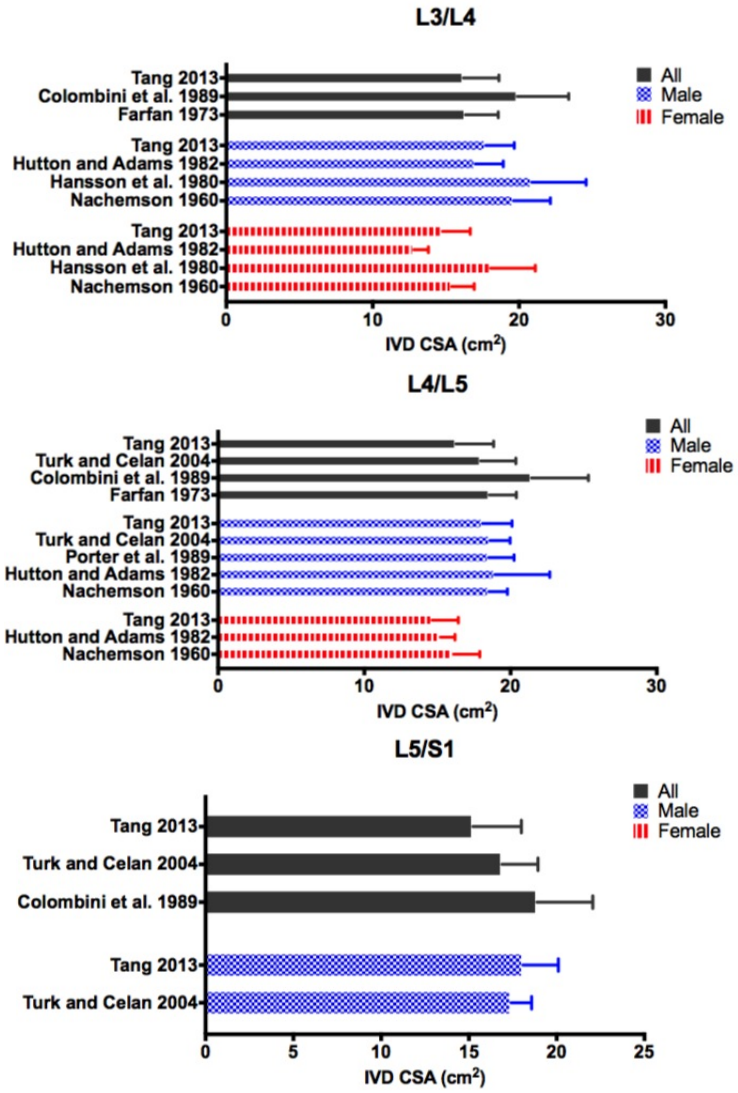


Figure 3.15: Cross-sectional area of the lumbar intervertebral discs at the L3/L4, L4/L5, and L5/S1 levels

Diameters in the transverse section

The present study may be the first to describe the linear geometry of the lumbosacral disc in the transverse section (as shown in Table 3.39). In general, males had larger

anteroposterior (APD) and frontal diameters (FD), corresponding to the larger cross-sectional area reported in male subjects. For the APDs, females exhibited significant decreases between the L5/S1 IVDs and the other two IVDs, while male IVDs had constant APDs across the lower lumbar spine. For the FDs, there was no significant cephalocaudal changes for both groups. Additional morphometric analyses also found no significant difference in ovality ratios across the lower lumbar spine, which indicate that even though the shape of lower lumbar IVDs was relatively constant, the craniocaudal decrease of CSA may be attributed to the decreasing APD.

It was also noted that other than the present study, only Farfan (1973) also reported the anteroposterior (APDs) and frontal diameters (FDs) of the L3/L4 and L4/L5 intervertebral discs (IVDs) among the previous studies. Hutton and Adams (1982) and Colombini et al. (1989) also measured these two dimensions since they both used the ellipsoid approximation method to calculate the cross-sectional area (CSA), but did not provide the results of their measurements. The diameters measured in the present study were similar to the data reported by Farfan (1973), however, the present study had a much larger sample of young subjects.

Vertebral endplates

As shown in Table 3.40 and Table 3.41, the geometric dimensions of the intervertebral discs have been described for selected lower lumbar levels in samples of cadavers with respect to the cross-sectional area (Brinckmann et al., 1989; Seidel et al., 2008), the linear diameters (Postacchini et al., 1983; J. L. Berry et al., 1987), and both aspects (Panjabi et al., 1992; Y. Wang et al., 2012). A number of studies also performed *in vivo* measurement

by sampling one or more spinal levels with radiographs (Nissan & Gilad, 1984; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999) and CT scans (Drerup et al., 1999; Zhou et al., 2000; van Schaik et al., 1985; van der Houwen et al., 2010; H. Chen et al., 2011). It was noted that the present study may be the first to comprehensively describe both the planar and linear aspects of the morphometry of the vertebral endplates adjacent to one IVD across the lower lumbar spine (from L3/L4 to L5/S1) using *in vivo* measurement on MR scans. Panjabi et al. (1992) measured the linear diameters of a small sample of cadaveric lower lumbar vertebrae, however the caudal endplate of the lumbosacral disc was not measured since it is located on the sacrum (S1 vertebra) and the cross-sectional area (CSA) was calculated using an ellipsoid approximation method. Y. Wang et al. (2012) also collected a large sample of cadavers and employed multiple approaches (e.g., caliper, x-ray, and laser scan) to measure the linear and planar aspects of the spinal geometry, and again did not include the caudal endplate of the L5/S1 IVDs.

Cross-sectional area

In accordance with Hall et al. (1998), the present study reported that male subjects had significantly larger CSAs of cranial and caudal endplates, corresponding to the larger CSAs of IVDs found in males. which could also be attributed to the significantly larger body height and weight associated with the males subjects. Geometric data reported by Brinckmann et al. (1989) and Zhou et al. (2000) also exhibited evidence of the influence of gender, yet no statistical analysis was performed.

With respect to the craniocaudal changes, the present study reported that the cross-sectional areas of the cranial endplates (CrEP_CSAs) were significantly smaller at the L5/S1 level, compared to the L3/L4 and L4/L5 levels with a 6% decrease on average,

corroborating similar decreases found by (Panjabi et al., 1992) (5% on average). Panjabi et al. (1992) had only 12 cadavers (4 females and 8 males) for measurement, yet reported geometric data with very small standard deviation, possibly due to the very small range in subject demographics (157 to 178 cm, 54 to 85 kg) compared to the present study (142 to 196 cm, 45 to 179 kg). Seidel et al. (2008) also reported that the CrEP_CSAs of L5/S1 IVDs were smaller than the ones of the L3/L4 and L4/L5 IVDs (6% on average), based on the actual measurement on CT scans of cadaveric lower lumbar segments obtained from a sample with similar ages (33.26 years) and weights (82.66 kg), but slightly taller heights (179.92 cm). The present study also found that when split by gender, female subjects exhibited significant decreases in CrEP_CSAs between the L3/L4 and L5/S1 IVDs and between the L4/L5 and L5/S1 IVDs. The changes in male IVDs, although not significant, were approaching the level of significance ($p=0.069$ and $p=0.098$). Y. Wang et al. (2012) measured 149 male cadavers of lumbar vertebrae and suggested similar evidence that CrEP_CSAs of the L5/S1 IVDs were considerably smaller than the ones of the L3/L4 and L4/L5 IVDs.

On the other hand, for the cross-sectional areas of the caudal endplates (CaEP_CSAs), the present study found no significant craniocaudal changes across the lower lumbar spine, in accordance with Panjabi et al. (1992) reporting almost identical CaEP_CSAs for the L3/L4 and L4/L5 IVDs. However, Seidel et al. (2008) reported a significant increase from the L3/L4 level to the L4/L5 level by 2%. Y. Wang et al. (2012) reported a large decrease (5%) from the L3/L4 level to the L4/L5 level, however no statistical analysis was performed to determine whether this decrease was significant or not.

With respect to a single-level lower lumbar motion segment, the present study reported significant differences in the cross-sectional area (CSA) between the two vertebral endplates (EPs) bordering the same disc. The caudal EPs were significantly larger than the cranial EPs across the three lower lumbar levels (p=0.000). Additionally, female subjects had more pronounced differences (12% on average) than the males (9%). In agreement with Seidel et al. (2008), the present study also reported significant differences in the CSAs regarding two EPs associated with each lumbar vertebra. Superior endplates of the L5 vertebrae were significantly larger than the inferior ones (12% on average), while only the female L4 vertebrae exhibited the same difference (11%). Geometric data reported by Y. Wang et al. (2012) exhibited evidence of a similar trend, however, the geometric data reported by Panjabi et al. (1992) exhibited a slight increase for the L4 lumbar vertebrae instead, which was also reported by Brinckmann et al. (1989) for the female L4 vertebrae. It should be noted that only speculation can be made regarding differences in spinal level geometries since the previous authors did not perform any statistical analyses. Unfortunately, the present study found very little in the literature regarding these trends to draw further comparisons.

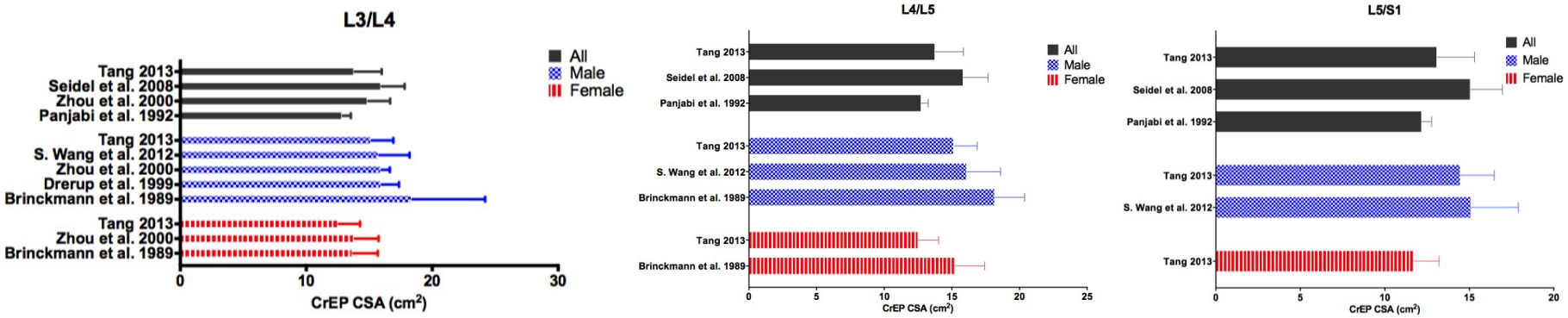
Meanwhile, some morphometric studies have also noted the cephalocaudal asymmetry associated with the vertebral endplates, particularly in the shape of the intradiscal spaces in sagittal sections (H. Chen et al., 2011; Lakshmanan et al., 2012). Several studies have indicated that the cranial EPs tend to be more concave in shape compared to the caudal ones which may be more flat across the lumbar spine (van der Houwen et al., 2010; Y. Wang et al., 2012), which may not be influenced by gender or age (H. Chen et al., 2011), but by disc degeneration (He et al., 2012). However, since it has been well

supported that the cranial endplate has higher bone mineral density than the corresponding caudal one (Y. Wang, Battié, Boyd, & Videman, 2011), it has been challenging to explain why mechanically stronger cranial endplates are more likely to be concave (Y. Wang et al., 2012), while more vertebral fractures have been found in the caudal endplate (Brinckmann et al., 1989; Adams et al., 2002; Zhao et al., 2009). With the results of present study, one could speculate that with larger cross-sectional area, the caudal endplate may contain a similar or larger amount of bone mineral content as the cranial endplate even with less bone mineral density, and possess greater mechanical capacities to withstand loads, since bone mineral content has also been found determine the ultimate strength of the spinal motion segment (Hansson et al., 1980; Biggemann et al., 1988; Gallagher et al., 2006, 2007). Unfortunately, our understanding is still very limited to explain the relationship between the morphometric characteristics and the mechanical behavior of the spinal motion segment. This remains an area requiring further research.

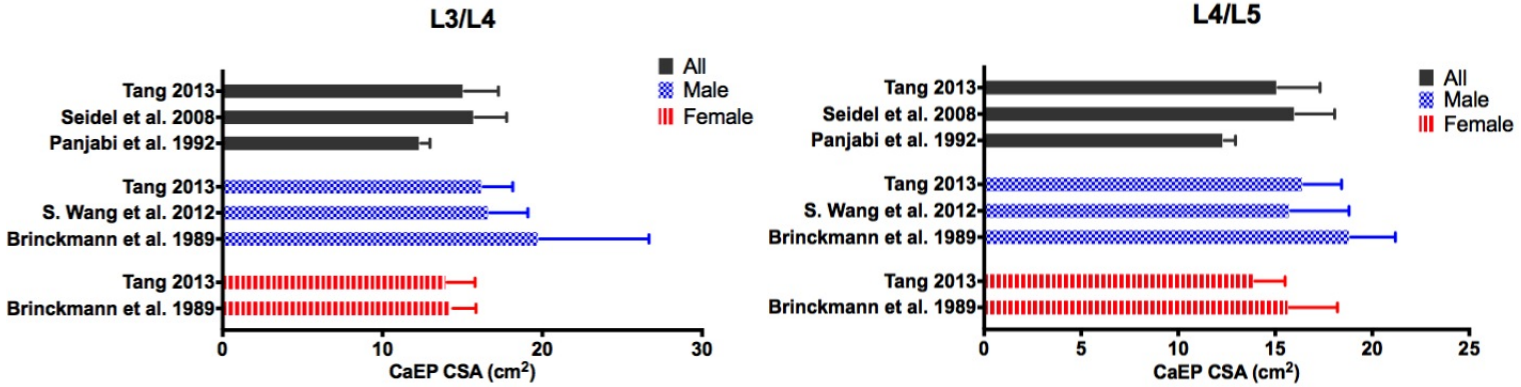
Compared to the literature (Figure 3.16), the present sample of subjects had smaller cross-sectional areas (CSAs) for both the cranial and caudal endplates, except for Panjabi et al. (1992). Compared to Panjabi et al. (1992), the present study had a larger sample size with much younger, slightly taller, and much heavier subjects and reported larger CSAs of both endplates. It should be noted that Panjabi et al. (1992) calculated the CSA using an ellipsoid approximation method which would underestimate the size of the EPs, therefore the differences may be smaller than the current ones. Similarly, the difference between the data reported by the present study and Seidel et al. (2008) may be related to systematic biases in data collection. Seidel et al. (2008) measured the geometric data on 53 cadavers without evaluating the pathological status of the segments, therefore the value of their data

was suspect as some pathological alterations would likely to result in an increase of size such as osteoporosis (Gilsanz et al., 1995). When split by gender, our data for males were fairly closed to some studies Y. Wang et al. (2012), even though their subjects were cadavers less than 64 years of age. Our data were relatively smaller than some studies (Drerup et al., 1999; Zhou et al., 2000). Both Drerup et al. (1999) and Zhou et al. (2000) had samples from an older population, which because of aging may exhibit larger cross-sectional area. However, compared to Brinckmann et al. (1989), our data were considerably smaller for both gender groups. Brinckmann et al. (1989) performed the measurement of diameters with a cadaver sample of male and female lower lumbar motion segments (50 years old on average), after the completion of ultimate compressive strength tests. According to Brinckmann et al. (1989), endplate failure was the most frequent failure mode for a lumbar motion segment, which may alter the geometric characteristics of the lumbar segment. Also, it should be noted that only three male segments at the L3/L4 level were available for mechanical test, hence a large standard deviation was reported. Therefore, their data may not be a good representation of living subjects.

Again, the present study may be the first to describe the cross-sectional area of the L5/S1 caudal endplate: 13.35 cm^2 for females, 15.93 cm^2 for males.



(a) Cross-sectional areas of the cranial endplates (CrEP_CSA)



(b) Cross-sectional areas of the caudal endplates (CaEP_CSA)

Figure 3.16: Comparison to the geometric data reported in the literature regarding the vertebral endplates

Diameters in the transverse section

The present study reported that gender significantly influenced the anteroposterior (APDs) and frontal diameters (FDs) of the two adjacent vertebral endplates (CrEP_APD, CrEP_FD, CaEP_APD, and CaEP_FD). In general, male endplates were significantly larger in all linear diameters (11% more in CrEP_APD, 10% more in CrEP_FD, 8% more in CaEP_APD, and 9% more in CaEP_FD), in accordance with van Schaik et al. (1985); Zhou et al. (2000); H. Chen et al. (2011). Unfortunately, these studies provided only age and gender and no further subject demographics, such as height and body weight as the present study did. Therefore, it was inconclusive whether the significant difference should be attributed to the influence of gender or other confounding factors.

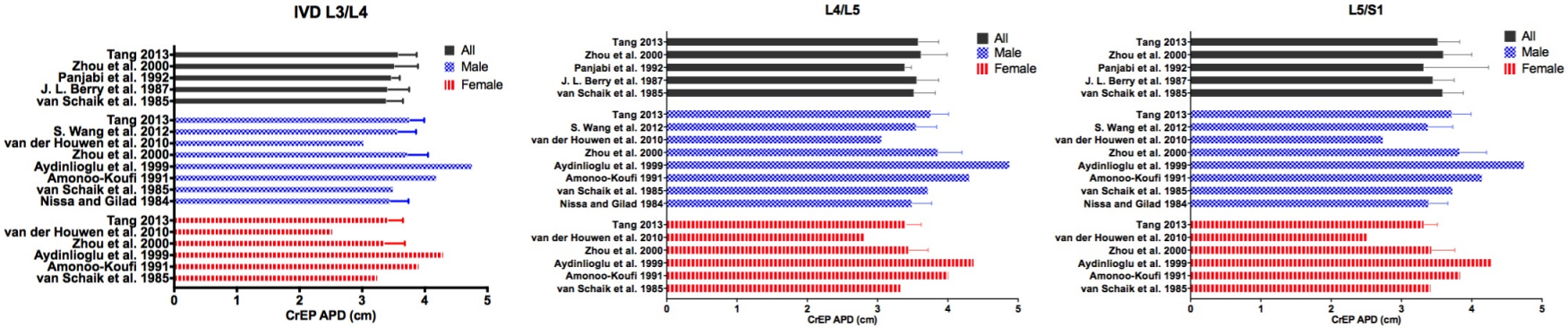
Secondly, the present study also noted that cephalocaudal changes were more pronounced in female subjects in the APDs of both EPs, and in the FDs of the CaEPs. Male subjects only had significant changes in the latter one (CaEP_FDs). In general, female L5/S1 IVDs had the smallest CrEP_APDs and CaEP_APDs, while female and male L3/L4 IVDs had the smallest CaEP_FDs. In the literature, there has been disagreement regarding the cephalocaudal changes. Nissan and Gilad (1984) also reported no cephalocaudal changes in APDs of EPs for male subjects, which were young and healthy. In the literature, a number of studies also reported significant cephalocaudal changes in both diameters (van Schaik et al., 1985; J. L. Berry et al., 1987; Aharinejad et al., 1990; Zhou et al., 2000), in the APDs (Twomey & Taylor, 1985, 1987), and in the FDs (Panjabi et al., 1992; van der Houwen et al., 2010; Y. Wang et al., 2012). It may be unwise to draw further conclusions since these studies differed in measurement modality (cadaver, x-ray, CT, and MRI) and definition of diameters in the anterior-posterior direction (mid-sagittal *vs.* anteroposterior).

However, the general comparison is helpful in understanding the morphometry of the lower lumbar endplates with respect to the range of geometric dimensions.

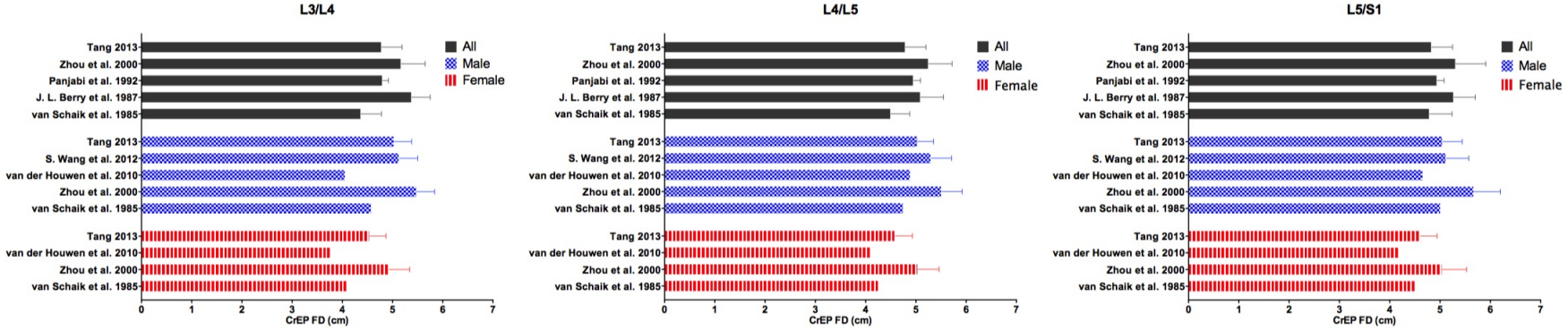
With respect to the shape of the vertebral endplate, the present study reported evidence that females may exhibit progressive changes in shape as the ovality ratio increases cephalocaudally for both cranial and caudal enplates, while males exhibited significant increase of ovality ratio only for the caudal endplate. van Schaik et al. (1985) also reported a significant increase in the ovality ratio of the cranial endplate from the L4/L5 to L5/S1 levels. Unlike van Schaik et al. (1985), the present study reported that the ovality ratio of caudal endplate was significantly greater in males at the L3/L4 level, rather than the cranial endplate. It was also revealed that the influence of gender on the shape (or configuration) of the endplates was weak, only significant at the L3/L4 level. Panjabi et al. (1992) also reported that the ovality ratio gradually increased for both endplates cephalocaudally. van der Houwen et al. (2010) also reported progressive increases in the frontal diameter while the mid-sagittal diameter remained relatively constant, which might indicate a difference in the configurations of the endplate across the lower lumbar spine.

Compared to the literature (Figure 3.17), the present geometric data appear consistent with other studies. However, it was noted that extreme values in CrEP_APDs were generally associated with two studies (Aydinlioglu et al., 1999; van der Houwen et al., 2010), and in CrEP_FDs with two studies (Zhou et al., 2000; van der Houwen et al., 2010). Aydinlioglu et al. (1999) reported remarkably large CrEP_APDs across the three lower lumbar levels, compared to the data reported by van der Houwen et al. (2010) which also reported the lowest CrEP_FD. Aydinlioglu et al. (1999) had a sample of 200 healthy subjects (93 female and 107 male) which may be a good representation, however, their

geometric data were highly susceptible to magnification error due to the mechanism of radiographic projection used to obtain their measurements (White III & Panjabi, 1990; Frobin et al., 1997), which may lead to larger geometric dimensions measured on the lateral radiographs. van der Houwen et al. (2010) had 77 patients with varying spinal problems (31 female and 46 male, 49.8 year of age) and only measured the diameters of intact vertebrae on CT scans. Rather than using traditional bony landmarks, their measurements were based on a series of coordinates arbitrarily defined by the authors. From their illustrated definitions, one would speculate that the bony landmarks identified for diameter measurements did not extend to the most peripheral border. Therefore, van der Houwen et al. (2010) reported smaller geometric data for both APD and FD. Zhou et al. (2000) measured the geometric dimensions using a patient group (50 years of age) with low back pain and varying degrees of disc degeneration, and only excluded cases with vertebral body abnormalities and pathologies, and therefore large dimensions could be the result of degenerative changes. Similar scenarios were also found regarding the caudal endplates, in which van der Houwen et al. (2010) reported smaller diameters (Figure 3.18). Unfortunately, a majority of the previous studies only reported measurement data and provided no or minimum subject demographics (age and gender), which may be inadequate to draw further comparisons.

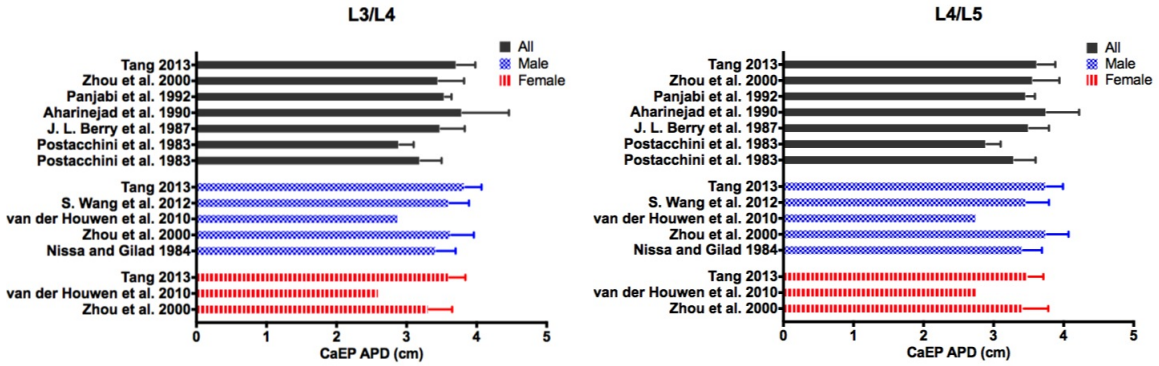


(a) Anteroposterior diameters of the cranial endplates (CrEP_APD)

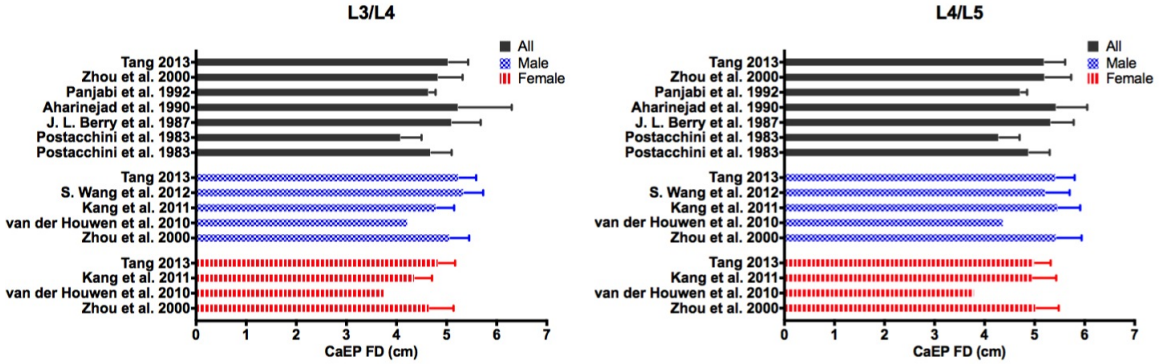


(b) Frontal diameters of the caudal endplates (CrEP_FD)

Figure 3.17: Comparison to the geometric data reported in the literature regarding the cranial vertebral endplates



(a) Anteroposterior diameters of the cranial endplates (CaEP_APD)



(b) Frontal diameters of the caudal endplates (CaEP_FD)

Figure 3.18: Comparison to the geometric data reported in the literature regarding the caudal vertebral endplates

3.5 Conclusion

The objective of the present study was to perform a morphometric analysis of the lower lumbar motion segment and establish a standardized protocol of future measurement of geometric dimensions, such as the cross-sectional area (CSA), anteroposterior diameter (APD), and frontal diameter (APD). Using MRI techniques, the present study was able to address the limitations in the literature after reviewing the previous studies and summarizing the geometric data. The present study more completely and consistently described the morphometric characteristics regarding the lower lumbar spine, which has

been lacking in the literature, particularly for the lumbosacral joint, achieving excellent measurement reliability. The present study also explored the effect of using an ellipsoid method to calculate the cross-sectional area of the lower lumbar discs and vertebral endplates and reported systematic error which was different from previous opinions.

The relatively large sample would help generate geometric data that have greater value to characterize the spinal morphometry for the general U.S. population, since our subject demographics well reflected an average U.S. adult (Female 162.05 cm and 73.57 kg; Male 176.02 cm and 88.68 kg), as reported by the National Center for Health Statistics (NCHS, 2012).

The present study found a significant influence of gender on spinal geometry, as male spinal segments were larger than female ones in both linear and planar aspects, which has been corroborated by a number of studies. Secondly, the present study also noted that significant cephalocaudal changes were evident, and appeared to be a function of gender. Although the present study failed to demonstrate definitively which lower lumbar level had the largest geometric dimensions, it was evident that L5/S1 IVDs had smaller geometric dimensions in general.

One study limitation is that all MR scans were collected from a medical database. Even though in the present study, MR scans were scrutinized to exclude patients with obvious spinal abnormalities and pathological diseases that might alter the spinal geometry and discs with severe degeneration were excluded, the present sample may not be a good representation of a healthy population. However, with the high prevalence of low back pain, it is difficult to define a "health" spine. Therefore, additional comparative study may be helpful to understand the differences in spinal morphometry between the healthy discs

of a patient and the discs of a healthy individual. Secondly, all MR scans were taken in supine position with minimal loading on the spine. The morphometric characteristics of the spine in the transverse section may be different once the subject is in standing posture. Currently, there is very limited knowledge regarding the correlation between spinal geometry and spinal loading (Botsford et al., 1994; LeBlanc et al., 1994; Kimura et al., 2001).

Future studies should investigate the influence of height and weight, rather than age alone, which might provide better understanding of the difference between reported geometric data associated with different subject demographic and anthropometric characteristics. Secondly, more research effort should address the asymmetry between vertebral endplates which might help improve the understanding of relationships between the spinal morphometry and the mechanical behavior of the spinal motion segments. Thirdly, the influence of unloading the spine (e.g., the supine position used to collect MR data) should be investigated to determine whether changes in spinal morphometry are significant or not. Additional research to relate supine data with standing data should be conducted to make these geometries more applicable for biomechanical analyses.

Chapter 4

PREDICTION OF THE CROSS-SECTIONAL AREA OF HUMAN LOWER LUMBAR INTERVERTEBRAL DISC AND VERTEBRAL ENDPLATE: REGRESSION MODELS OF GEOMETRIC DIMENSIONS DERIVED FROM ARCHIVED MR SCANS

The manuscript in the following pages is in preparation for submission to a peer-reviewed academic journal.

Prediction of the morphometry of human lower lumbar intervertebral disc and vertebral endplate: regression models of geometric dimensions derived from archived MR scans

4.1 Introduction

One of the most challenging issues in occupational ergonomics and health practices has been the reliable estimation of risks of work-related musculoskeletal disorders (WMSDs), particularly low back pain and injuries (Andersson, 1979; Garg & Moore, 1992; Andersson, 1998). The majority of the research effort to date has been devoted to the development of evaluation tools or measures that are intended to pinpoint jobs with an elevated risk of the work-related low back pain (WRLBP) (NIOSH, 1981; Chaffin, 1988; Marras & Sommerich, 1991a, 1991b; Waters et al., 1993; Bloswick & Villanve, 2000). These evaluation tools or measures primarily rely on biomechanical models of the musculoskeletal structure of the human spine to estimate the internal response in terms of muscle induced compressive forces and to characterize the risk associated with the postures, the magnitude of loading, and the physiology of forceful motions. To date, a number of biomechanical models have been developed to describe the musculature related to spinal motions, such as sagittal extension and lateral bending (A. B. Schultz, Andersson, Haderspeck, et al., 1982; A. B. Schultz, Andersson, Ortengren, Haderspeck, & Nachemson, 1982; McGill & Norman, 1985; Németh & Ohlsén, 1986; Chaffin, 1988; Jorgensen et al., 2001; Marras et al., 2001). Contrary to the well developed models of human trunk musculature, the significance of the morphometry of the human spine has not yet been thoroughly investigated the development of biomechanical models, even though a few studies have reported some

geometric data to characterize spinal geometry in the sagittal (Fisher, 1967; Sicard & Gagnon, 1993; Y. L. Chen, 1999) and frontal planes (Nussbaum & Chaffin, 1996). Morphometric representations of the human spine have been employed as critical inputs in mathematical models to characterize the biomechanical behavior of the human spine in different postures and under forceful loadings by translating external loadings into the internal response of the lumbar spine (Chaffin, 1969; Campbell-Kyureghyan et al., 2005). The model output, as muscle induced compressive forces, is then related to the ultimate strength of the lumbar structures typically obtained by testing one motion segment per spinal level (F. G. Evans & Lissner, 1959; Sonoda, 1962; Eie, 1966; Hutton & Adams, 1982; Jager & Luttmann, 1989), which leads to the determination of risks of the WLBDs (Chaffin & Park, 1973; NIOSH, 1981; Waters et al., 1993). As a major component of a single-level motion segment, the intervertebral disc (IVD) connects two vertebral bodies together, forming the main joints of the spinal column and providing spine the mechanical properties necessary to perform complex movements, such as flexion and rotation (S. J. Ferguson & Steffen, 2003; Raj, 2008). The mechanical properties of the IVD are largely determined by its structural integrity in terms of the mode and magnitude of loading transmitted from one segment to another (Adams & Hutton, 1981; Adams et al., 1980). A number of studies have reported that the size of a motion segment in the transverse section has great influence on its ultimate compressive strength along with bone mineral density (BMD) (Biggemann et al., 1988; Brinckmann et al., 1989; Singer et al., 1995). With porcine cadavers, it has been reported that the cross-sectional area (CSA) of the vertebral endplate alone can be used to predict the ultimate compressive strength of a spinal motion segment (Parkinson et al., 2005). This evidence suggests the necessity to

account for spinal geometry when determining the risk of injury. More importantly, it may become possible to actually estimate the risk on an individual level, rather than on a population basis. Evaluation of job activities on an individual basis might help change the paradigm of evaluations for the WLBDs and provide more personalized risk estimation.

During recent decades, finite element models (FEM) have been performed to better characterize the biomechanics of the lumbar spine. To date, numerous complex FEMs have been developed to simulate the internal loading conditions of the lumbar spine and investigate the influence of spinal motions, postures, and forceful loadings on the spinal structures with respect to potential tissue damages and pathological alterations (Nerurkar et al., 2010; Chan et al., 2011). As geometric data exert a noticeable influence on the output behavior of the lumbar spine (Robin et al., 1994; Lu et al., 1996; Natarajan & Andersson, 1999; Noailly et al., 2007; Niemeyer et al., 2012), FEMs require specific geometric data of the elements to characterize their mechanical behavior and the influences of spinal motions and forceful loadings on spinal structures using models for a single-level motion segment (Natarajan et al., 1994; Martinez et al., 1997; Natarajan et al., 2008; Y. Schroeder et al., 2010) and models for multi-level motion segments (Zander et al., 2001; Noailly et al., 2005, 2007; Schmidt et al., 2007; Rohlmann et al., 2008; Arjmand et al., 2009; Rohlmann et al., 2009; Kuo et al., 2010; K. S. Han et al., 2011).

Unfortunately, the morphometry of the human lumbar spine in transverse section has typically been obtained, *ex vivo* through cadaveric specimens (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Postacchini et al., 1983; J. L. Berry et al., 1987; Brinckmann et al., 1989; Panjabi et al., 1992) and *in vivo* primarily through the reconstruction of medical images, including radiographs (Nissan & Gilad, 1984;

Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999; Y. Wang et al., 2012), computed tomography (van Schaik et al., 1985; Colombini et al., 1989; Zhou et al., 2000; van der Houwen et al., 2010; H. Chen et al., 2011), and magnetic resonance imaging (Aharinejad et al., 1990). These techniques can provide accurate morphometric assessment. However, they also require very restrictive measurement protocols and considerably high cost associated with the medical imaging usage. It may be financially impractical to rely on these techniques to determine an individual's specific spinal morphometry when evaluating the personalized risk of low back pain. Secondly, the majority of the previous studies only documented the subject gender and age, and provide no further information regarding the subject height and weight. It is very difficult to compare their data and draw valid conclusions, since evidence has been reported that some anthropometric characteristics are significantly correlated with the size of the lumbar motion segment (Colombini et al., 1989; Turk & Celan, 2004). More importantly, in the presence of strong statistical correlation, it is possible to estimate the cross-sectional area of the lumbar motion segment using statistical regression models (Colombini et al., 1989; Turk & Celan, 2004).

The aim of this study was to perform regression analyses with geometric data measured on MR scans to generate prediction equations for the cross-sectional areas (CSAs) of the human lower lumbar motion segments from the L3/L4 to L5/S1 level.

4.2 Material and methods

4.2.1 Acquisition of MRI-derived geometric dimensions

Morphometric data regarding the cross-sectional area (CSA) were collected from the previous study (described in Chapter 3). The subjects with missing height data were excluded from the final regression analysis. Approval of the research protocol and experimental design was obtained by the Institutional Review Boards (IRBs) at both participating institutions (University of Utah and Auburn University, Appendix A). In total, 79 subjects (41 females and 38 males) were included in the present study, where the morphometric data for 59 subjects (32 females and 27 males) were used for regression model development, and the data from 20 subjects (9 females and 11 males) were used for model validation. All subjects were randomly selected from the database. Body mass index (BMI) was calculated using subject's body height and weight, and then classified into four body composition levels: 1) **underweight**, less than 18.5 kg/m^2; 2) **normal**, between 18.5 kg/m^2 and 25.0 kg/m^2; 3) **overweight**, between 25.1 kg/m^2 and 29.9 kg/m^2; and 4) **obese**, greater than 30.0 kg/m^2.

Table 4.1 summarizes the detailed descriptive statistics for the subjects' demographic data with respect to the two subgroups. There was no statistically significant difference in subject variables (anthropometric characteristics) between the "model development" subgroup and the "model validation" subgroup ($p>0.05$). On average, subjects in both subgroups were identified as "overweight" ($25\ kg/m^2<BMI<30 kg/m^2$).

Table 4.1: Demographic data of anthropometric characteristics

			N	Mean	SD	Min	Max	t	df	Sig.
Age (years)	Female	Development	32	29.0	5.6	21	39	-1.998	39	0.053
		Validation	9	33.0	3.9	26	38			
	Male	Development	27	30.3	5.8	21	39	0.348	36	0.730
		Validation	11	29.6	5.0	21	36			
	Total	Development	59	29.6	5.7	21	39	-1.086	77	0.281
		Validation	20	31.2	4.8	21	38			
Ht (cm)	Female	Development	32	165.58	9.77	142.20	195.60	-0.177	39	0.860
		Validation	9	166.22	8.82	147.30	175.30			
	Male	Development	27	178.55	10.08	157.50	200.70	0.221	36	0.826
		Validation	11	177.80	7.53	165.10	193.00			
	Total	Development	59	171.51	11.79	142.20	200.70	-0.366	77	0.715
		Validation	20	172.59	9.88	147.30	193.00			
Wt (kg)	Female	Development	32	72.46	20.05	45.36	131.54	-0.381	39	0.705
		Validation	9	75.30	18.37	54.43	102.06			
	Male	Development	27	89.96	22.09	65.77	178.71	1.881	36	0.068
		Validation	11	76.66	11.77	58.06	90.72			
	Total	Development	59	80.47	22.61	45.36	178.71	0.817	77	0.417
		Validation	20	76.05	14.68	54.43	102.06			
BMI (kg/m^2)	Female	Development	32	26.49	7.43	19.05	45.37	-0.313	39	0.756
		Validation	9	27.36	6.69	19.38	36.33			
	Male	Development	27	28.14	5.87	22.32	51.99	1.987	36	0.055
		Validation	11	24.31	3.92	17.86	30.62			
	Total	Development	59	27.25	6.75	19.05	51.99	0.941	77	0.350
		Validation	20	25.68	5.42	17.86	36.33			

4.2.2 Model development

There were two major steps of statistical analyses performed to develop the regression model, including preliminary analysis and regression analysis. All statistical analyses were performed using SPSS statistics package (v.19.0 IBM SPSS Statistics, IBM Corporation, Armonk, NY). The level of significance (α) was set at 0.05.

Preliminary analysis

During the preliminary analysis, outlier detection in the dependent variable set was performed using Tukey's outlier labeling method. Regression models are very sensitive to extreme values (outliers) within the dataset. The presence of outliers could affect the normality of the dataset and prevent parametric statistical analysis, such as regression analysis. Secondly, many statistical tests rely on the assumption that data are normally distributed to provide valid parametric analysis. In the present study, Kolmogorov-Smirnov (K-S) and Shapiro-Wilk tests were performed for the normality of the geometric data (dependent variables). According to Razali and Wah (2011), the Shapiro-Wilk test is more powerful for small sample sizes (around 50) than the Kolmogorov-Smirnov test. Therefore, judgements about the normality of geometric data were based on the results of Shapiro-Wilk tests. In addition, skewness and kurtosis were also analyzed to characterize the shape and symmetry of geometric data distribution. The skewness of a distribution detects how much its shape is deviating from a symmetrical shape. The kurtosis of a distribution refers to its peakedness or flatness, whether is high and sharp or short and broad.

Regression analysis

The present study evaluated the performance of regression models developed by linear and polynomial methods. **Responses (dependent variables)** of the prediction equation were the cross-sectional area of the intervertebral disc (IVD_CSA), the cranial endplate (CrEP_CSA), and the caudal endplate (CaEP_CSA).

Linear method

Predictors (independent variables) included 4 linear terms, including gender (G), age (A), height (Ht), and body weight (Wt). Body mass index (BMI), owing to its definition, is highly correlated with height and weight. Therefore, it is excluded from the predictor list to avoid further multicollinearity issues. Correlation coefficients were determined among the independent (linear term predictors) and dependent (responses) variables at each lower lumbar level (from L3/L4 to L5/S1).

Backward regression analyses were performed to determine the prediction equations for the cross-sectional area of the intervertebral disc (IVD_CSA), the cranial endplate (CrEP_CSA), and the caudal endplate (CaEP_CSA). At each lower lumbar level (from L3/L4 to L5/S1), three equations were developed for dependent variables (Y_{IVD_CSA}, Y_{CrEP_CSA}, and Y_{CaEP_CSA}), respectively, with the independent variables: gender (X_G), age (X_A), height (X_H), and body weight (X_W). The "use of probability of F" was selected as 0.05 for entry, and 0.0501 for removal of the predictor when using the statistical analysis software package. The prediction equation for each response is listed below (Formula 4.1).

$$Y_{ij\_CSA} = \alpha_{ij\_0} + \alpha_{ij\_G} X_G + \alpha_{ij\_A} X_A + \alpha_{ij\_H} X_H + \alpha_{ij\_W} X_W + \epsilon_{ij} \tag{4.1}$$

where i stands for the L3/L4, L4/L5, and L5/S1 level, and j stands for the intervertebral disc (IVD), cranial endplate (CrEP), and caudal endplate (CaEP); α_{ij_0} is the constant, α_{ij}'s are the coefficient of the independent variables and ϵ_{ij} is the unknown true error term.

Polynomial method

To investigate the effectiveness of polynomial regression methods, artificial variables were derived from the four original independent variables (height, body weight, age, and gender) to obtain quadratic terms, cubic terms, square terms. The artificial variables included in the polynomial regression analysis are listed in Table 4.2. Polynomial methods were also employed using backward regression analysis to explore the level of significance of these artificial variables and the linear terms to predict the cross-sectional area of the intervertebral disc (IVD_CSA), the cranial endplate (CrEP_CSA), and the caudal endplate (CaEP_CSA). At each lower lumbar level (from L3/L4 to L5/S1), three prediction equations were developed for the dependent variables (Y_{IVD_CSA}, Y_{CrEP_CSA}, and Y_{CaEP_CSA}), respectively.

Table 4.2: Predictor list for polynomial regression analysis

	Artificial Variables
Quadratic terms	Ht^4, Wt^4, A^4, G^4, Ht^3Wt, Ht^3A, Ht^3G, Ht^2Wt^2, Ht^2A^2, Ht^2G^2, Ht^2WtA, Ht^2WtG, Ht^2AG, $HtWt^3$, HtA^3, HtG^3, $HtWt^2A$, $HtWt^2G$, $HtWtA^2$, $HtWtG^2$, HtA^2G, $HtAG^2$, $HtWtAG$, Wt^3A, Wt^3G, Wt^2A^2, Wt^2G^2, Wt^2AG, WtA^2G, $WtAG^2$, WtA^3, WtG^3, A^3G, A^2G^2, AG^3
Cubic terms	Ht^3, Wt^3, A^3, G^3, Ht^2Wt, Ht^2A, Ht^2G, $HtWt^2$, HtA^2, HtG^2, $HtWtA$, $HtWtG$, $HtAG$, Wt^2A, Wt^2G, $WtAG$, WtA^2, WtG^2, A^2G, AG^2
Square terms	Ht^2, Wt^2, A^2, G^2 $HtWt$, HtA, HtG, WtA, WtG, AG
Linear terms	Ht, Wt, A, G

Model diagnosis

ANOVA tests were performed to determine the significance of each prediction equation developed by linear and polynomial methods. Variance inflation factor (VIF) was also used to detect the presence of multicollinearity among the predictors, which occurs

when two or more predictors are correlated and provide redundant information about the response. The presence of high multicollinearity can increase the standard error of estimates of coefficients associated with predictors and lead to decreased reliability and misleading results.

For linear models, residuals, defined as the difference between the "measured" and the "predicted" value, were plotted to verify the principal assumptions for linearity and constant variance (homoscedasticity), and analyzed to verify the principal assumption of normality. Outliers in residual error were also detected, since their presence may jeopardize the normality of the overall sample residual. New linear regression models (adjusted) were developed, since the exclusion of the "measured" data corresponding to the outliers can improve a model's ability to explain variance within the dependent varaibles. Necessary iterations of model diagnosis were performed to ensure the linearity, homoscedasticity, and normality of the residuals.

The preference of method (linear or polynomial) to predict the cross-sectional area of the lumbar motion segment was based on which method 1) provides more consistent results of predictor selection that can help understand the relationships between the predictors and the responses, and 2) provides regression model that has greater capability to explain the variance in the spinal morphometry.

4.2.3 Model validation

Prediction equations developed by the preferred regression method were applied to estimate the cross-sectional areas (CSAs) of the lower lumbar intervertebral disc and the adjacent cranial and caudal endplates of the 20 random subjects. Paired sample t tests

were performed to analyze the level of significance for the differences between the "measured" and "predicted" value. Absolute error terms were calculated to depict the difference between the "measured" and "predicted" values to analyze the actual effectiveness of the prediction equations.

4.3 Results

4.3.1 Preliminary analysis

Outlier detection on the dependent variables

The outlier detection was performed in the present study in accordance with the method proposed by Tukey (1977) (Formula 4.2)

$$Y<(Q1 - 1.5 \times IQR) \qquad or \qquad Y>(Q3 + 1.5 \times IQR) \tag{4.2}$$

where Q1 denotes the lower quartile (25^{th}), Q3 denotes the upper quartile (75^{th}), and IQR = (Q3 - Q1) denotes the interquartile range.

As shown in Table 4.3, outlier detection suggested that two outliers of the IVD_CSA, one outlier of the CrEP_CSA, and two outliers of the CaEP_CSA, all of which were associated with male subject at the L5/S1 level.

Table 4.3: Outliers in morphometric data at each lower lumbar level

	Subject Number		
Dimension	L3/L4	L4/L5	L5/S1
CrEP_CSA			M18
IVD_CSA			M18, M89
CaEP_CSA			M18, M89

Outliers of the geometric data detected were associated with two male subjects for the L5/S1 level, as shown in Table 4.4, which were then removed from the dataset for regression analysis. Descriptive statistics are provided regarding the mean, standard deviation, and range of data, split by subgroups for model development (Table 4.5) and model validation (Table 4.6), respectively. It was noted that the sample size of geometric data was different at both L4/L5 and L5/S1 levels, due to missing data from the database, particularly for the vertebral endplates at the L5/S1 level.

Table 4.4: Demographic data of subjects producing outliers in geometry data

Subject	Gender	Ht (cm)	Wt (kg)	Age (years)	BMI	L5/S1		
						CrEP CSA	IVD CSA	CaEP CSA
M18	M	180.30	58.06	32	17.86	20.45 cm^2	22.98 cm^2	22.13 cm^2
M89	M	193.00	90.72	33	24.36		22.50 cm^2	22.46 cm^2

Normality tests

Table 4.7 lists the results of Kolmogorov-Smirnov and Shapiro-Wilk tests. Both tests indicated that geometric data regarding the intervertebral disc and vertebral endplates included in the present study had significance level greater than 0.05 across the lower lumbar levels. Therefore, it was concluded that all geometric data (dependent variables) were normally distributed. Hence, it was valid to process the geometric data with parametric regression analyses.

In addition to numeric tests, normal quartile-quartile (Q-Q) plots also provide a graphical alternative to assess the normality. Normal Q-Q plots for the CrEP_CSA, IVD_CSA, and CaEP_CSA were drawn for each lower lumbar level (L3/L4 to L5/S1), as illustrated in Figure 4.1. The data points, in general, exhibited linear plot for every

Table 4.5: Descriptive statistics of morphometric data for ***model development***

			N	Mean	SD	Min	Max
L3/L4	CrEP_CSA	Female	32	12.68	1.96	9.77	17.74
		Male	27	15.08	1.82	11.52	19.14
		Total	59	13.78	2.23	9.77	19.14
	IVD_CSA	Female	32	14.87	2.18	11.48	20.82
		Male	27	17.64	2.26	13.59	22.51
		Total	59	16.14	2.60	11.48	22.51
	CaEP_CSA	Female	32	14.14	2.00	10.36	20.00
		Male	27	16.16	1.98	11.61	19.94
		Total	59	15.06	2.22	10.36	20.00
L4/L5	CrEP_CSA	Female	33	12.53	1.70	9.90	15.95
		Male	26	15.06	1.64	11.96	18.79
		Total	59	13.65	2.09	9.90	18.79
	IVD_CSA	Female	33	14.63	1.98	10.63	18.36
		Male	26	17.99	2.14	13.78	22.17
		Total	59	16.11	2.64	10.63	22.17
	CaEP_CSA	Female	33	13.92	1.67	10.46	17.31
		Male	26	16.40	2.23	12.37	20.50
		Total	59	15.02	2.29	10.46	20.50
L5/S1	CrEP_CSA	Female	23	11.81	1.53	9.25	15.11
		Male	19	13.87	1.49	11.32	17.36
		Total	42	12.75	1.82	9.25	17.36
	IVD_CSA	Female	33	13.50	2.07	10.21	17.95
		Male	24	16.30	1.63	13.15	19.37
		Total	57	14.68	2.34	10.21	19.37
	CaEP_CSA	Female	23	13.69	1.92	10.32	17.60
		Male	19	14.88	1.55	12.26	17.78
		Total	42	14.23	1.84	10.32	17.78

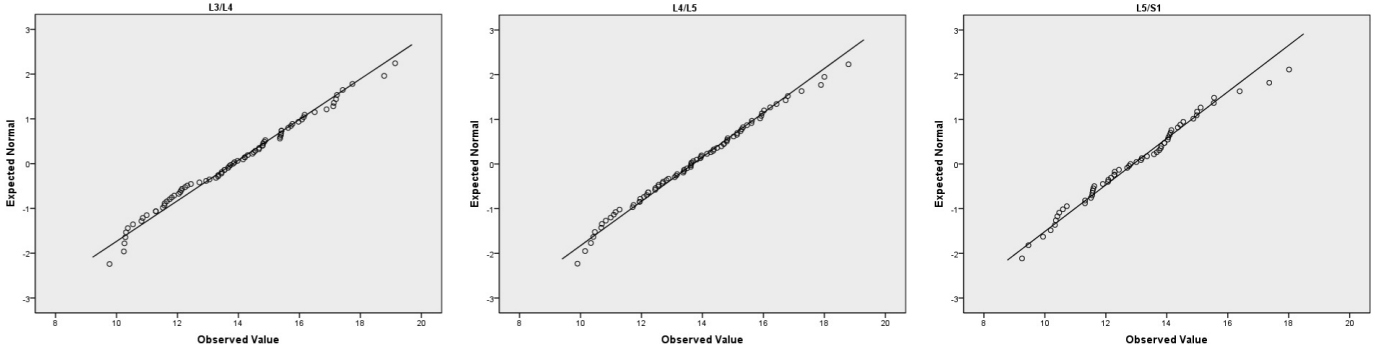
dependent variable at each lower lumbar level. Normal distribution was concluded based on the graphical representation.

Table 4.6: Descriptive statistics of morphometric data for ***model validation***

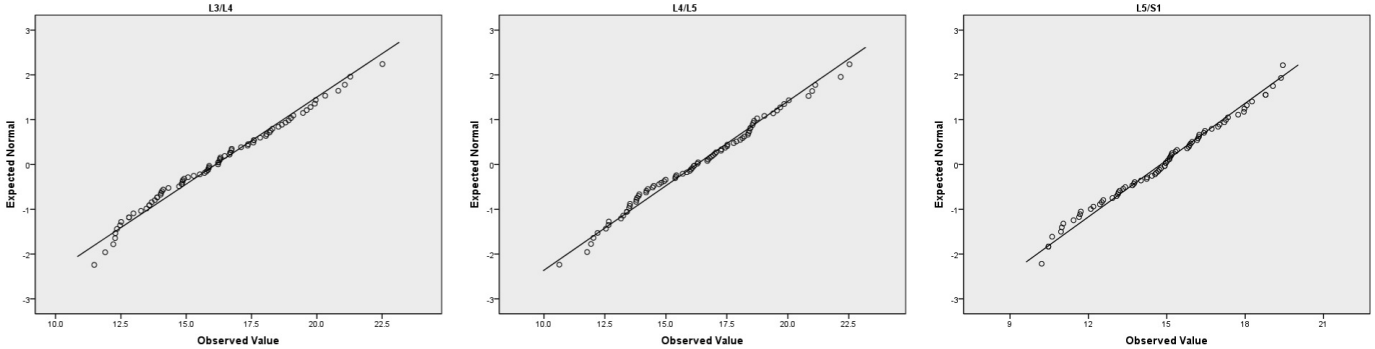
			N	Mean	SD	Min	Max
L3/L4	CrEP_CSA	Female	9	12.25	1.11	10.82	13.74
		Male	11	15.38	1.76	13.54	18.78
		Total	20	13.97	2.17	10.82	18.78
	IVD_CSA	Female	9	13.90	1.30	12.29	15.83
		Male	11	17.90	1.78	14.86	21.28
		Total	20	16.10	2.56	12.29	21.28
	CaEP_CSA	Female	9	13.44	1.01	12.02	15.16
		Male	11	16.65	2.09	14.13	19.92
		Total	20	15.21	2.33	12.02	19.92
L4/L5	CrEP_CSA	Female	8	12.48	1.04	10.99	13.64
		Male	10	14.88	1.59	12.55	18.00
		Total	18	13.81	1.81	10.99	18.00
	IVD_CSA	Female	8	14.26	1.18	12.54	16.08
		Male	11	18.52	1.93	15.98	22.53
		Total	19	16.73	2.70	12.54	22.53
	CaEP_CSA	Female	8	13.62	1.10	11.65	14.70
		Male	11	17.00	1.90	14.58	21.04
		Total	19	15.58	2.33	11.65	21.04
L5/S1	CrEP_CSA	Female	6	11.39	0.97	10.19	12.76
		Male	9	14.62	1.76	12.17	18.01
		Total	15	13.33	2.19	10.19	18.01
	IVD_CSA	Female	8	13.00	1.35	10.95	14.92
		Male	9	16.91	1.65	15.03	19.44
		Total	17	15.07	2.49	10.95	19.44
	CaEP_CSA	Female	6	12.63	1.46	10.51	14.40
		Male	8	16.04	1.98	13.65	18.73
		Total	14	14.58	2.45	10.51	18.73

Table 4.7: Results of normality tests

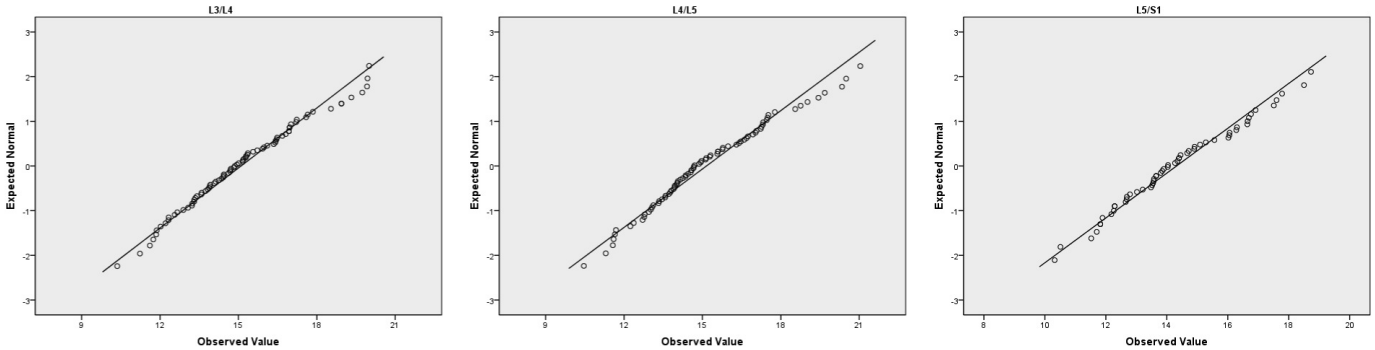
		Kolmogorov-Smirnova			Shapiro-Wilk		
Level	Geometry	Statistic	df	Sig.	Statistic	df	Sig.
L3/L4	CrEP_CSA	0.069	79	0.200	0.981	79	0.279
	IVD_CSA	0.074	79	0.200	0.980	79	0.236
	CaEP_CSA	0.074	79	0.200	0.979	79	0.228
L4/L5	CrEP_CSA	0.039	77	0.200	0.987	77	0.613
	IVD_CSA	0.069	78	0.200	0.985	78	0.503
	CaEP_CSA	0.091	78	0.175	0.976	78	0.146
L5/S1	CrEP_CSA	0.063	57	0.200	0.982	57	0.541
	IVD_CSA	0.058	74	0.200	0.980	74	0.288
	CaEP_CSA	0.080	56	0.200	0.980	56	0.460



(a) CrEP_CSA (left to right: L3/L4, L4/L5, and L5/S1)



(b) CrEP_CSA (left to right: L3/L4, L4/L5, and L5/S1)



(c) CrEP_CSA (left to right: L3/L4, L4/L5, and L5/S1)

Figure 4.1: Normal quantile-quantile (Q-Q) plots of the morphometric data

Skewness and Kurtosis

Table 4.8 provides the skewness and kurtosis of the geometric data. Since all skewness values fell within the range from -0.5 to +0.5 for each dependent variable, it was concluded that the skewness of the data was relatively low, and the distribution was approximately symmetric. When skewness is positive, the distribution of data is positively skewed (or "right-skewed"), exhibiting a longer right tail. A negative values indicates a "left-skewed" distribution.

As for the kurtosis of the geometric data, all values were within -3 and +3 for each dependent variable, therefore it was concluded that the kurtosis was not significant and the data distribution was approximately normal (mesokurtic). A data distribution with positive kurtosis (leptokurtic) has a more acute peak around the mean and flatter tails, while a distribution with negative kurtosis (platykurtic) has a lower, wider peak around the mean and thinner tails.

Table 4.8: Skewness and kurtosis of the morphometric data

		Skewness		Kurtosis	
		Statistic	Std. Error	Statistic	Std. Error
L3/L4	CrEP_CSA	0.166	0.271	-0.606	0.535
	IVD_CSA	0.255	0.271	-0.646	0.535
	CaEP_CSA	0.338	0.271	-0.335	0.535
L4/L5	CrEP_CSA	0.198	0.274	-0.407	0.541
	IVD_CSA	0.156	0.272	-0.565	0.538
	CaEP_CSA	0.481	0.272	-0.082	0.538
L5/S1	CrEP_CSA	0.306	0.316	-0.054	0.623
	IVD_CSA	-0.038	0.279	-0.664	0.552
	CaEP_CSA	0.264	0.319	-0.506	0.628

4.3.2 Regression analysis

Linear method

Correlations among the predictors and the cross-sectional area (CSA) of the intervertebral disc and adjacent endplates are given in Table 4.9. At the L3/L4 and L4/L5 levels, significant correlations were found between all responses (IVD_CSA, CrEP_CSA, and CaEP_CSA) and all predictors ($p<0.05$) except for age ($p>0.05$). At the L5/S1 level, IVD_CSA was significantly correlated with all predictors except for age ($p=0.545$) and both CrEP_CSA and CaEP_CSA were significantly correlated with gender ($p<0.05$) and height ($p=0.000$), rather than age ($p>0.05$) and weight ($p>0.05$). Among the predictors, gender was significantly correlated with subject height ($p=0.000$) and weight ($p=0.002$). Subject height was significantly correlated with weight ($p=0.000$). Subject age was not correlated with other predictors ($p>0.05$).

Prediction equation

ANOVA tests (Table 4.10) indicated that all regression models (9 in total) were significant ($p=0.000$), which indicated that each response (dependent variable) can be estimated by the predictors and that at least one predictor should be included in the model to explain the variability in the cross-sectional area of the lower lumbar spine.

The results of the regression analyses are given in Table 4.11. At the L3/L4 level, four iterations of regression analysis were performed for each prediction model (CrEP_CSA, IVD_CSA, and CaEP_CSA), which removed subject age, body weight, and gender in sequence, leaving subject height as the only significant predictor ($p=0.000$). At the L4/L5 and L5/S1 levels, three iterations of regression analysis were performed for the models of

Table 4.9: Correlation among the predictors and the IVD_CSA, CrEP_CSA, and CaEP_CSA

			IVD_CSA	CaEP_CSA	Gender	Age	Height	Weight
L3/L4	CrEP_CSA	Pearson Correlation	0.880	0.866	0.539	0.056	0.704	0.469
		Sig.	***0.000*****	***0.000*****	***0.000*****	0.675	***0.000*****	***0.000*****
	IVD_CSA	Pearson Correlation		0.930	0.534	0.007	0.732	0.398
		Sig.		***0.000*****	***0.000*****	0.960	***0.000*****	***0.002*****
	CaEP_CSA	Pearson Correlation			0.457	0.043	0.634	0.451
		Sig.			***0.000*****	0.747	***0.000*****	***0.000*****
	Gender	Pearson Correlation				0.118	0.553	0.389
		Sig.				0.375	***0.000*****	***0.002*****
	Age	Pearson Correlation					-0.131	0.016
		Sig.					0.323	0.903
	Height	Pearson Correlation						0.471
		Sig.						***0.000*****

			IVD_CSA	CaEP_CSA	Gender	Age	Height	Weight
L4/L5	CrEP_CSA	Pearson Correlation	0.874	0.805	0.607	0.028	0.712	0.419
		Sig.	***0.000*****	***0.000*****	***0.000*****	0.835	***0.000*****	***0.001*****
	IVD_CSA	Pearson Correlation		0.891	0.637	-0.098	0.758	0.330
		Sig.		***0.000*****	***0.000*****	0.459	***0.000*****	***0.011****
	CaEP_CSA	Pearson Correlation			0.543	-0.111	0.723	0.424
		Sig.			***0.000*****	0.404	***0.000*****	***0.001*****
	Gender	Pearson Correlation				0.104	0.561	0.394
		Sig.				0.427	***0.000*****	***0.002*****
	Age	Pearson Correlation					-0.152	0.009
		Sig.					0.248	0.946
	Height	Pearson Correlation						0.472
		Sig.						***0.000*****

			IVD_CSA	CaEP_CSA	Gender	Age	Height	Weight
L5/S1	CrEP_CSA	Pearson Correlation	0.806	0.637	0.571	0.092	0.640	0.007
		Sig.	***0.000*****	***0.000*****	***0.000*****	0.564	***0.000*****	0.967
	IVD_CSA	Pearson Correlation		0.837	0.596	0.082	0.769	0.413
		Sig.		***0.000*****	***0.000*****	0.545	***0.000*****	***0.001*****
	CaEP_CSA	Pearson Correlation			0.323	-0.049	0.706	0.271
		Sig.			***0.037*****	0.759	***0.000*****	0.083
	Gender	Pearson Correlation				0.104	0.561	0.394
		Sig.				0.427	***0.000*****	***0.002*****
	Age	Pearson Correlation					-0.152	0.009
		Sig.					0.248	0.946
	Height	Pearson Correlation						0.472
		Sig.						***0.000*****

(**) indicates a significant correlation at the 0.01 level (2-tailed)
(*) indicates a significant correlation at the 0.05 level (2-tailed)

CrEP_CSA and IVD_CSA, which removed subject age and body weight, leaving subject gender and height as the significant predictors ($p<0.05$). Subject gender was removed from the models of CaEP_CSA for the L4/L5 and L5/S1 level after another iteration.

Table 4.10: ANOVA results for the prediction equations

			SS	df	MS	F	Sig.
L3/L4	CrEP_CSA	Regression	143.431	1	143.431	55.940	***0.000****
		Residual	146.150	57	2.564	-	-
		Total	289.581	58	-	-	-
	IVD_CSA	Regression	210.171	1	210.171	65.699	***0.000****
		Residual	182.342	57	3.199	-	-
		Total	392.513	58	-	-	-
	CaEP_CSA	Regression	114.912	1	114.912	38.377	***0.000****
		Residual	170.677	57	2.994	-	-
		Total	285.589	58	-	-	-
L4/L5	CrEP_CSA	Regression	145.283	2	72.642	37.801	***0.000****
		Residual	107.613	56	1.922	-	-
		Total	252.897	58	-	-	-
	IVD_CSA	Regression	260.123	2	130.062	50.684	***0.000****
		Residual	143.704	56	2.566	-	-
		Total	403.827	58	-	-	-
	CaEP_CSA	Regression	158.709	1	158.709	62.342	***0.000****
		Residual	145.109	57	2.546	-	-
		Total	303.818	58	-	-	-
L5/S1	CrEP_CSA	Regression	69.278	2	34.639	20.361	***0.000****
		Residual	66.347	39	1.701	-	-
		Total	135.625	41	-	-	-
	IVD_CSA	Regression	196.042	2	98.021	47.453	***0.000****
		Residual	111.546	54	2.066	-	-
		Total	307.587	56	-	-	-
	CaEP_CSA	Regression	69.405	1	69.405	39.754	***0.000****
		Residual	69.834	40	1.746	-	-
		Total	139.239	41	-	-	-

Table 4.11 also provides the results of collinearity statistics. The ideal VIF value is 1, indicating no collinearity issues among the independent variables. In the present study, all VIFs slightly deviated from 1 (range from 1.250 to 1.425), which indicated some collinearity between the subject gender and height. However, since the deviation was very small, it was concluded that the regression models were not exhibiting severe multicollinearity issues and further investigation was not necessary. In general, with the presence of high variance inflation factors (VIFs) (>5), further investigation should be performed to remove certain independent variables and reduce the collinearity. Otherwise, the regression analysis may provide false predictors and result in invalid models.

Table 4.11: Coefficients of the predictors in the prediction equations and the collinearity statistics

Model				Unst. Coeff.		St. Coeff.	t	Sig.	Collinearity Statistics	
i	j	X	α_{ij}	B	St. Err.	Beta			Tolerance	VIF
L3/L4	CrEP_CSA	Constant	α_0	-9.097	3.066	-	-2.967	***0.004****	-	-
		Height	α_H	0.133	0.018	0.704	7.479	***0.000****	-	-
	IVD_CSA	Constant	α_0	-11.552	3.424	-	-3.374	***0.001****	-	-
		Height	α_H	0.161	0.020	0.732	8.106	***0.000****	-	-
	CaEP_CSA	Constant	α_0	-5.414	3.313	-	-1.634	0.108	-	-
		Height	α_H	0.119	0.019	0.634	6.195	***0.000****	-	-
L4/L5	CrEP_CSA	Constant	α_0	-4.423	2.827	-	-1.565	0.123	-	-
		Height	α_H	0.095	0.018	0.542	5.203	***0.000****	0.700	1.429
		Gender	α_G	1.293	0.435	0.310	2.975	***0.004****	0.700	1.429
	IVD_CSA	Constant	α_0	-8.345	3.266	-	-2.555	0.013	-	-
		Height	α_H	0.129	0.021	0.584	6.125	***0.000****	0.700	1.429
		Gender	α_G	1.671	0.502	0.317	3.327	***0.002****	0.700	1.429
	CaEP_CSA	Constant	α_0	-8.661	3.006	-	-2.881	***0.006****	-	-
		Height	α_H	0.139	0.018	0.723	7.896	***0.000****	-	-
L5/S1	CrEP_CSA	Constant	α_0	-2.442	3.236	-	-0.755	0.455	-	-
		Height	α_H	0.078	0.020	0.481	3.839	***0.000****	0.800	1.250
		Gender	α_G	1.285	0.452	0.356	2.842	***0.007****	0.800	1.250
	IVD_CSA	Constant	α_0	-9.025	3.098	-	-2.914	***0.005****	-	-
		Height	α_H	0.129	0.020	0.632	6.480	***0.000****	0.707	1.414
		Gender	α_G	1.196	0.459	0.254	2.608	***0.012****	0.707	1.414
	CaEP_CSA	Constant	α_0	-5.594	3.151	-	-1.775	0.083	-	-
		Height	α_H	0.116	0.018	0.706	6.305	***0.000****	-	-

Prediction equations of the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and the adjacent endplates (CrEPs and CaEPs) are given in Table 4.12. The influence of height was consistent for all regression models. The positive coefficient associated with height indicates that the sizes of the lower lumbar intervertebral discs and vertebral endplates increase with the elevation of a individual's height. On the contrary, the influence of gender was found inconsistent and only significant in 4 out of 9 regression models for the CrEP_CSA and IVD_CSA at the L4/L5 and L5/S1 level. Given "0" for females and "1" for males, the positive coefficient associated with gender indicates that female subjects have smaller CSAs than male subjects. Therefore, the prediction equation produces two response lines in parallel with different intercepts dedicated for male

and female subjects. Regression models for the L4/L5 level reported the highest R^2 and Adjusted-R^2 values, compared to the models for the L3/L4 which reported the lowest values. For a given lower lumbar level, regression models for the intervertebral discs reported the highest R^2 and Adjusted-R^2 values, compared to the models for the caudal endplate which reported the lowest R^2 and adjusted-R^2 values.

Table 4.12: Prediction equations for the IVD_CSA, CrEP_CSA, and CaEP_CSA of the lower lumbar spine

Prediction equations		R^2	Adj-R^2	S.E.	p-value
$Y_{L3/L4\_CrEP\_CSA}$	$= -9.097 + 0.133 \times X_H$	0.495	0.486	1.601	***0.000****
$Y_{L3/L4\_IVD\_CSA}$	$= -11.552 + 0.161 \times X_H$	0.535	0.527	1.789	***0.000****
$Y_{L3/L4\_CaEP\_CSA}$	$= -5.414 + 0.012 \times X_H$	0.402	0.392	1.730	***0.000****
$Y_{L4/L5\_CrEP\_CSA}$	$= -3.130 + 0.095 \times X_H + 1.293 \times X_G$	0.574	0.559	1.386	***0.000****
$Y_{L4/L5\_IVD\_CSA}$	$= -6.674 + 0.129 \times X_H + 1.671 \times X_G$	0.644	0.631	1.602	***0.000****
$Y_{L4/L5\_CaEP\_CSA}$	$= -8.661 + 0.139 \times X_H$	0.522	0.514	1.600	***0.000****
$Y_{L5/S1\_CrEP\_CSA}$	$= -1.157 + 0.078 \times X_H + 1.285 \times X_G$	0.511	0.486	1.304	***0.000****
$Y_{L5/S1\_IVD\_CSA}$	$= -7.829 + 0.129 \times X_H + 1.196 \times X_G$	0.637	0.624	1.437	***0.000****
$Y_{L5/S1\_CaEP\_CSA}$	$= -5.594 + 0.116 \times X_H$	0.498	0.486	1.321	***0.000****

CSA (cm^2); X_G gender (0 for female, 1 for male); X_H height (cm)

Polynomial method

The results of polynomial regression analyses are given in Table 4.13, 4.14, and 4.15, for each lower lumbar spinal level, with respect to the level of significance of the predictors and the regression models.

L3/L4 level

At the L3/L4 level (Table 4.13), the polynomial method reported significant prediction equations for the cross-sectional areas of the intervertebral disc (IVD_CSA), and the cranial and caudal endplate cross-sectional areas (CrEP_CSA and CaEP_CSA)

(p=0.000). However the significant predictors selected differed by the component of lower lumbar motion segment (intervertebral disc and two adjacent vertebral enplates).

For the L3/L4_CrEP_CSA, significant predictors with positive coefficients were age (A), height-cubic-gender (Ht^3G), weight-cubic-gender (Wt^3G), height-square-weight-age (Ht^2WtA), weight-age-square-gender (WtA^2G), and age-gender-square (AG^2). Significant predictors with negative coefficients were weight-square-gender-square (Wt^2G^2), age-cubic-gender (A^3G), height-square-age-gender (Ht^2AG), and height-weight-gender-square ($HtWtG^2$). For the L3/L4_IVD_CSA, height (Ht) was the only significant predictor with a positive coefficient. For the L3/L4_CaEP_CSA, height-quadratic (Ht^4) was the only significant predictor with a positive coefficient. A positive coefficient indicates that the response increases with the predictor, while a negative coefficient indicates that the response decreases with the predictor.

The analyses of collinearity (Table 4.13) reported that large variance inflation factors (VIFs) associated with the predictors for the L3/L4_CrEP_CSA model (from 27.382 to 456.371). No VIF was reported for the predictors for the IVD_CSA and CaEP_CSA model, since in both models only one predictor was present.

L4/L5 level

At the L4/L5 level, the polynomial method also reported significant prediction equations for the cross-sectional areas (CSAs) (p=0.000). The significant predictors selected also differed by the component of lower lumbar motion segment (intervertebral disc and two adjacent vertebral enplates), as shown in Table 4.14.

For the L4/L5_CrEP_CSA, significant predictors with positive coefficients were height-cubic-age (Ht^3A), height-cubic-gender (Ht^3G), weight-quadratic (Wt^4),

Table 4.13: Results of polynomial regression analysis for the L3/L4 level

Model		Unst. Coeff.		St. Coeff.	t	Sig.	Collinearity Statistics	
Response	Predictor (s)	B	St. Err.	Beta			Tolerance	VIF
CrEP_CSA	Constant	-5.462	4.208	-	-1.298	0.200	-	-
	A	0.578	0.181	1.474	3.196	***0.002****	0.031	32.389
	Ht^3G	2.24E-6	7.59E-7	3.767	2.957	***0.005****	0.004	247.240
	Wt^3G	2.58E-6	6.06E-7	1.804	4.255	***0.000****	0.037	27.382
	Wt^2G^2	-1.83E-6	4.23E-07	-4.032	-4.312	***0.000****	0.008	133.118
	A^3G	-2.24E-4	7.11E-5	-3.022	-3.150	***0.003****	0.007	140.206
	Ht^2WtA	1.51E-7	5.87E-8	2.006	2.572	***0.013****	0.011	92.564
	Ht^2AG	-1.73E-5	5.88E-6	-4.811	-2.943	***0.005****	0.002	407.093
	$HtWtG^2$	-3.49E-4	1.01E-4	-4.550	-3.459	***0.001****	0.004	263.488
	WtA^2G	1.61E-4	5.03E-5	5.548	3.204	***0.002****	0.002	456.371
	AG^2	0.135	0.043	2.969	3.139	***0.003****	0.007	136.209
IVD_CSA	Constant	-11.552	3.424	-	-3.374	***0.001****	-	-
	Ht	0.161	0.020	0.732	8.106	***0.000****	-	-
CaEP_CSA	Constant	9.964	0.840	-	11.858	***0.000****	-	-
	Ht^4	5.73E-9	0.000	0.640	6.293	***0.000****	-	-

		SS	df	MS	F	Sig.
CrEP_CSA	Regression	198.302	10	19.830	10.428	***0.000****
	Residual	91.280	48	1.902	-	-
	Total	289.581	58	-	-	-
IVD_CSA	Regression	210.171	1	210.171	65.699	***0.000****
	Residual	182.342	57	3.199	-	-
	Total	392.513	58	-	-	-
CaEP_CSA	Regression	117.067	1	117.067	39.596	***0.000****
	Residual	168.522	57	2.957	-	-
	Total	285.589	58	-	-	-

age-cubic-weight (A^3Wt), and age-gender-square (AG^2). Significant predictors with negative coefficients were weight-square-age-square (Wt^2A^2), age-cubic-gender (A^3G), and height-square-age-gender (Ht^2AG). For the L4/L5_IVD_CSA, significant predictors with positive coefficients were height-cubic-gender (Ht^3G), height-square-age-square (Ht^2A^2), and age-gender-square (AG^2). Significant predictors with negative coefficients were age-cubic-gender (A^3G), gender-cubic (G^3), and height-square-age-gender (Ht^2AG). For the L4/L5_CaEP_CSA, significant predictors were height-cubic-gender (Ht^3G) with positive coefficients and gender-cubic (G^3) with a negative coefficient.

Table 4.14: Results of polynomial regression analysis for the L4/L5 level

Model		Unst. Coeff.		St. Coeff.	t	Sig.	Collinearity Statistics	
Response	Predictor (s)	B	St. Err.	Beta			Tolerance	VIF
CrEP_CSA	Constant	4.310	1.203	-	3.582	***0.001****	-	-
	Ht^3A	6.80E-8	2.28E-8	1.189	2.980	***0.004****	0.036	28.105
	Ht^3G	1.96E-6	4.57E-7	3.477	4.283	***0.000****	0.009	116.270
	Wt^4	2.89E-8	7.69E-9	1.859	3.760	***0.000****	0.023	43.140
	Wt^2A^2	-2.02E-6	5.56E-7	-4.486	-3.626	***0.001****	0.004	270.038
	A^3Wt	8.06E-6	2.25E-6	5.285	3.590	***0.001****	0.003	382.477
	A^3G	-4.04E-4	1.03E-4	-5.798	-3.942	***0.000****	0.003	381.693
	G^3	-4.161	1.014	-6.985	-4.102	***0.000****	0.002	511.637
	Ht^2AG	-2.35E-5	5.49E-6	-6.853	-4.283	***0.000****	0.002	451.665
	AG^2	0.587	0.123	13.689	4.767	***0.000****	0.001	1454.834
IVD_CSA	Constant	6.961	1.747	-	3.985	***0.000****	-	-
	Ht^3G	2.71E-6	7.85E-7	3.808	3.448	***0.001****	0.005	188.035
	Ht^2A^2	5.11E-7	1.97E-7	1.918	2.592	***0.012****	0.012	84.410
	A^3G	-2.06E-04	7.87E-05	-2.335	-2.614	***0.012****	0.008	122.981
	G^3	-3.391	1.157	-4.505	-2.932	***0.005****	0.003	364.043
	Ht^2AG	-2.68E-7	1.05E-7	-6.170	-2.556	***0.014****	0.001	898.740
	AG^2	0.461	0.167	8.507	2.765	***0.008****	0.001	1459.390
CaEP_CSA	Constant	10.621	0.603	-	17.603	***0.000****	-	-
	Ht^3G	8.26E-7	0.000	1.340	5.706	***0.000****	0.144	6.927
	G^3	-0.454	0.153	-0.696	-2.964	***0.004****	0.144	6.927

		SS	df	MS	F	Sig.
CrEP_CSA	Regression	182.663	9	20.296	14.160	***0.000****
	Residual	70.234	49	1.433	-	-
	Total	252.897	58	-	-	-
IVD_CSA	Regression	267.632	6	44.605	17.031	***0.000****
	Residual	136.195	52	2.619	-	-
	Total	403.827	58	-	-	-
CaEP_CSA	Regression	168.417	2	84.209	34.828	***0.000****
	Residual	135.401	56	2.418	-	-
	Total	303.818	58	-	-	-

The analyses of collinearity (Table 4.14) revealed that all polynomial models for the L4/L5 level were highly susceptible to the effect of multicollinearity, due to the elevated variance inflation factors associated with each predictor, particularly for the CrEP_CSA (from 28.105 to 1454.834) and CaEP_CSA (from 84.410 to 1459.390).

L5/S1 level

At the L5/S1 level, prediction equations also exhibited inconsistency in predictor selection for the regression models, despite the fact that all regression models were significant (p=0.000) (Table 4.15).

Table 4.15: Results of polynomial regression analysis for the L5/S1 level

Model		Unst. Coeff.		St. Coeff.	t	Sig.	Collinearity Statistics	
Response	Predictor (s)	B	St. Err.	Beta			Tolerance	VIF
CrEP_CSA	Constant	20.545	10.433	-	1.969	0.057	-	-
	Ht	0.132	0.021	0.814	6.168	***0.000****	0.501	1.996
	Wt	-1.109	0.002	-10.222	-2.882	***0.007****	0.001	1440.559
	A	0.070	0.032	0.215	2.157	***0.038****	0.883	1.133
	Wt^2	0.010	0.003	15.656	2.964	***0.006****	0.000	3195.973
	Wt^4	-2.03E-07	6.62E-08	-5.471	-3.059	***0.004****	0.003	366.233
	G^3	0.951	0.228	1.844	4.168	***0.000****	0.045	22.419
	G^2Wt^2	-2.72E-04	7.60E-05	-1.889	-3.582	***0.001****	0.031	31.851
IVD_CSA	Constant	-18.015	4.214	-	-4.275	***0.000****	-	-
	Ht	0.143	0.018	0.698	8.129	***0.000****	0.795	1.257
	A	0.355	0.128	0.850	2.785	***0.007****	0.063	15.916
	A^4	-3.61E-06	1.14E-06	-1.013	-3.155	***0.003****	0.057	17.598
	A^3G	2.99E-05	1.22E-05	0.370	2.449	***0.018****	0.257	3.891
CaEP_CSA	Constant	-0.851	3.751	-	-0.227	0.882	-	-
	Ht	0.126	0.020	0.771	6.467	***0.000****	0.816	1.226
	Wt	-0.171	0.083	-1.555	-2.057	***0.047****	0.020	49.220
	Wt^2	0.001	0.000	1.624	2.181	***0.035****	0.021	47.800

		SS	df	MS	F	Sig.
CrEP_CSA	Regression	95.359	7	13.623	11.503	***0.000****
	Residual	40.266	34	1.184	-	-
	Total	135.625	41	-	-	-
IVD_CSA	Regression	213.906	4	53.477	29.683	***0.000****
	Residual	93.681	52	1.802	-	-
	Total	307.587	56	-	-	-
CaEP_CSA	Regression	77.819	3	25.940	16.049	***0.000****
	Residual	61.420	38	1.616	-	-
	Total	139.239	41	-	-	-

For the L5/S1_CrEP_CSA, significant predictors with positive coefficients were height (Ht), age (Age), weight-square (Wt^2), and gender-cubic (G^3). Significant predictors with negative coefficients were weight (Wt), weight-quadratic (Wt^4), and gender-square-weight-square (G^2Wt^2). For the L5/S1_IVD_CSA, significant predictors with

positive coefficients were height (Ht), age (Age), and age-cubic-gender (A^3G). Significant predictors with negative coefficients were age-quadratic (A^4). For the L5/S1_CaEP_CSA, significant predictors were height (Ht) and weight-square (Wt^2) with positive coefficients and weight (Wt) with a negative coefficient.

The analyses of collinearity (Table 4.15) also revealed that all polynomial models were highly susceptible to the effect of multicollinearity, due to the elevated variance inflation factors associated with combination variables.

Model diagnosis

The plots of unstandardized residual against the unstandardized prediction are illustrated for each lower lumbar level, L3/L4 level (Figure 4.2), L4/L5 level (Figure 4.3), and L5/S1 level (Figure 4.4). For all linear models, residuals appeared to be randomly distributed around the horizontal line of zero; therefore the linearity assumption was sustained. Also, residual plots indicated no evidence that the residuals were getting larger (spreading-out) as a function of the "predicted" value; therefore the assumption of constant variance was satisfied.

Normality tests of residuals (Table 4.16) revealed that residuals were not normally distributed for the L3/L4_IVD_CSA (p=0.003) and L3/L4_CaEP_CSA (p=0.045). It was also noted that the P values for the L3/L4_CrEP_CSA (p=0.067) and L4/L5_CrEP_CSA (p=0.085) were approaching the level of significance. Normal quartile-quartile (Q-Q) plots of these residuals (Figure 4.5) indicated the presence of possible outliers, They were also evident in the residual plots (Figure 4.2 and 4.3) that for these linear models, some residuals were remarkably deviated from the base line (line zero).

Tukey's method detected two outliers in the residuals for the L3/L4_CrEP_CSA; one outlier each for the L3/L4_IVD_CSA and L3/L4_CaEP_CSA; and three outliers for the L4/L5_CrEP_CSA. All of these outliers were associated with one female and two male subjects.

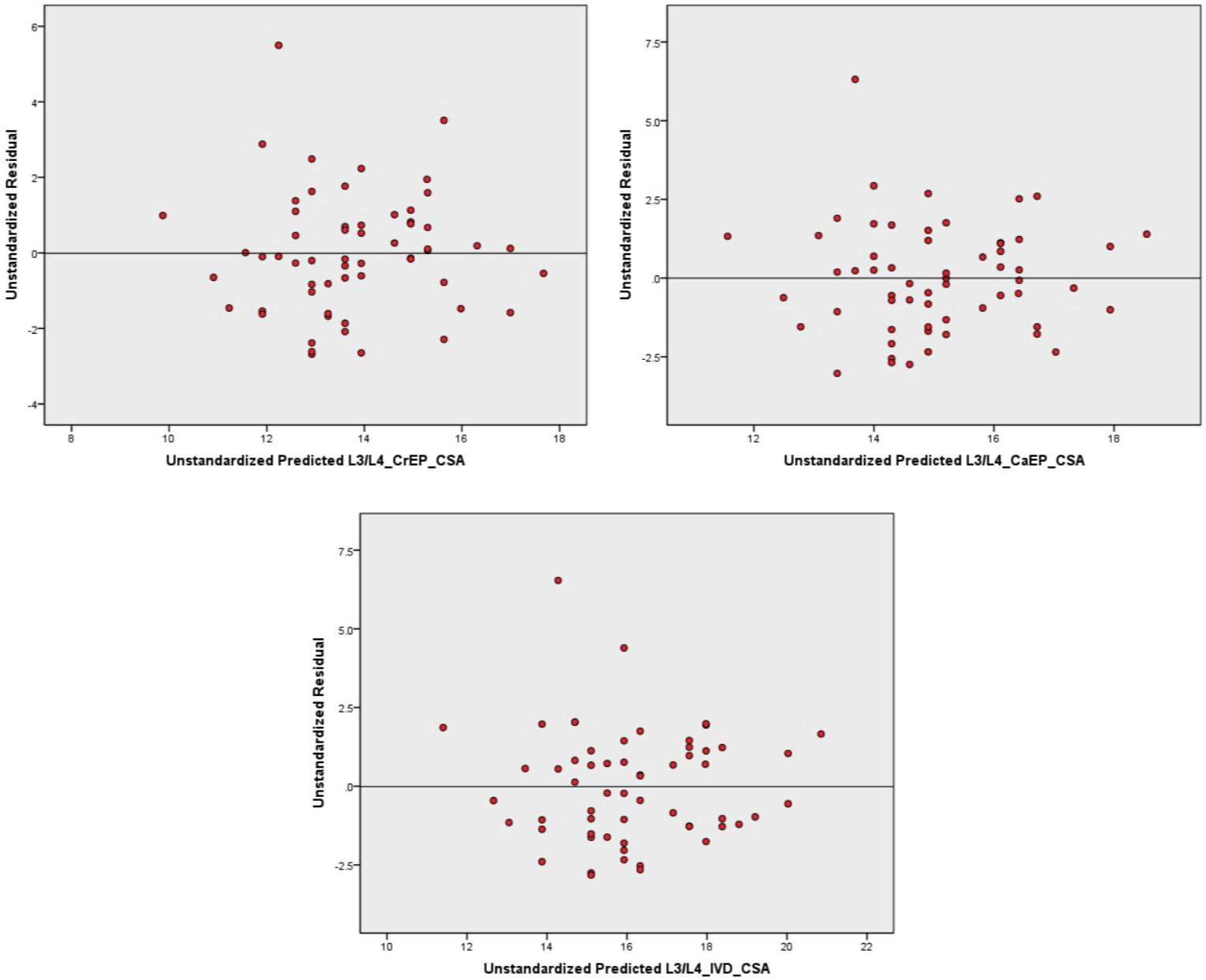


Figure 4.2: Residual plots against "predicted" value at the L3/L4 level

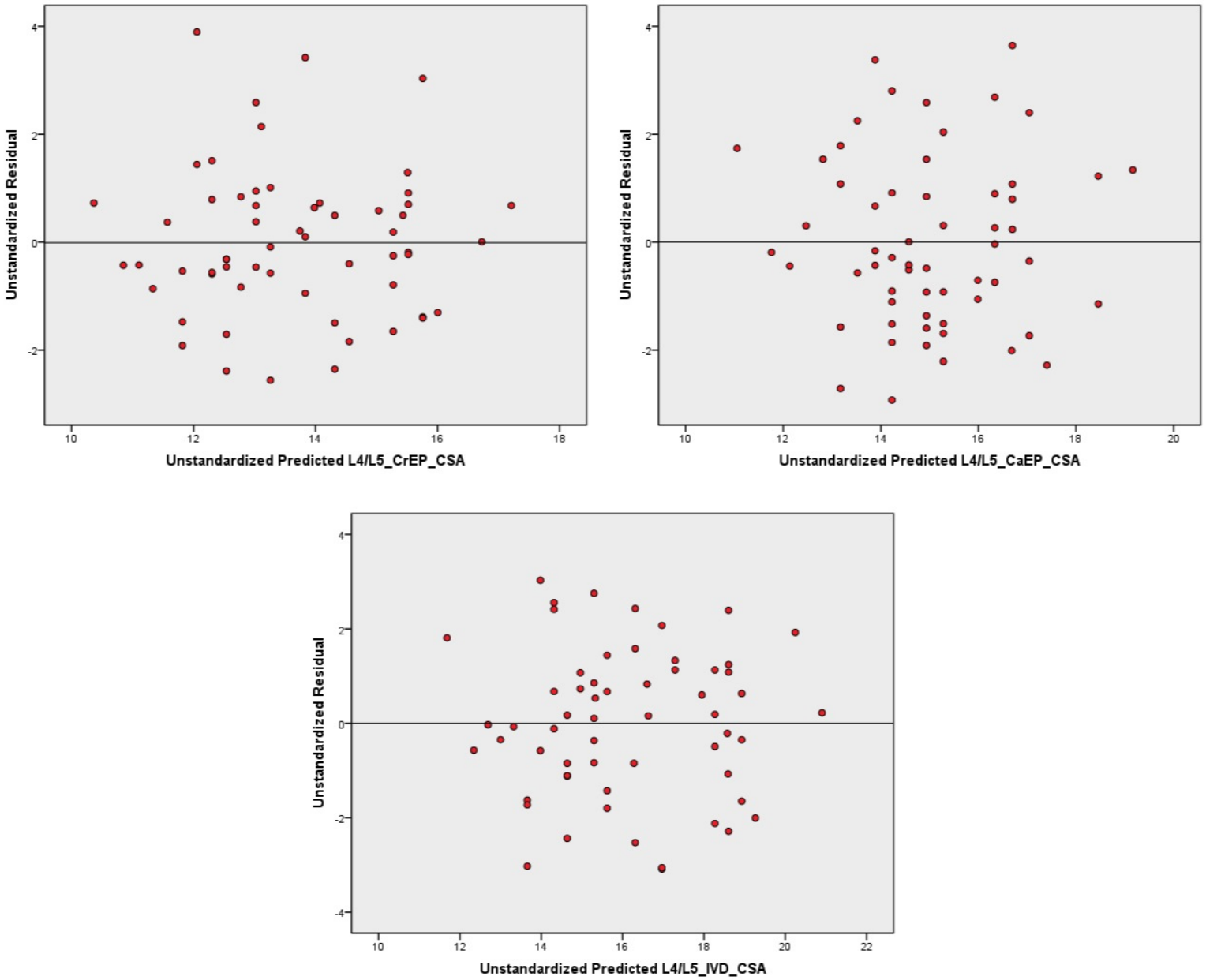


Figure 4.3: Residual plots against "predicted" value at the L4/L5 level

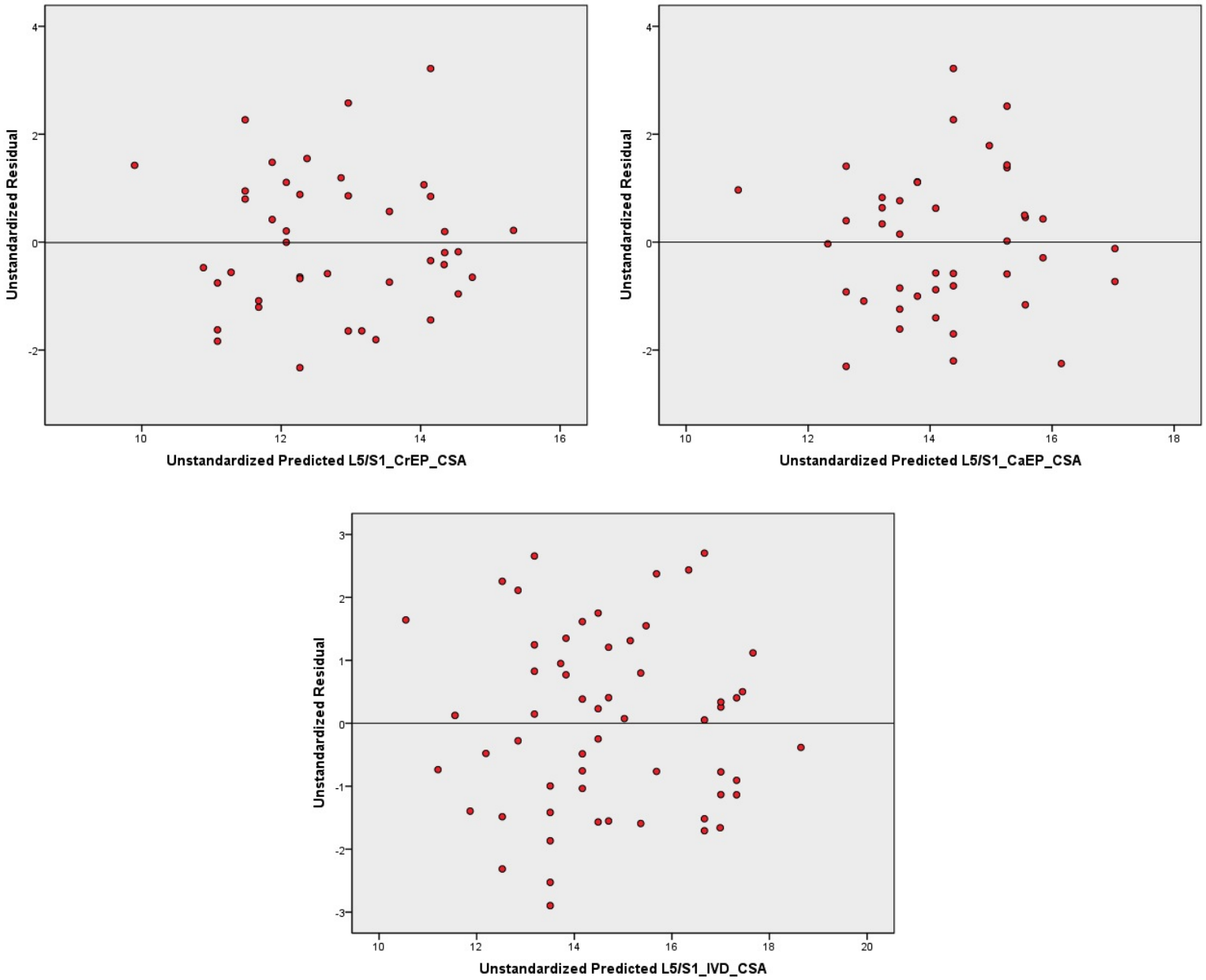
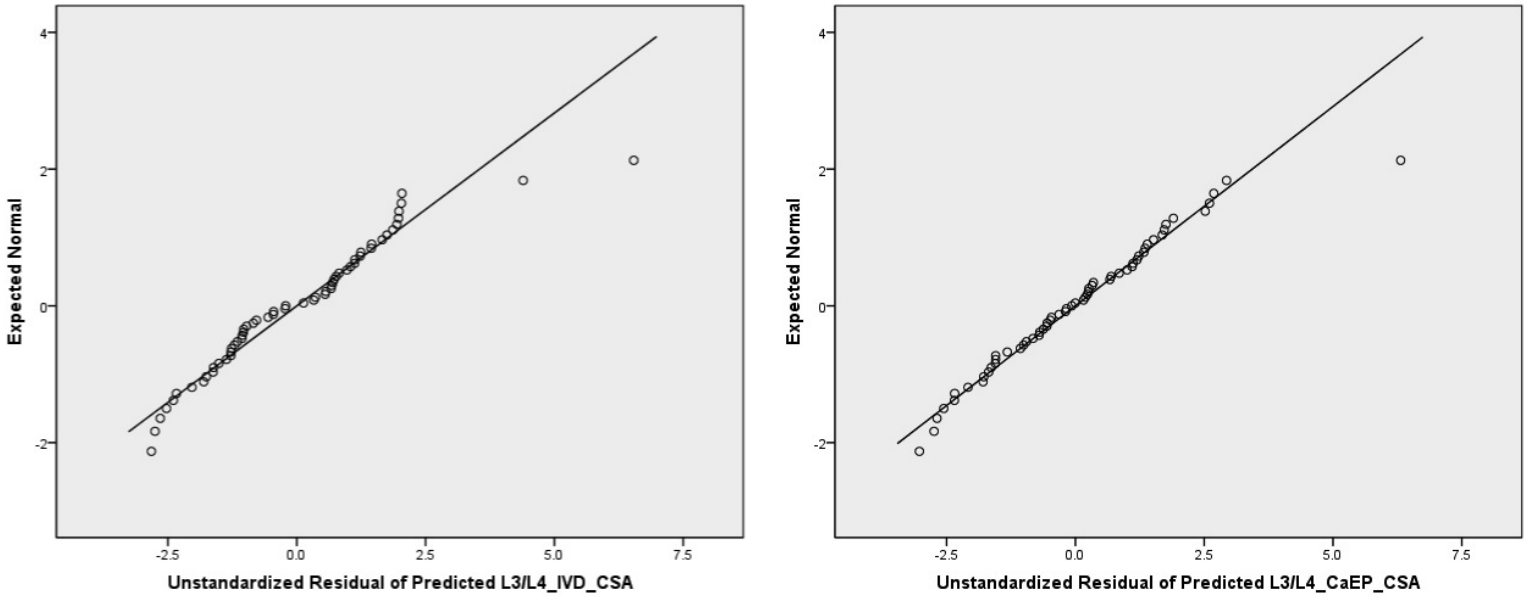
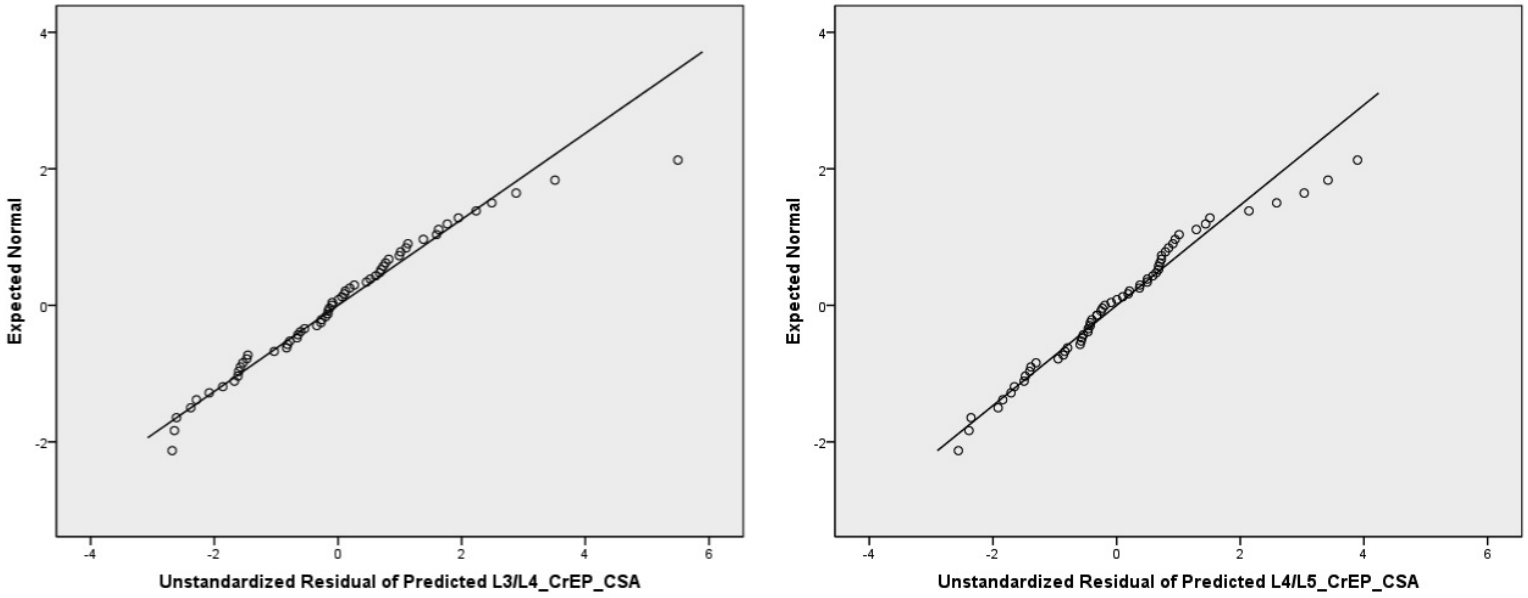


Figure 4.4: Residual plots against "predicted" value at the L5/S1 level



(a) P value less than 0.05



(b) P value close to significance level

Figure 4.5: Normal quantile-quantile (Q-Q) plots of residuals

Table 4.16: Results of normality tests for residuals

			Kolmogorov-Smirnova		Shapiro-Wilk	
		df	Statistic	Sig.	Statistic	Sig.
L3/L4	CrEP_CSA	59	0.069	0.200	0.963	0.067
	IVD_CSA	59	0.098	0.200	0.934	***0.003****
	CaEP_CSA	59	0.063	0.200	0.959	***0.045****
L4/L5	CrEP_CSA	59	0.093	0.200	0.965	0.085
	IVD_CSA	59	0.056	0.200	0.981	0.472
	CaEP_CSA	59	0.083	0.200	0.976	0.305
L5/S1	CrEP_CSA	42	0.082	0.200	0.977	0.545
	IVD_CSA	57	0.085	0.200	0.977	0.350
	CaEP_CSA	42	0.098	0.200	0.982	0.749

Table 4.17 provides demographic statistics and geometric data with corresponding residuals. One male subject (M23) had a considerably larger body weight (178.71 kg) and a taller statue (185.4 cm) than the other male (65.77 kg and 165.1 cm). Residuals associated with the female subject (F76) were much larger than those of male subjects.

Table 4.17: Subject demographics associated with the outliers in the residuals

Subject	Age (years)	Ht (cm)	Wt (kg)	Model		"Measured"	"Predicted"	Residual
F76	31	160.0	73.48	L3/L4	CrEP	17.74	12.24	5.50
					IVD	20.82	14.28	6.54
					CaEP	20.00	13.69	6.31
				L4/L5	CrEP	15.95	12.05	3.90
M23	31	185.4	178.71	L3/L4	CrEP	19.14	15.63	3.51
				L4/L5	CrEP	18.79	15.76	3.03
M63	29	165.1	65.77	L4/L5	CrEP	17.25	13.83	3.42

The following normality tests (Table 4.18) indicated the residuals were normally distributed after removal of outliers. It was noted that the p value for residuals of L3/L4_IVD_CSA were still close to the level of significance (p=0.074).

A second iteration of regression analysis was performed to develop new (adjusted) linear prediction equations for the L3/L4_CrEP_CSA, L3/L4_IVD_CSA,

Table 4.18: Results of normality tests for residuals before and after the removal of outliers

			Kolmogorov-Smirnova		Shapiro-Wilk	
	Outliers	df	Statistic	Sig.	Statistic	Sig.
L3/L4_CrEP_CSA	with	59	0.069	0.200	0.963	0.067
	w/out	57	0.078	0.200	0.984	0.645
L3/L4_IVD_CSA	with	59	0.098	0.200	0.934	***0.003****
	w/out	58	0.106	0.162	0.963	0.074
L3/L4_CaEP_CSA	with	59	0.063	0.200	0.959	***0.045****
	w/out	58	0.071	0.200	0.981	0.495
L4/L5_CrEP_CSA	with	59	0.093	0.200	0.965	0.085
	w/out	56	0.073	0.200	0.985	0.730

L3/L4_CaEP_CSA, and L4/L5_CrEP_CSA, without the geometric data corresponding to the previous outliers. Table 4.19 provides the adjusted models and reveals the increases of R^2 and adjusted R^2, indicating that the adjusted models may provide better explanations for the variance within the geometric data.

Table 4.19: Prediction equations for the IVD_CSA, CrEP_CSA, and CaEP_CSA of the lower lumbar spine

Prediction equations			R^2	Adj-R^2	S.E.	p-value
$Y_{L3/L4\_CrEP\_CSA}$	w/out	$= -6.115 + 0.112 \times X_H + 0.996 \times X_G$	0.622	0.608	1.306	***0.000****
	with	$= -9.097 + 0.133 \times X_H$	0.495	0.486	1.601	***0.000****
$Y_{L3/L4\_IVD\_CSA}$	w/out	$= -9.453 + 0.146 \times X_H + 1.096 \times X_G$	0.660	0.648	1.513	***0.000****
	with	$= -11.552 + 0.161 \times X_H$	0.535	0.527	1.789	***0.000****
$Y_{L3/L4\_CaEP\_CSA}$	w/out	$= -7.125 + 0.129 \times X_H$	0.504	0.495	1.520	***0.000****
	with	$= -5.414 + 0.119 \times X_H$	0.402	0.392	1.730	***0.000****
$Y_{L4/L5\_CrEP\_CSA}$	w/out	$= -4.565 + 0.103 \times X_H + 1.041 \times X_G$	0.665	0.652	1.141	***0.000****
	with	$= -3.130 + 0.095 \times X_H + 1.293 \times X_G$	0.574	0.559	1.386	***0.000****

CSA (cm^2); X_G gender (0 for female, 1 for male); X_H height (cm)

Normality tests of residuals (Table 4.20) revealed that residuals were normally distributed for all 9 linear models. The plots of unstandardized residuals against the unstandardized predictions are illustrated for each linear model across the lower lumbar levels, L3/L4 level (Figure 4.6), L4/L5 level (Figure 4.7), and L5/S1 level (Figure 4.8). For

all linear models, residuals appeared to be randomly distributed around the horizontal line of zero; therefore the linearity assumption was sustained. Also, residual plots indicated no evidence that the residuals were getting larger (spreading-out) as a function of the "predicted" value; therefore the assumption of constant variance was satisfied.

Table 4.20: Results of normality test for residuals of adjusted linear models

			Kolmogorov-Smirnova		Shapiro-Wilk	
		df	Statistic	Sig.	Statistic	Sig.
L3/L4	CrEP_CSA	57	0.110	0.083	0.975	0.290
	IVD_CSA	58	0.091	0.200	0.976	0.303
	CaEP_CSA	58	0.053	0.200	0.981	0.505
L4/L5	CrEP_CSA	56	0.065	0.200	0.987	0.802
	IVD_CSA	59	0.056	0.200	0.981	0.472
	CaEP_CSA	59	0.083	0.200	0.976	0.305
L5/S1	CrEP_CSA	42	0.082	0.200	0.977	0.545
	IVD_CSA	57	0.085	0.200	0.977	0.350
	CaEP_CSA	42	0.098	0.200	0.982	0.749

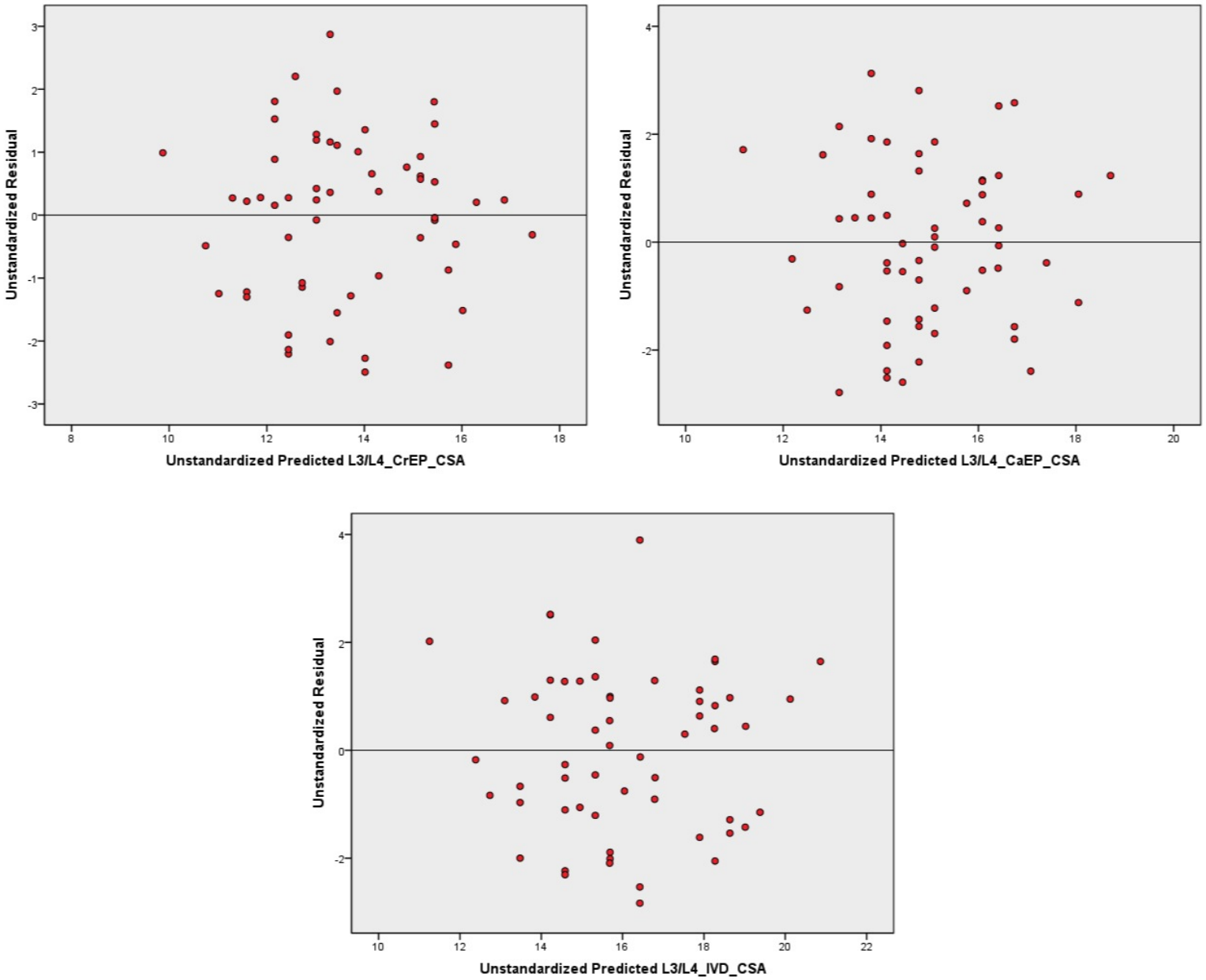


Figure 4.6: Residual plots against "predicted" value at the L3/L4 level (second iteration of linear regression)

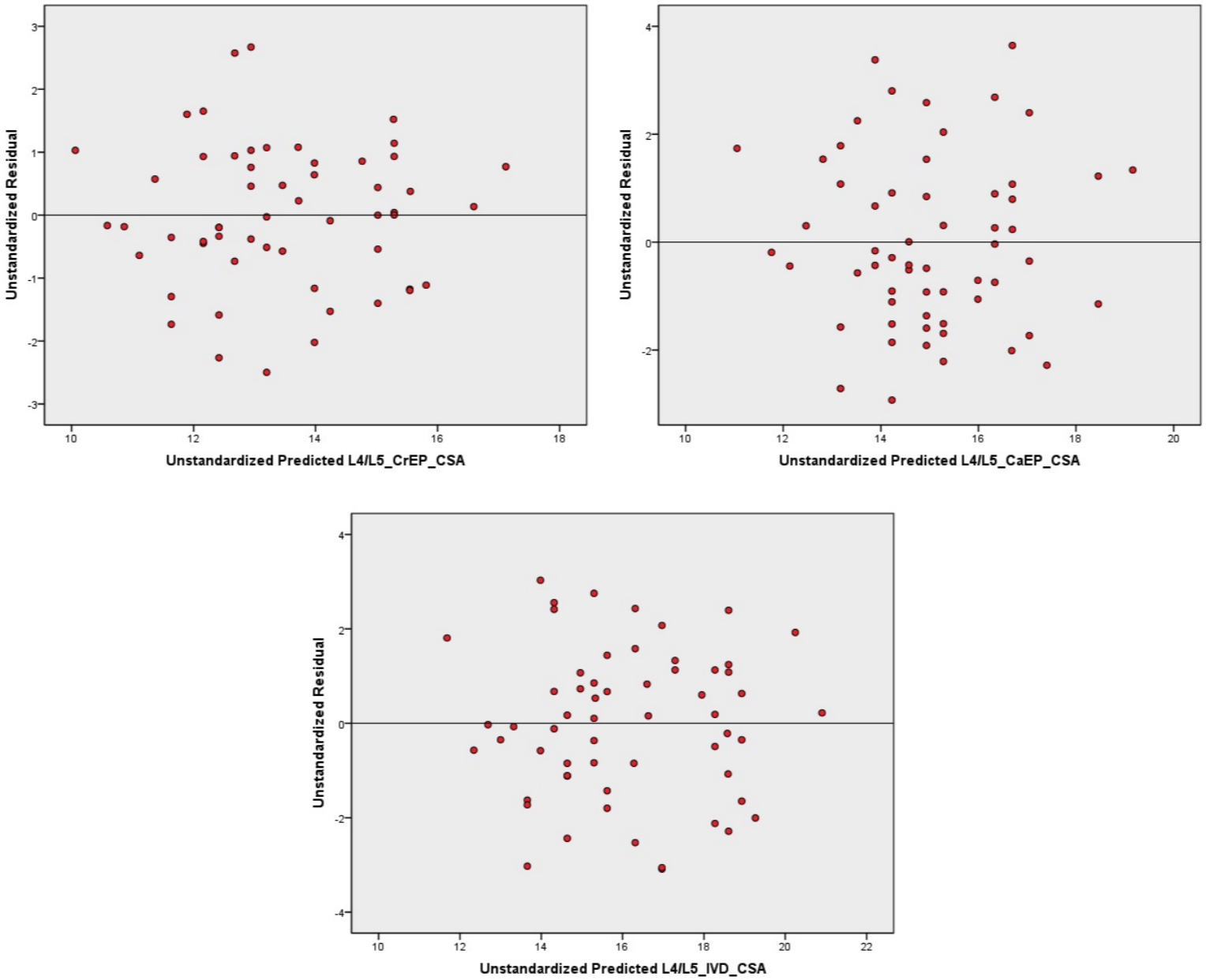


Figure 4.7: Residual plots against "predicted" value at the L4/L5 level (second iteration of linear regression)

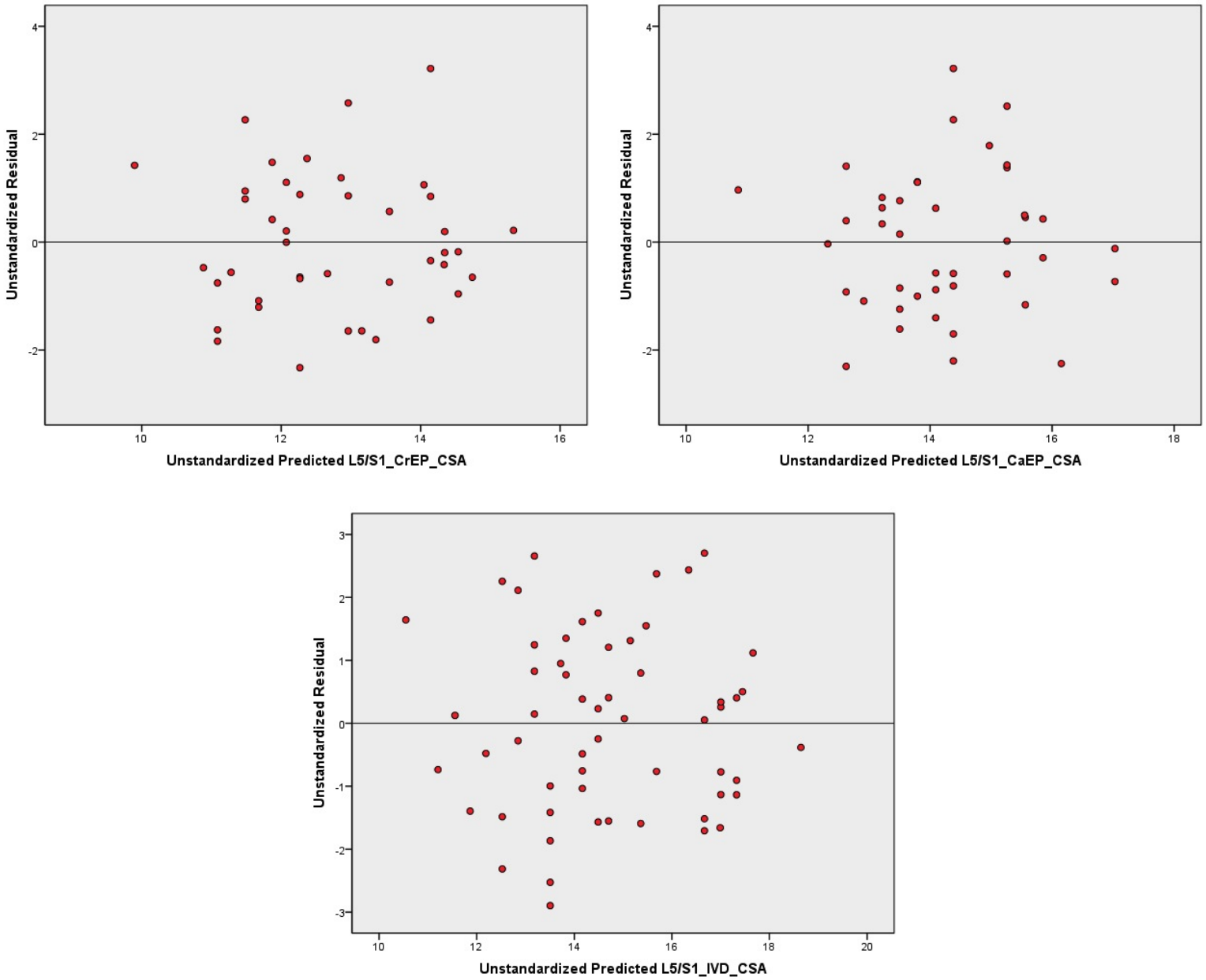


Figure 4.8: Residual plots against "predicted" value at the L5/S1 level (second iteration of linear regression)

Model preference

The comparison of regression models (Table 4.21) revealed that compared to corresponding linear equations, polynomial prediction equations generally yielded larger values of R-square (R^2) and adjusted R-square (Adj-R^2) and smaller standard error (S.E.), except for the L3/L4_IVD_CSA and L3/L4_CaEP_CSA. The increases of R^2 and Adj-R^2 were possibly due to effect of the presence of more predictors. However, it cannot be assumed that polynomial models are superior to the corresponding linear models, since polynomial models are highly susceptible to the effects of multicollinearity introduced by artificial variables. Secondly, polynomial methods failed to provide the same consistency in predictor selections, which makes it difficult to obtain clear understandings about the influence of each predictors.

On the other hand, linear models consistently revealed that subject height (Ht) was a significant predictor in all regression equations and subject gender (G) was also a significant predictor for the CrEP_CSA and IVD_CSA for all three lower lumbar levels. In addition, linear models exhibited minimal effects of multicollinearity (VIF<1.5).

Therefore, the present study selected linear regression models (Table 4.22) to predict the cross-sectional areas of the intervertebral disc and vertebral endplates. Model validation was only performed for the linear models.

Table 4.21: Comparison of models developed by linear and polynomial regressions

	Prediction equations		R^2	Adj-R^2	S.E.	p-value
L3/L4	$Y_{L3/L4\_CrEP\_CSA}$	Linear	0.622	0.608	1.306	***0.000****
		Polynomial	0.685	0.619	1.379	***0.000****
	$Y_{L3/L4\_IVD\_CSA}$	Linear	0.660	0.648	1.513	***0.000****
		Polynomial	0.535	0.527	1.789	***0.000****
	$Y_{L3/L4\_CaEP\_CSA}$	Linear	0.504	0.495	1.520	***0.000****
		Polynomial	0.410	0.400	1.719	***0.000****
L4/L5	$Y_{L4/L5\_CrEP\_CSA}$	Linear	0.665	0.652	1.386	***0.000****
		Polynomial	0.722	0.671	1.197	***0.000****
	$Y_{L4/L5\_IVD\_CSA}$	Linear	0.644	0.631	1.602	***0.000****
		Polynomial	0.663	0.624	1.618	***0.000****
	$Y_{L4/L5\_CaEP\_CSA}$	Linear	0.522	0.514	1.600	***0.000****
		Polynomial	0.554	0.538	1.555	***0.000****
L5/S1	$Y_{L5/S1\_CrEP\_CSA}$	Linear	0.511	0.486	1.304	***0.000****
		Polynomial	0.703	0.642	1.088	***0.000****
	$Y_{L5/S1\_IVD\_CSA}$	Linear	0.637	0.624	1.437	***0.000****
		Polynomial	0.695	0.672	1.342	***0.000****
	$Y_{L5/S1\_CaEP\_CSA}$	Linear	0.498	0.486	1.321	***0.000****
		Polynomial	0.559	0.524	1.271	***0.000****

Table 4.22: Final linear prediction equations for the IVD_CSA, CrEP_CSA, and CaEP_CSA of the lower lumbar spine

Prediction equations		R^2	Adj-R^2	S.E.	p-value
$Y_{L3/L4\_CrEP\_CSA}$	$= -6.115 + 0.112 \times X_H + 0.996 \times X_G$	0.622	0.608	1.306	***0.000****
$Y_{L3/L4\_IVD\_CSA}$	$= -9.453 + 0.146 \times X_H + 1.096 \times X_G$	0.660	0.648	1.513	***0.000****
$Y_{L3/L4\_CaEP\_CSA}$	$= -7.125 + 0.129 \times X_H$	0.504	0.495	1.520	***0.000****
$Y_{L4/L5\_CrEP\_CSA}$	$= -4.565 + 0.103 \times X_H + 1.041 \times X_G$	0.665	0.652	1.141	***0.000****
$Y_{L4/L5\_IVD\_CSA}$	$= -6.674 + 0.129 \times X_H + 1.671 \times X_G$	0.644	0.631	1.602	***0.000****
$Y_{L4/L5\_CaEP\_CSA}$	$= -8.661 + 0.139 \times X_H$	0.522	0.514	1.600	***0.000****
$Y_{L5/S1\_CrEP\_CSA}$	$= -1.157 + 0.078 \times X_H + 1.285 \times X_G$	0.511	0.486	1.304	***0.000****
$Y_{L5/S1\_IVD\_CSA}$	$= -7.829 + 0.129 \times X_H + 1.196 \times X_G$	0.637	0.624	1.437	***0.000****
$Y_{L5/S1\_CaEP\_CSA}$	$= -5.594 + 0.116 \times X_H$	0.498	0.486	1.321	***0.000****

CSA (cm^2); X_G gender (0 for female, 1 for male); X_H height (cm)

4.3.3 Model validation

Table 4.23 lists the results of error analysis for differences between the "measured" and "predicted" values for each lower lumbar level. Results of paired sample t tests indicated that there were no statistically significant differences between the "measured" values and the ones predicted by the linear models ($p>0.05$). Absolute errors associated with linear models, on average, were 7% for the L3/L4 models, 6% for the L4/L5 models, and 8% for the L5/S1 level. The range of absolute error appeared to be wide, except for the L4/L5_CrEP_CSA model corresponding to the lowest absolute difference reported (5.1%). It was also noted that absolute errors appeared to increase from the cranial side to the caudal side for a given single-level lower lumbar motion segment.

Table 4.23: Error analysis of the "measured" and "predicted" value (cm^2)

				Paired Sample T Tests					Absolute Error				
			Mean	Diff.	SD	t	df	Sig.	Mean	SD	Min	Max	%
L3/L4	CrEP_CSA	Measured	13.97	0.21	1.30	0.720	19	0.480	0.87	0.97	0.02	3.71	6.0
		Predicted	13.76										
	IVD_CSA	Measured	16.10	-0.25	1.41	-0.787	19	0.441	1.05	0.94	0.05	3.31	6.9
		Predicted	16.35										
	CaEP_CSA	Measured	15.21	0.07	1.65	0.185	19	0.855	1.27	1.01	0.01	3.61	8.2
		Predicted	15.14										
L4/L5	CrEP_CSA	Measured	13.81	-0.08	0.95	-0.344	17	0.735	0.70	0.63	0.01	1.71	5.1
		Predicted	13.89										
	IVD_CSA	Measured	16.73	0.00	1.51	-0.008	18	0.993	1.06	1.04	0.14	4.27	6.3
		Predicted	16.73										
	CaEP_CSA	Measured	15.58	0.06	1.69	1.161	18	0.874	1.23	1.12	0.01	4.64	8.0
		Predicted	15.51										
L5/S1	CrEP_CSA	Measured	13.33	0.15	1.23	0.467	14	0.647	0.91	0.80	0.01	2.83	6.8
		Predicted	13.18										
	IVD_CSA	Measured	15.07	0.03	1.39	0.072	16	0.943	1.10	0.81	0.05	2.84	7.5
		Predicted	15.05										
	CaEP_CSA	Measured	14.58	0.16	1.77	0.337	13	0.742	1.37	1.05	0.04	3.34	9.6
		Predicted	14.42										

4.4 Discussion

This study may be among the first few studies to develop regression models with geometric data that were obtained from a U.S. sample population. In the present study, a series of regression analyses were performed with the geometric data derived from the dataset reported in Chapter 3 to generate prediction equations for the cross-sectional areas (CSAs) of the intervertebral disc and the adjacent vertebral endplates for each lower lumbar level (L3/L4, L4/L5, and L5/S1) as a function of an individual's gross anthropometric measures (e.g., height and body weight). Two assumptions were necessary in the present study. First, the current dataset of the spinal geometry data was assumed to be a good representation of the adult U.S. population without spinal pathologies that may alter the geometric characteristics of the spine. The dataset was obtained from a relatively large sample of subjects (41 females and 38 males) between the age of 21 and 39 with no severe disc degenerations. The average height and body weight were 165.72 cm and 73.08 kg for the females, and 178.33 cm and 86.11 kg for males, which were in good approximation of an average U.S. adults (Female 162.05 cm and 73.57 kg; Male 176.02 cm and 88.68 kg) as reported by the National Center for Health Statistics (NCHS, 2012). Secondly, it was assumed that the geometric data of cross-sectional areas (CSAs) were measured precisely, since the geometric data were obtained from the previous study described in Chapter 3, in which excellent measurement reliability was achieved by measuring the geometric dimensions on the magnetic resonance (MR) scans with an advanced image processing software.

Previous studies, in general, had relatively small sample sizes to investigate the correlations between the spinal geometry and the anthropometric characteristics (Colombini et al., 1989; Turk & Celan, 2004; Seidel et al., 2008). Colombini et al. (1989) first suggested the feasibility to predict the cross-sectional area of the lower lumbar intervertebral disc with anthropometric measures, such as body weight. However, the relatively low R^2 reported suggests that their model may be inadequate to explain the overall variance within the size of the disc. In addition, as discussed in Chapter 3, their measurement of spinal geometry could be compromised with systematic error due to the use of an ellipsoid approximation method. Their geometric data were also found considerably larger than others reported in the literature (refer to Chapter 3), indicating that their data may not be a good representation of the overall population. Therefore, their regression models are more likely to overestimate the cross-sectional area as reported by Turk and Celan (2004). Turk and Celan (2004) measured actual cross-sectional areas (CSAs) of the L4/L5 and L5/S1 discs with 21 females and 19 males and reported that height exhibited greater correlation with the CSA than body weight, contradicting Colombini et al. (1989). The regression models developed by Turk and Celan (2004) reported much less absolute error compared to the ones developed by Colombini et al. (1989), but unfortunately, were not validated with new dataset to evaluate the model performance. On the other hand, Seidel et al. (2008) measured the CSAs of the lumbar vertebral endplates of cadaveric specimens and reported no significant regression model was available to predict the CSAs by anthropometric measures.

Compared to the previous studies, the present investigation performed comprehensive statistical procedures (e.g., Tukey's outlier detection and residual analysis) to ensure the

representativeness of the dataset and improve the validity of the final regression models, which was statistically validated by predicting the actual measured geometric dimensions of 20 random subjects.

4.4.1 Prediction equations for the cross-sectional areas (CSAs) of the lower lumbar motion segments

In the present study, subject gender (G) and height (Ht) were significant anthropometric measures which consistently predicted the cross-sectional areas of the lower lumbar intervertebral disc, the cranial endplate, and caudal endplate (by Ht alone), compared to subject age and weight which were not significant in any regression models.

Differing from the present study, previous researchers performed regression analyses regardless of subject gender (Colombini et al., 1989; Turk & Celan, 2004) and despite the possible influence of gender on the spinal morphometry as reported by some studies (van Schaik et al., 1985; Twomey & Taylor, 1985, 1987; Zhou et al., 2000; van der Houwen et al., 2010; H. Chen et al., 2011). Even though, none of these studies has measured the planar aspects (the cross-sectional area) of the lumbar motion segments rather than the linear dimensions, such as the anteroposterior and the frontal diameters, the study in Chapter 3 has concluded that the same influence of gender on linear dimensions was also evident on measurements of the cross-sectional area. A number of studies has also reported the geometric data of the cross-sectional area of the lumbar motion segment as supplementary to the mechanical testings of the ultimate strength, which has also shown the difference between two gender groups (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Brinckmann et al., 1989; Porter et al., 1989). The present study noted

that the coefficient of gender varied in models for the cranial endplate and the intervertebral disc was also inconsistent across all lower lumbar levels, which suggested that the influence of gender may be spinal-level-dependent.

Differing from the present study in which subject height was an independent predictor, Colombini et al. (1989) and Turk and Celan (2004) reported that bony structure weight (an artificial anthropometric measure) was a significant predictor for the cross-sectional areas of the lower lumbar intervertebral discs. The influence of height was confounded in their regression models, because bony structure weight was intended to estimate the weight of the complete skeleton and was calculated using subject height Matiegka (1921).

As indicated by the equations, cross-sectional areas (CSAs) of the lower lumbar motion segment, in general, are larger in male subjects than female ones and increase with the elevation of height for both gender groups, except for the CSA of the caudal endplate which is not affect by gender. This pattern of change may be very helpful to explain the considerably large differences found in geometric data summarized from the previous mechanical studies (Nachemson, 1960; Hutton & Adams, 1982; Brinckmann et al., 1989). The study in Chapter 3 (refer to Table 3.49) revealed that geometric data reported by Nachemson (1960) had very large differences between genders (4.22 cm^2 at the L3/L4 level and 2.42 cm^2 at the L4/L5 level), where Hutton and Adams (1982) exhibited 4.20 cm^2 (L3/L4) and 3.72 cm^2 (L4/L5) female/male differences and Brinckmann et al. (1989) exhibited 5.43 cm^2 (L3/L4) and 3.16 cm^2 (L4/L5) female/male differences. The present study suggested that the large variations in the cross-sectional areas may be attributed to not only the influence of gender but also the difference in height. Unfortunately, consistent

documentation and reporting of subject height are lacking in the literature, particularly since a majority of morphometric studies to date have only reported gender and age (refer to Table 3.49 to 3.51).

On the other hand, the present study reported that body weight, in general, was significantly correlated with some cross-sectional areas, but consistently weaker than height and gender. Therefore, it was not a significant predictor in the final regression models, in agreement with Turk and Celan (2004) but contradicting Colombini et al. (1989). This may be explained by the fact that the present geometric data exhibited much smaller variance compared to the body weight which had a very large standard deviation (22.61 kg) with respect to the mean (80.47 kg). Therefore, body weight was not a significant factor. In addition, one can speculate that the adult spinal structures may be associated with normal body weight to some extent as suggested by Wolff's Law that the bone can reconstruct in response to mechanical stimulation (Chaffin et al., 2006). It is very difficult, however, to predict the actual size of the spine based on body weight alone since one can easily change weight with no corresponding changes in height or other anthropometric characteristics.

Age was also not a significant predictor in the present study. The present regression models attempted to predict the characteristics of lower lumbar spines that were relatively healthy, therefore all geometric data were collected from a sample of subjects between the ages 21 and 39 years to minimize the incidence of severe disc degeneration. As a result, there was less spread of the spinal geometry over age, hence the potential significance of age could not be evaluated. In the literature, there has been disagreement regarding the influence of age. Amonoo-Kuofi (1991) measured the linear dimensions of the intradiscal space in the sagittal sections of a large sample of subjects (over 600), compared the

measurements of 5 age groups, and reported a significant influence of age, while H. Chen et al. (2011) reported no significant influence of age with much smaller sample size (83 in total). It should be noted that neither study provided information regarding the subject height and geometric dimensions were limited to the linear aspects. Therefore, the correlation between the age and the cross-sectional area of the lumbar motion segment is still unclear.

4.4.2 Model exploration

Detailed distributions of residuals (in percentage) are represented in scatter plots and illustrated in Figure 4.9 (L3/L4 level), Figure 4.10 (L4/L5 level), and Figure 4.11 (L5/S1 level). For each regression model, a majority of residuals were within the ±15% (marked as the dotted lines) from the baseline (0%). Since the residuals are defined as the difference between the "measured" value and the "predicted" value, a positive percentage indicates a case of underestimate while a negative one indicates a case of overestimate.

Extreme cases of under- and over-estimation were also evident ($> 15\%$ in absolute error). At the L3/L4 level, regression model for CrEP_CSA yielded two cases of underestimation and one case of overestimation. The model for L3/L4 IVD_CSA yielded one case of underestimation and two cases of overestimation. The model for L3/L4 CaEP_CSA yielded two cases of underestimation and two cases of overestimation. At the L4/L5 level, regression model for CrEP_CSA yielded one case of overestimation. The model for L4/L5 IVD_CSA yielded one case of underestimation and one case of overestimation. The model for L4/L5 CaEP_CSA yielded one case of underestimation and two cases of overestimation. At the L5/S1 level, regression model for CrEP_CSA yielded

one case of underestimation and one case of overestimation. The model for L5/S1 IVD_CSA yielded one case of overestimation. The model for L5/S1 CaEP_CSA yielded two cases of underestimation and one case of overestimation. Table 4.24 presents the demographic and anthropometric data associated with these extreme cases along with the "measured", "predicted" values and residuals.

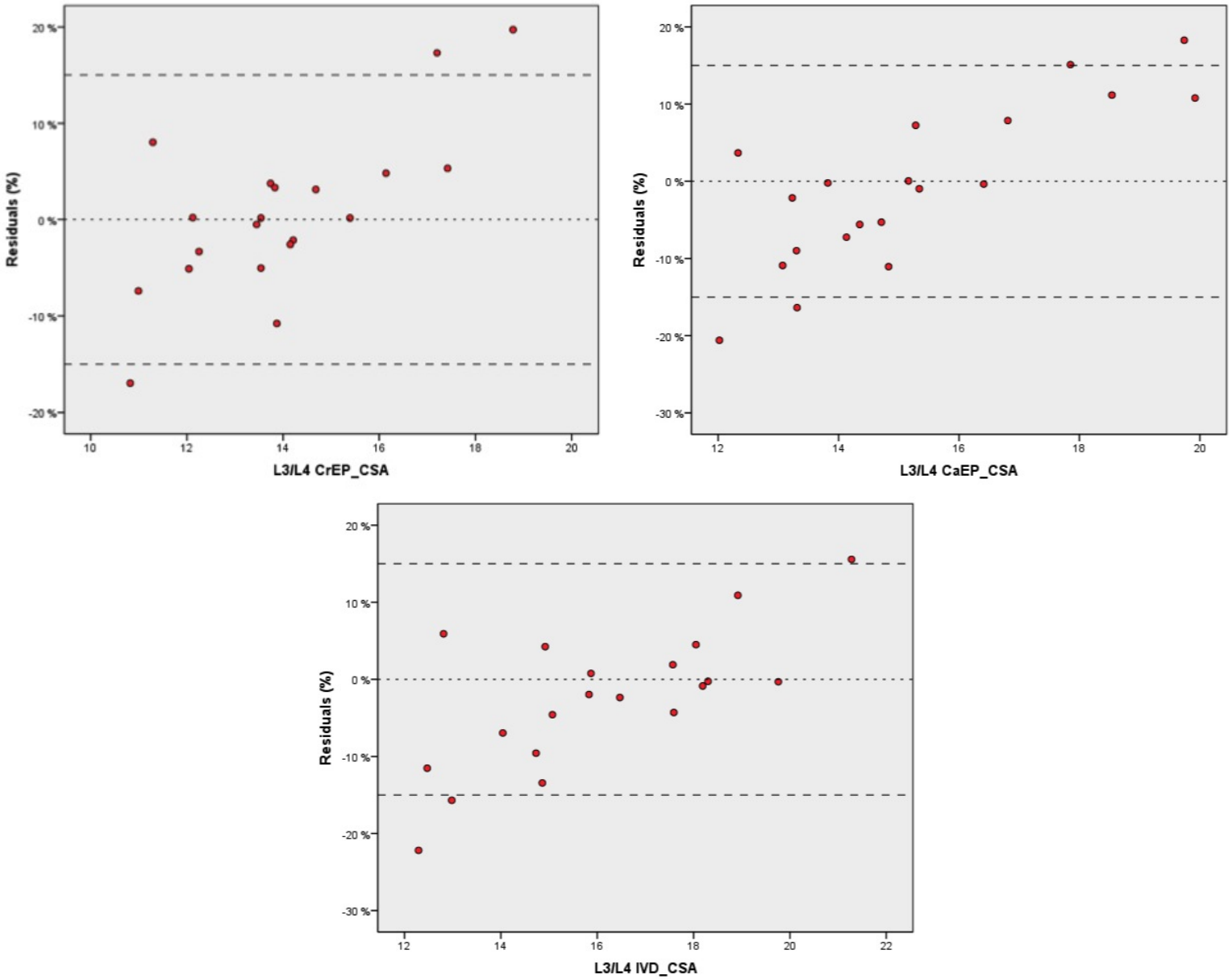


Figure 4.9: Residuals in percentage between the "measured" and "predicted" value at the L3/L4 level

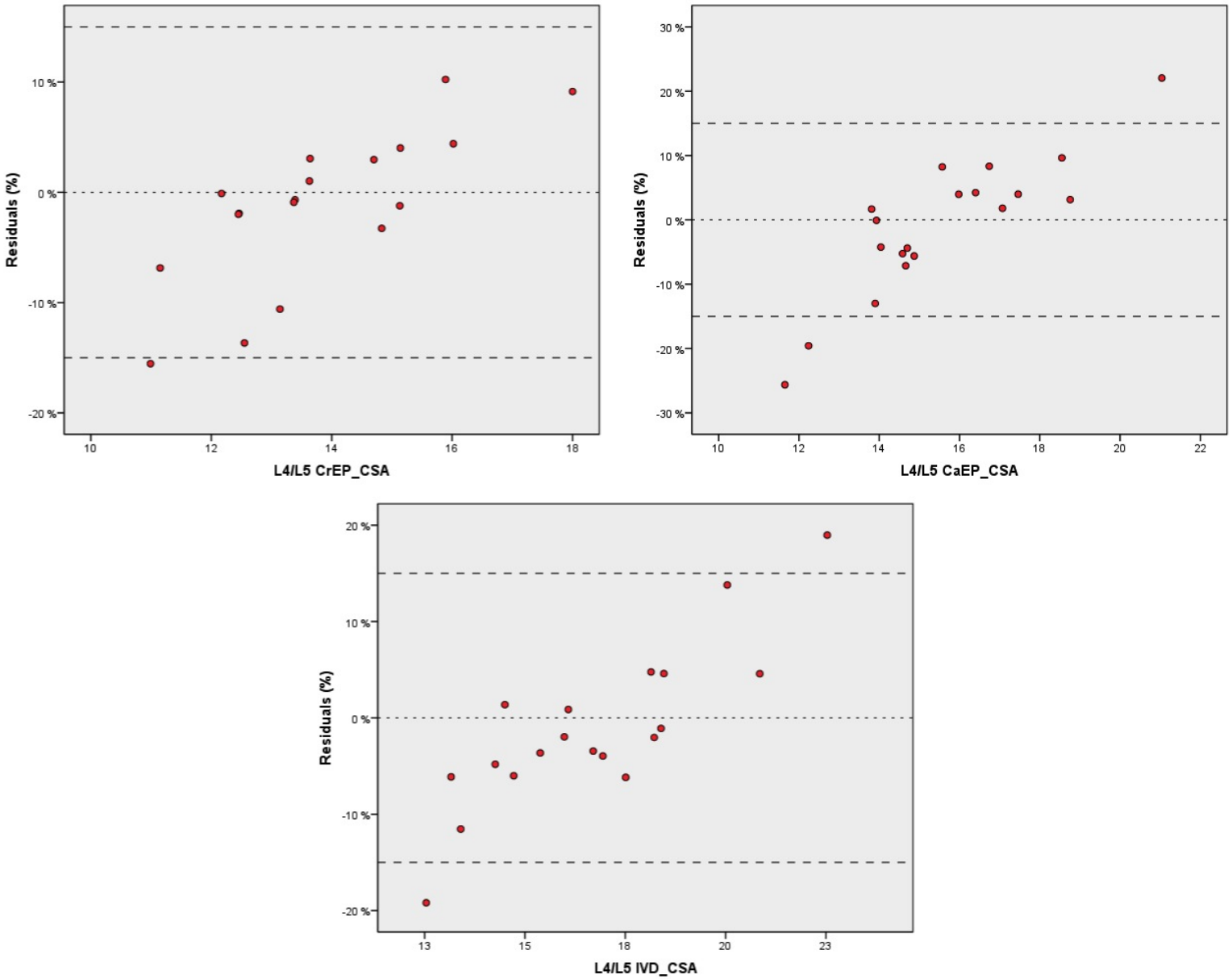


Figure 4.10: Residuals in percentage between the "measured" and "predicted" value at the L4/L5 level

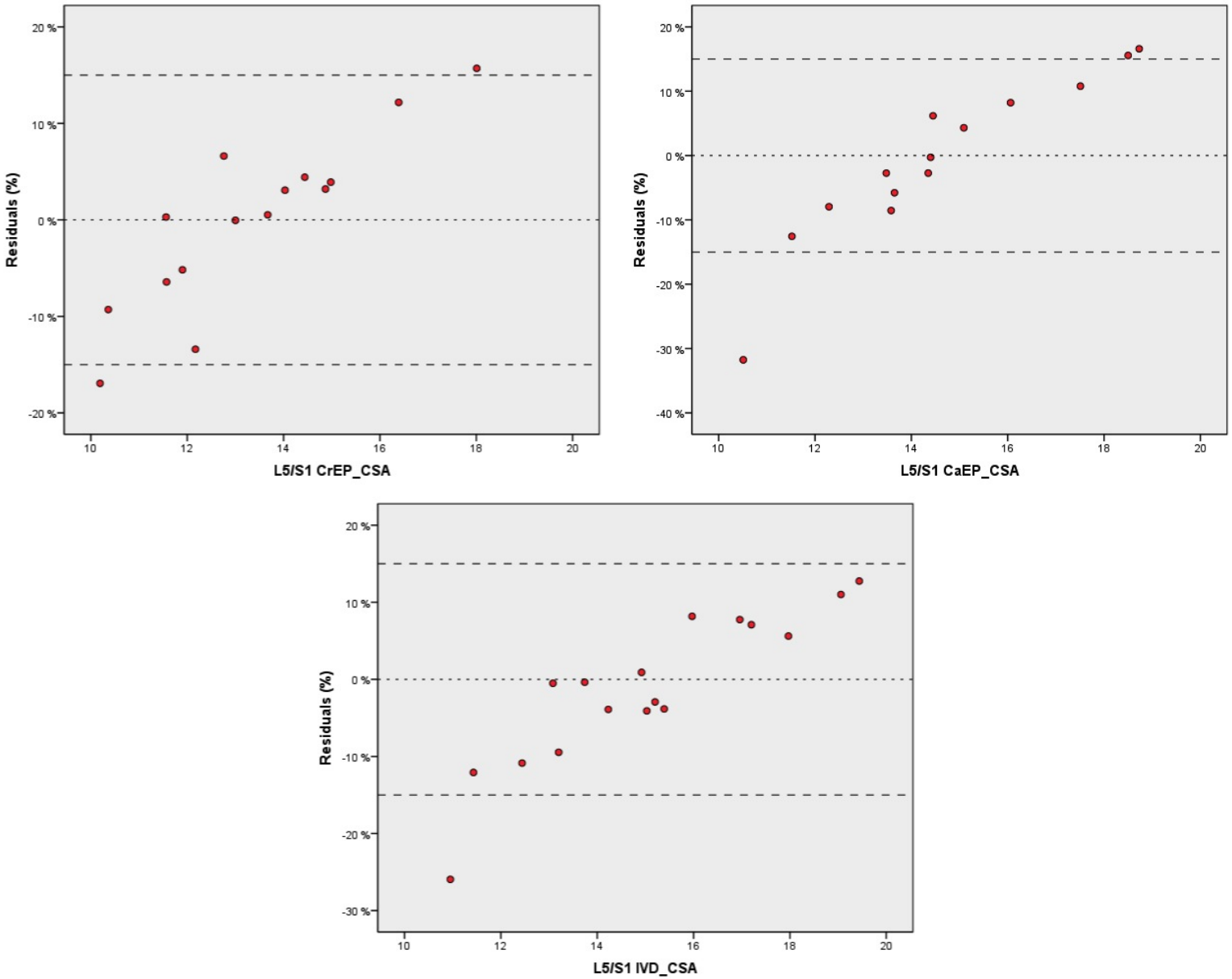


Figure 4.11: Residuals in percentage between the "measured" and "predicted" value at the L5/S1 level

Table 4.24: Subject profile associated with the extreme residuals (in %)

				L3/L4			L4/L5			L5/S1		
Subject	Ht (cm)	Wt (kg)	Age (years)	CrEP	IVD	CaEP	CrEP	IVD	CaEP	CrEP	IVD	CaEP
F16	175.3	100.70	38			-16.4						
F47	167.6	54.43	30		-15.7	-20.6			-25.6			
F84	167.6	102.06	37	-17.0	-22.2		-15.5	-19.2	-19.6	-16.9	-26.0	-31.8
M12	182.9	88.45	36									15.6
M15	182.9	81.65	31									16.6
M18	180.3	58.06	32	19.7	15.6	18.3		19.0	22.1			
M54	172.7	89.36	21	17.3		15.1						
M89	193.0	90.72	33							15.7		

As indicated in Table 4.24, most (all but one) extreme cases were associated with subjects with taller height than the average U.S. adult (162.05 cm for females and 176.02 cm for males) reported by the National Center for Health Statistics (NCHS, 2012). Since the present prediction models only included height to estimate cross-sectional area for both gender groups, the taller height yielded larger estimates. However, the estimates for female and male subjects exhibited different deviation from the baseline. All extreme cases of overestimation were associated with three female subjects, compared to the cases of underestimation which were associated with five males. This may suggest that height alone is inadequate to characterize the size of the human spine. In the present study, these female subjects had much smaller spinal morphometry compared to other females with the same height, which may be attributed to other factors, such as malnutrition and bone mineral density. On the contrary, the male subjects may have a large body frame which would lead to larger cross-sectional areas. Some studies have provided evidence that geometric dimensions of the major joints (e.g., diameters of wrist and knee) should also be included in models to predict the morphometry of the human spine (Colombini et al., 1989; Turk & Celan, 2004).

4.5 Conclusion

The objective of the present study was to develop regression models with easy-to-measure predictors (e.g., height, weight, gender, and age) to predict the cross-sectional areas of the lower lumbar motion segments in the transverse sections, since the morphometric data regarding these segments are extremely lacking in the literature. Superior to the previous studies, the present models were not only developed using a larger database with improved measurement accuracy, they addressed the irregular shapes of the lower lumbar intervertebral discs and vertebral endplates (refer to Chapter 3), and also the model performance of these regression equations was tested using another dataset. The relatively large sample and thorough regression analyses helped generate reliable prediction models which obtained statistically satisfactory performance in the validation process. The present study also compared the performance of linear and polynomial models and suggested that linear models may be more appropriate to characterize the variance of the cross-sectional area within the dataset. The present study found that subject height, along with gender, were two significant predictors in the linear models, compared to weight and age which were not significant. This may help explain the relatively large differences found in some previous studies. Absolute errors associated with linear models, on average, were 7% for the L3/L4 models, 6% for the L4/L5 models, and 8% for the L5/S1 level.

However, it was also noted that for some cases, the regression models performed poorly, suggesting that height and gender alone may be inadequate to explain the variances, which was also evident in terms of model statistics (e.g., R^2). Secondly, the regression models provided in the present study may not be applicable for adolescent or

subjects over 40 years. It also should be noted that the morphometric data from previous study were obtained while subjects were in supine position, which may not be a good representation of a standing posture. Lastly, the present regression models were tested using morphometric data which were also derived from an archived medical database. Future studies should validate these models using data from asymptomatic subjects. Future regression analyses should also include more anthropometric characteristics (e.g., major joints and segments) to better characterize the human spinal morphometry.

Chapter 5

PREDICTION OF THE CROSS-SECTIONAL AREA OF HUMAN LOWER LUMBAR INTERVERTEBRAL DISC AND VERTEBRAL ENDPLATE: REGRESSION MODELS OF GEOMETRIC DIMENSIONS DERIVED FROM MR SCANS USING ASYMPTOMATIC SUBJECTS

The manuscript in the following pages is in preparation for submission to a peer-reviewed academic journal.

Prediction of the cross-sectional areas of the human lower lumbar intervertebral discs and vertebral endplates: regression models of geometric dimensions derived from MR scans using asymptomatic subjects

5.1 Introduction

The reliable estimation of the risks of work-related musculoskeletal disorders (WRMSDs) has been one of the most challenging issues in occupational ergonomics and health practices, particularly the attempt to characterize the risk of work-related low back pain (WRLBP) in the manual material handling industry (Andersson, 1979; Garg & Moore, 1992; Andersson, 1998). Research effort has primarily been devoted to the development of ergonomic evaluation measures (or "tools") to pinpoint jobs with elevated risks (NIOSH, 1981; Chaffin, 1988; Marras & Sommerich, 1991a, 1991b; Waters et al., 1993; Bloswick & Villanve, 2000). Biomechanical models of the musculoskeletal structures of the human spine represent one of the primary foundations for ergonomic evaluation measures. (NIOSH, 1981; Waters et al., 1993). The paradigm of this approach is to mathematically model the translation of force introduced by external loadings or upper body weight into internal response in terms muscle induced compressive forces and, therefore, quantify the associated risk of WRLBP (Chaffin & Park, 1973; Chaffin, 1988). To date, complex models have been developed to model the complexity of spinal motions (e.g., sagittal extension and lateral bending), with respect to the human low back spinal musculature (A. B. Schultz, Andersson, Haderspeck, et al., 1982; A. B. Schultz, Andersson, Ortengren, et al., 1982; McGill & Norman, 1985; Németh & Ohlsén, 1986; Chaffin, 1988; Jorgensen et al., 2001; Marras et al., 2001).

Unfortunately, the significance of the morphometry of the human spine has not yet been thoroughly investigated regarding the development of biomechanical models (as discussed in Chapter 3), despite the fact that geometric representations of the human spine (Fisher, 1967; Sicard & Gagnon, 1993; Nussbaum & Chaffin, 1996; Y. L. Chen, 1999) have been critical in the development of some biomechanical models, translating external loadings into the internal response of the lumbar spine (Chaffin, 1969) and characterizing the biomechanical behavior of the lumbar spine (Campbell-Kyureghyan et al., 2005). As the primary model output, muscle induced compressive force is calculated and is typically related to an established ultimate compressive strength of the human lumbar motion segment (Jager & Luttmann, 1989; NIOSH, 1981; Waters et al., 1993) and the corresponding elevated risk of WRLBP (Chaffin & Park, 1973). In the literature, the general agreement on the ultimate compressive force was based on a summary of historical data that were obtained by testing single-level lumbar motion segments (one intervertebral disc and two adjacent vertebral endplates) (F. G. Evans & Lissner, 1959; Sonoda, 1962; Eie, 1966; Hutton & Adams, 1982; Jager & Luttmann, 1989). However, as discussed in Chapter 2, depending on the mechanical measure used (force vs. pressure), the profile of ultimate compressive strength may exhibit a different pattern.

On the other hand, a number of studies have reported that bone mineral content (BMC), as a function of the cross-sectional area (CSA) of the motion segment and the bone mineral density (BMD), can be used to predict the ultimate compressive strength of a lumbar motion segment (Biggemann et al., 1988; Brinckmann et al., 1989; Singer et al., 1995; Gallagher et al., 2007). With animal cadavers, some researchers reported a linear relationship between the CSA of the vertebral endplate and the ultimate compressive

strength (Parkinson et al., 2005). As discussed in Chapter 2, it is necessary to account for spinal geometry when determining the risk of WRLBP. In additon, it may be possible to actually estimate the risk on an individual basis, rather than on a population basis, which can provide a new paradigm of ergonomic evaluation for WRLBP and more personalized risk estimation.

As discussed in Chapter 3, current understading of the morphometry of human lumbar motion segments is still unclear, due to insufficient geometric data and lack of a standardized measurement protocol. It was also noted in Chapter 3, that the majority of geometric data reported were obtained through complex measurements on cadaveric specimens (Nachemson, 1960; Hansson et al., 1980; Hutton & Adams, 1982; Postacchini et al., 1983; J. L. Berry et al., 1987; Brinckmann et al., 1989; Panjabi et al., 1992) and medical images, including radiographs (Nissan & Gilad, 1984; Amonoo-Kuofi, 1991; Aydinlioglu et al., 1999; Y. Wang et al., 2012), computed tomography (CT) scans (van Schaik et al., 1985; Colombini et al., 1989; Zhou et al., 2000; van der Houwen et al., 2010; H. Chen et al., 2011), and magnetic resonance (MR) scans (Aharinejad et al., 1990). As discussed in Chapter 4, these techniques may provide better accuracy. However it is financially infeasible for most of industry to rely on such techniques to determine an individual's specific spinal morphometry when evaluating the personalized risk of WRLBP. As discussed in Chapter 4, predicton models using simple subject variables (e.g., gender, age, and other anthropometric measures) as a cost-effective means has been investigated with respect to feasibility and accuracy (Colombini et al., 1989; Turk & Celan, 2004; Seidel et al., 2008). Some researchers suggested that it was feasible to predict the CSAs (Colombini et al., 1989; Turk & Celan, 2004); and certain anthropometric measures may be superior

predictors to estimate CSAs (Colombini et al., 1989). On the other hand, contradicting results were also reported, challenging the feasibility, since no significant correlations between the proposed anthropometric measures and the CSAs were found (Seidel et al., 2008). However, as discussed in Chapter 3 and Chapter 4, for these studies, the accuracy of the geometric data, as well as the soundness of the regression analyses are questionable.

With more accurate data and thorough regression analyses, the study in Chapter 4 corroborated that it is feasible to obtain satisfactory predictions for CSAs of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs). However, it may be unwise to assume that regresson models using geometric data from a sample of pre-screened medical MR scans share homogeneity with a healthy population without any further investigation. Secondly, in Chapter 4, prediction models were based on regression analyses of four subject variables available with the MR scans (age, gender, height, and weight), which limited the regression models' ability to explain more variance in the morphometry of the lower lumbar motion segment. Additonaly, certain anthropometric measures have been shown to exhibit superior prediction in regression models (Colombini et al., 1989; Turk & Celan, 2004) and better characterize the overall development and weight distribution of the human skeletal system (Matiegka, 1921). Other anthropometric measures regarding major body segments may also be closely correlated with the CSAs (Jorgensen et al., 2003; Stemper et al., 2008).

Therefore, the present study conducted morphometric analysis using MR scans with a young and healthy sample, and developed regression models using comprehensive anthropometric measures in order to better predict the cross-sectional areas (CSAs) of the human lumbar intervertebral discs (IVDs) and vertebral endplates (EPs). Comparisons of

model performance were also made between the models developed in the present study and the models in Chapter 4.

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. All subjects were in good health condition and between 20 to 40 years of age. The average age was 26.9 years old, ranging from 21 to 35 years. The average age for male subjects was 27.8 years old with a range from 22 to 35 years, and the average age for female subjects was 25.5 years old, ranging from 21 to 34 years. At the time of study, no subjects had any self-reported episodes of low back pain (LBP) for the previous two years and no previous medical treatment for low back pain (e.g., surgical procedure). Subject personal identifiers were not included in the dataset, such as name, birth date, and student identification number. The research protocol of this study was approved by the Institutional Review Board (IRB) at Auburn University (Appendix B).

5.2.2 Acquisition of magnetic resonance (MR) scans

Lumbar spine MR scans of the subjects were performed on a 70 cm Open Bore 3 Tesla scanner (MAGNETOM Verio, Siemens AG, Erlangen, Germany) at the Auburn University MRI Research Center. All subjects were examined in head-first-supine position (HFS) with arm and leg supports available at subject request (Figure 5.1). The imaging protocols included:

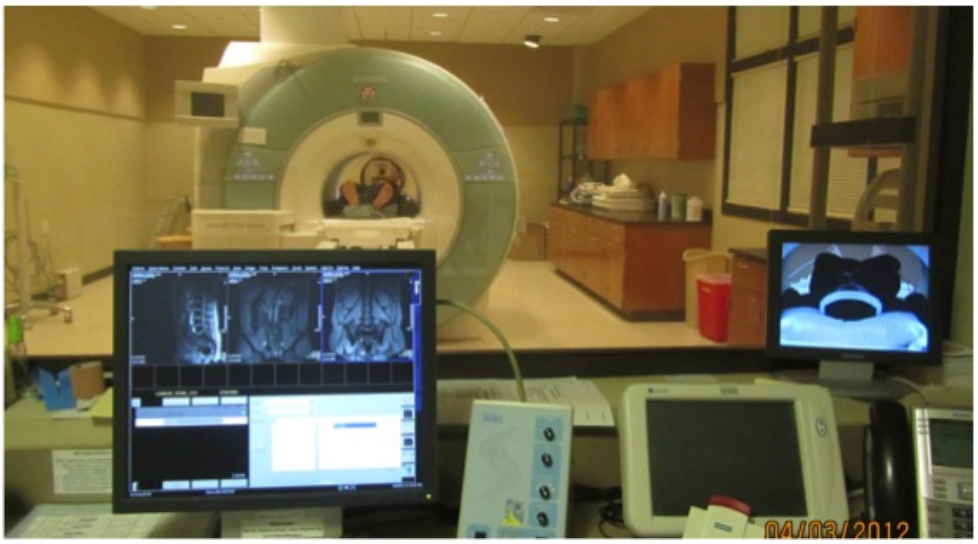
1. A standard morphological T2-weighted turbo-spin-echo (TSE) sequence in the mid-sagittal plane, including at least L2 to S1, with a repetition time (TR) of 4400 ms, a echo time (TE) of 100 ms, a matrix of 384 × 288. The section thickness was 4.5 mm and the voxel size was 0.78 mm × 0.78mm × 4.5mm.

2. A standard morphological T2-weighted TSE sequence of the lower lumbar intervertebral discs and vertebral endplates in the axial plane, with a TR of 7880 ms, a TE of 94 ms and a matrix of 320 × 240. The section thickness was 3mm and the voxel size was 0.69 mm × 0.69 mm × 3mm. The axial slicing planes were manually adjusted according to the orientation of the structures of interest (Figure 5.2) to minimize errors and distortions in spinal structure reconstruction. For each lower lumbar level, at least three MR scans were obtained with respect to 1) the intervertebral disc (IVD) (Figure 5.2 (B)), 2) vertebral endplate cranial to the IVD (CrEP) (Figure 5.2 (A)), and 3) vertebral endplate caudal to the IVD (CaEP) (Figure 5.2 (C)).

All MR scans were anonymized and stored in the picture archiving and communication system (PACS; Siemens Healthcare Global), and then transferred tp a local workstation through a secure file sharing system: Auburn University Network (AUNET) (Auburn University, Auburn, AL, USA).

5.2.3 Image analysis

All transferred MR scans were analyzed using OsiriX® (v.4.0, Pixmeo, Geneva, Switzerland), an open source image analysis software package for the Apple Mac OS (Microsoft Corp, Redmond, Washington), which has been used in a wide variety of clinical diagnoses and scientific research studies (Rosset et al., 2004; Yamauchi et al., 2010). All



(a) MR scan in progress, communication through the earphone

(b) Subject in head-first-spine postion

Figure 5.1: Demonstration of MR scan operation

discs were assessed for health status according to the grading system developed by Pfirrmann et al. (2001), which has well-accepted validity to evaluate the status of disc degeneration (Pappou et al., 2007; Takatalo et al., 2009; D. S. Schultz et al., 2009; Rodriguez et al., 2012). Table 5.1 provides the detailed description of each degeneration grade. Figure 5.3 illustrates examples of MR scans showing each degeneration grade. The

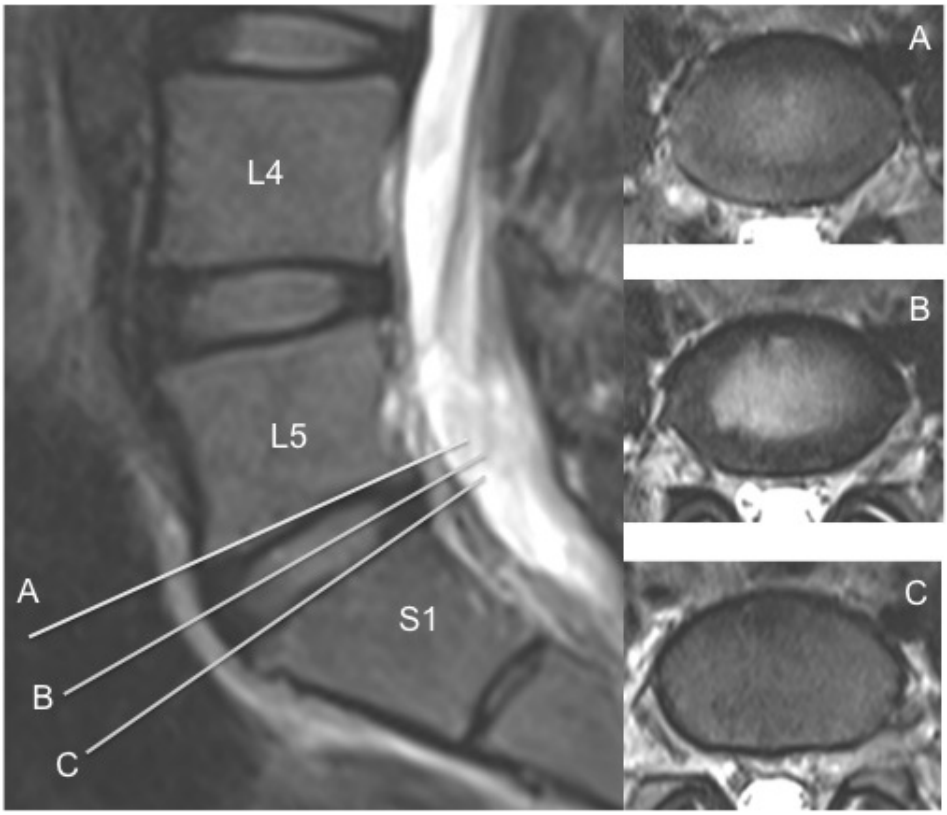


Figure 5.2: Axial T2 weighted scan of the anatomical structures of interest: A) cranial endplate, B) intervertebral disc, and C) caudal endplate

grade of degeneration was analyzed on the sagittal T2-weighted MR scans. In this study, with respect to spinal morphometry, discs in Grade I and Grade II were grouped as "healthy", discs in Grade III and IV were regarded as "moderately degenerated", and Grade V were regarded as "severely degenerated". According to Table 5.1, discs in Grade V have collapsed disc space, which would alter their geometric characteristics. For the purposes of this study, data regarding Grade V discs and their adjacent endplates were excluded from the final analyses.

Measurement for the cross-sectional area (CSA)

Three measurements for cross-sectional area were obtained for the intervertebral disc (IVD) and the two adjacent vertebral endplates (EPs) at each lower lumbar level from

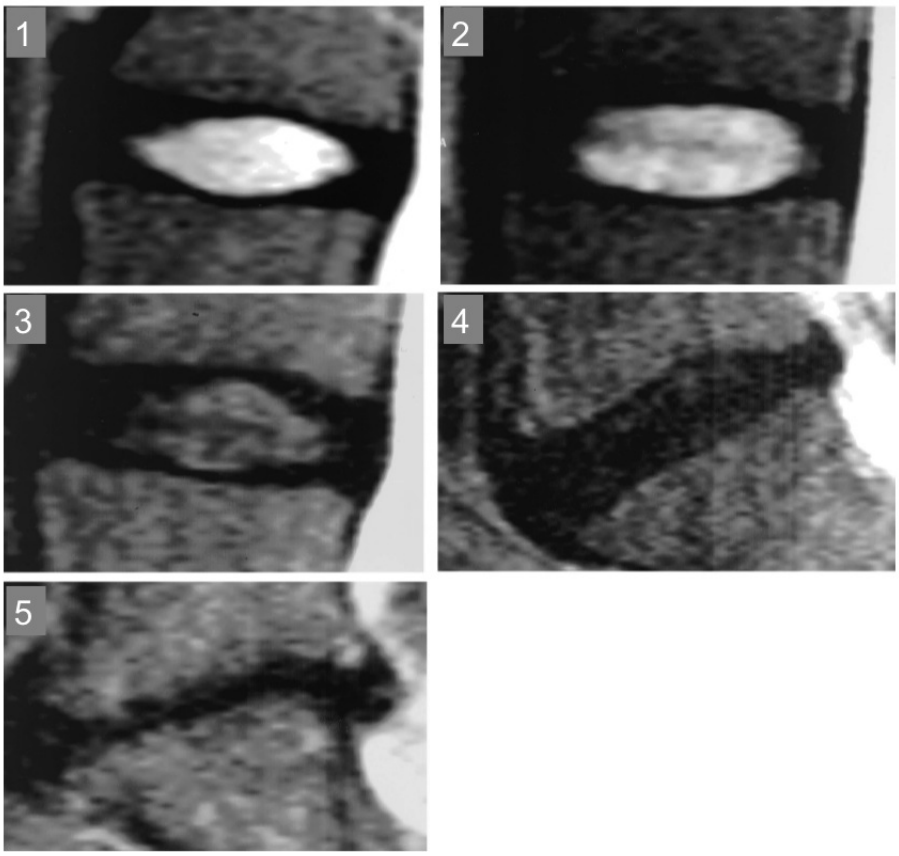


Figure 5.3: **Grade 1-5**, The numbered pictures represent examples of disc in corresponding degeneration grade. (reproduced from Pfirrmann et al. 2001)

Table 5.1: Classification of disc degeneration*

Grade	Structure	Nucleus/Annulus Distinction	Signal Intensity	Intervertebral Disc Height
I	Homogeneous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
II	Inhomogeneous, with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal
III	Inhomogeneous, gray	Unclear	Intermediate	Normal to slightly decreased
IV	Inhomogeneous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased
V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space

∗ Table reproduced from Pfirrmann et al. 2001

L3/L4 to L5/S1. Cross-sectional areas (CSAs) were determined by tracing the actual periphery of the intervertebral disc and endplate (Figure 5.4). The landmarks for geometric dimensions were manually identified and traced using a Mac work workstation equipped with high resolution display monitor (27-inch, 2560× 1440 resolution, 60 Hertz, Apple Inc., Cupertino, CA). Results of the measurement were displayed in corresponding dialog boxes.

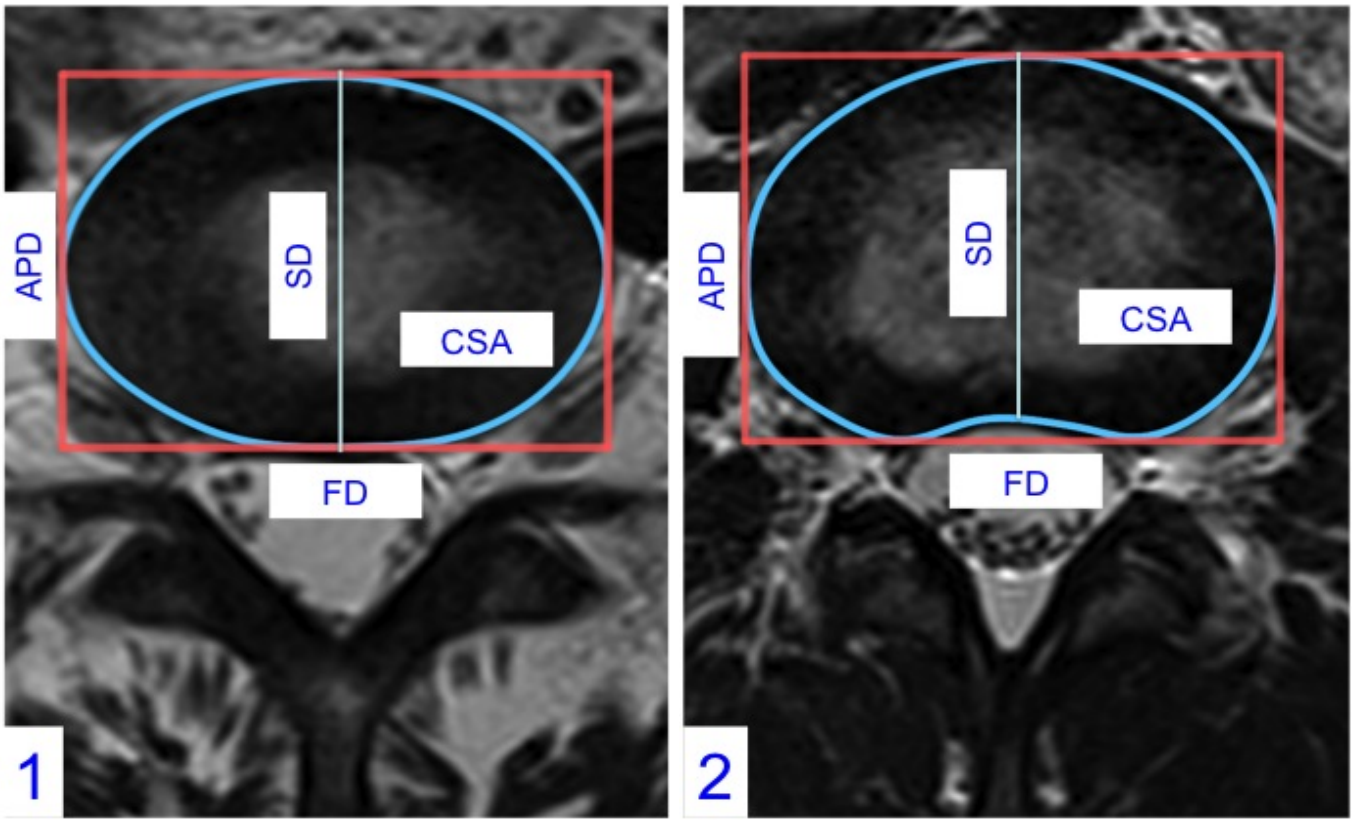


Figure 5.4: Illustrations of geometric dimensions in the transverse section (Note the different APD measurements for **1. oval-shaped** (frequently found in the L5/S1 level) and **2. "kidney-shaped"** (frequently found in the L3/L4 and L4/L5 levels))

5.2.4 Subject characteristics and anthropometrics

Subject characteristics

A series of survey questions were answered by subjects regarding their dominant side (right-, left-hand dominant, or ambidextrous) and physical activity levels with respect to exercise type (weight lifting and cardiovascular training) and frequency (1. everyday, 2. every 2 to 3 days, and 3. every week) (Appendix C).

Anthropometric measurements

Anthropometric measurements were taken while subjects were wearing sports clothing. Subjects were weighed using a metric unit (kg) scale. Other anthropometric measurements were made using an anthropological instrument kit (GPM, Switzerland). An anthropometer was used to measure subject sitting and standing heights, chest breadth and depth, shoulder width, head depth, and arm length. Figure 5.5 shows how these anthropometric measurements are defined. Sliding (Martin type) and spreading calipers were used to measure the widths (W) of the head, elbow, wrist, hand, knee, and the length (L) of hand. Circumferences (C) of head, elbow, wrist, hand, knee, and ankle were measured using a Gulick anthropometric tape. Sitting height, chest breadth and depth, and the dimensions of head (width, depth, and circumference) were measured while subjects were sitting on a chair with feet flat on the floor and knees flexed at 90^o. Standing height, shoulder width, arm length, hand length, and the dimensions of the elbow, wrist, hand, knee, and ankle (width and circumference) were measured while subjects were in erect position (standing upright). Anthropometric measurements for the limbs (hand, elbow, arm, knee, and ankle) were taken from both the right and left side.

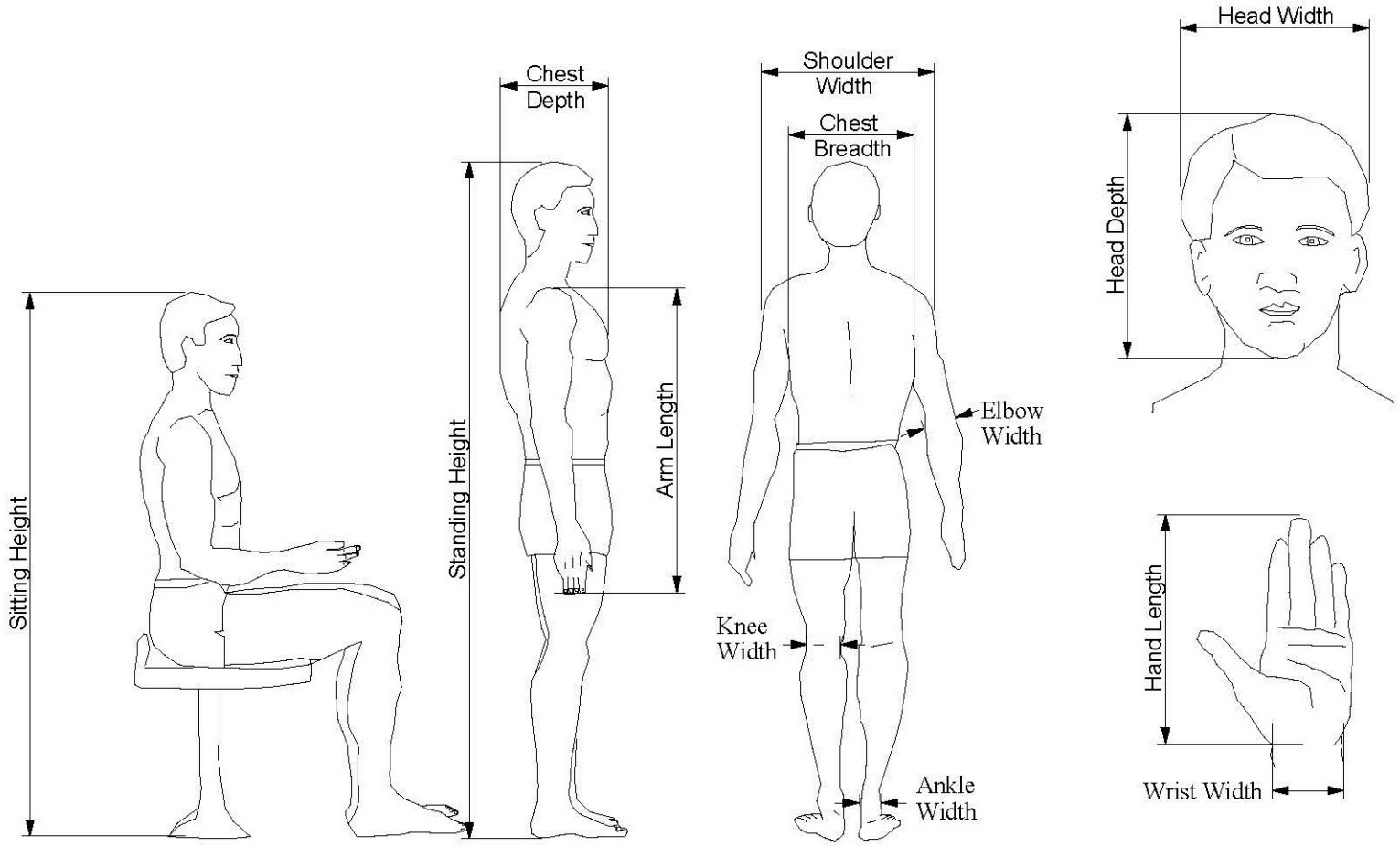


Figure 5.5: Anthropometric measurements

To characterize the overall human skeleton, two additional anthropometric characteristics, the average square thickness of bony structures (AST) and the bony structure weight (SW), were calculated using formulas originally developed by Matiegka (1921) (Formula 5.1 and 5.2). A modified formula (Formula 5.3) to calculate AST was also employed, which was proposed by Turk and Celan (2004).

$$AST = \left(\frac{W_{wrist} + W_{elbow} + W_{knee} + W_{ankle}}{4}\right)^2 \tag{5.1}$$

$$SW = AST \times Ht \times 1.1 \tag{5.2}$$

$$AST_{Turk} = \left(\frac{W_{wrist} + W_{elbow} + W_{knee}}{3}\right)^2 \tag{5.3}$$

Body composition

Lean body mass (LBM) is the "fat-free" portion of a subject's body weight which is comprised of all nonfat tissues including bones, muscles, and connective tissues. Body composition, as the ratio of fat weight to subject total mass is an anthropometric measure to describe the relative distribution of body weight. Skinfold methods are a simple, quick, and cost-effective means to measure the body composition and provide satisfactory results, when compared to the "gold standard" of hydrodensitometry (ACSM, 2009). The accuracy of predicting percent fat from skinfold measurements is very high ($\pm 3.5\%$) when appropriate skinfold sites, techniques, and equations are used (ACSM, 2009). In the present study, a three-site approach was employed using a calibrated Lange Skinfold Caliper (Beta Technologies, Santa Cruz, CA, USA) to measure the abdominal, chest-pectoral, and thigh

for males and superiliac, triceps, and thigh for females (Figure 5.6). Descriptions of skifold sites and measurements are given below, as standardized by ACSM (2009).

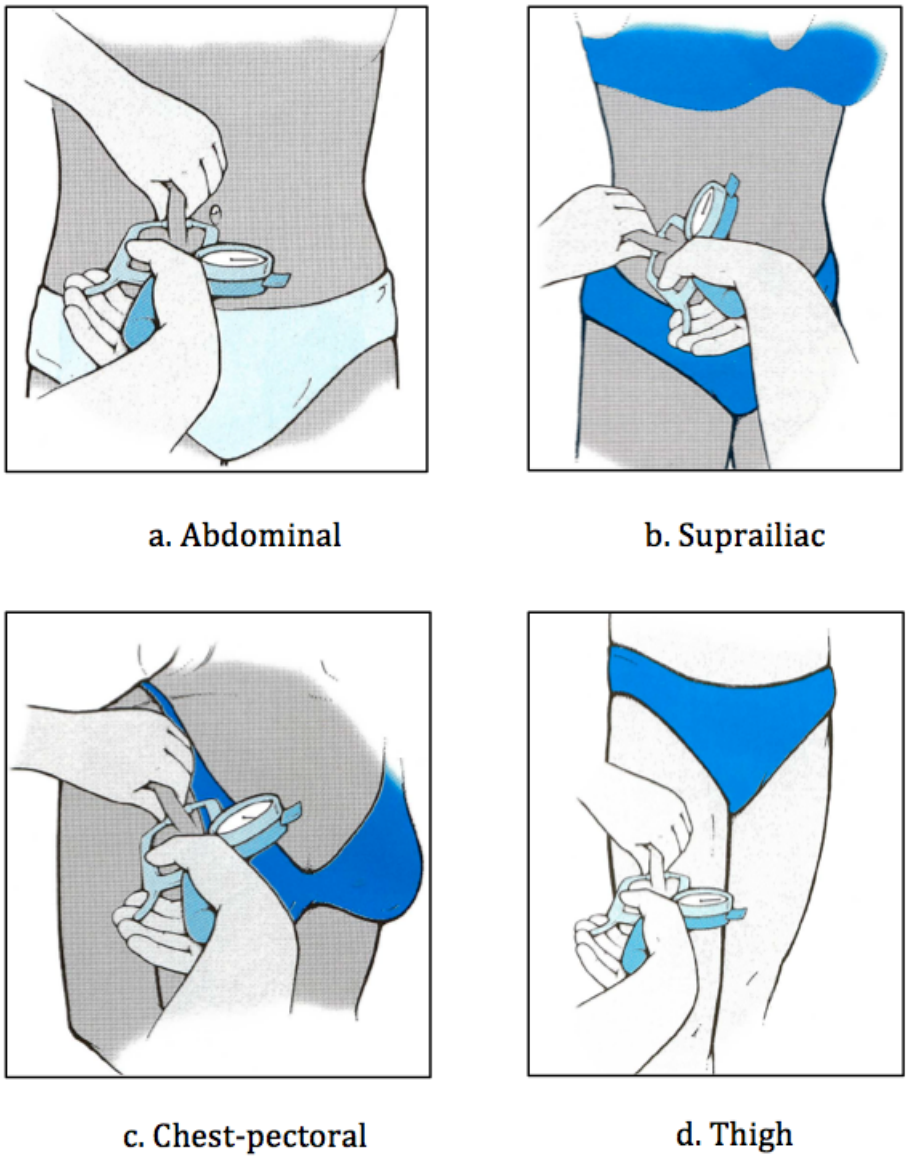


Figure 5.6: Anatomical locations for skinfold sites

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.

***Abdominal (male)*:** vertical fold; 2 cm to the right of the umbilicus (Figure 5.6a),

***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 5.6b),

***Chest-pectoral (male)*:** diagonal fold; half the distance between the anterior axillary line and the nipple (Figure 5.6c),

***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 5.6d).

In this study, all skinfold measurements were taken on subjects' dominant sides while in an erect posture, except for the measurement of thigh, for which subjects stood on their non-dominant leg and supported the dominant leg with the toe. At each site, three duplicate measurements were taken, and if duplicate measurements were not within 1 to 2 mm, they were re-measured as ACSM (2009) suggests. The average of three measurements was recorded as the skinfold thickness for each site. Generalized prediction skinfold equations (three-site formulas) for both gender (given below) were used to calculate the body density (BD).

$$BD_{\text{Male (chest, abdomen, thigh)}} = 1.10938 - 0.0008267 \times Sum + 0.0000016 \times Sum^2 - 0.0002574 \times Age \tag{5.4}$$

$$BD_{\text{Female (triceps, suprailiac, thigh)}} = 1.099421 - 0.0009929 \times Sum + 0.0000023 \times Sum^2 - 0.0001392 \times Age \tag{5.5}$$

Subject body density (BD) values were converted to body fat percentage (BFP) by using the generalized formula (Formula 5.6), which then were used to calculate subject lean body

mass (LBM) (Formula 5.7).

$$BFP = \frac{(495 \div BD) - 450}{100} \tag{5.6}$$

$$LBM = Wt \times (1 - BFP) \tag{5.7}$$

5.2.5 Statistical analysis

Independent Student's T-tests were used to compare subject characteristics and anthropometric measures, such as subject height and body weight. Independent t tests were also used to analyze the difference between physical exercising and non-excercise groups and between the present study and the previous study (Chapter 3) in terms of the cross-sectional areas (CSAs).

Split Plot Factorial Design (2×3 ANOVA) were used to determine the effect of gender, spinal level, and interactions of these two on the CSAs of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs).

Tukey's post-hocs tests were performed, using honestly significant difference (HSD) (Montgomery, 2005), to determine the trend of changes in the spinal morphometry across the three lower lumbar spinal levels (L3/L4, L4/L5, and L5/S1).

HSD = $q(a,\ df) \times \sqrt{MS_{Within}/n}$; where **q** is the studentized range statistic, **a** is the number of treatments, and **df** is the number of degree of freedom associated with MS_{Within} at α=0.05), MS_{Within} is mean square term within subjects, and **n** is the number of subjects.

Independent Student T-tests were also used to analyze the main effect of gender on the spinal morphometry and also used to compare the morphometric data of the same structure of interest across the lower lumbar spine (e.g., L3/L4 IVD_CSA vs L4/L5 IVD_CSA and L4/L5 CrEP_CSA vs L5/S1 CrEP_CSA). **Paired sample T-tests** were also used to compare measurements regarding the structures of interest which have been assumed to be related to each other, for example the two adjacent endplates in a single-level lumbar motion segment (CrEP_CSA vs CaEP_CSA), or the two endplates associated with one lumbar vertebra (L3/L4 CaEP_CSA vs L4/L5 CrEP_CSA and L4/L5 CaEP_CSA vs L5/S1 CrEP_CSA).

Correlation analyses were performed to characterize the association between the subject variables (characteristics and anthropometrics) and the CSAs (CrEP_CSA, IVD_CSA, and CaEP_CSA) of the lower lumbar spine (L3/L4, L4/L5, and L5/S1). Correlation among subject variables were also analyzed to determine the ones highly correlated so that they may be removed from analyses or combined into an index variable.

Best subset regression analyses were performed to determine models with the "best" subset of predictors for the CSAs, for which the coefficients and significance of each predictor were determined using an **enter method**. ANOVA tests were performed to determine whether the models are significant. In addition, regression models with easy-to-measure subject variables (gender, age, height, and body weight) were also developed using a **backward method** and then compared to the previous models (discussed in Chapter 4). Best subset regression analyses were performed using Minitab (version 15 Minitab Inc., State College, PA). Other statistical analyses were performed

using SPSS (version 19.0 IBM SPSS Statistics, IBM Corporation, Armonk, NY). The level of significance was set at 0.05.

5.3 Results

5.3.1 Descriptive statistics

Subject characteristics and anthropometrics

Subject characteristics

Table 5.2 summarizes subject characteristics for subject physical activities (weight lifting and cardiovascular exercise) and dominant side. Approximately, half of subjects (46%) reported regularly performing weight lifting or resistance exercise. Eighty percent of subjects (80%) were regular cardiovascular exercisers. Both genders exhibited similar level of physical activity in terms of physical exercising.

With respect to the dominant side, approximately 89% of subjects were right-hand-dominant, 9% of them were left-hand-dominant, and 3% of them self-reported as ambidextrous. Three male subjects were left-hand dominant and only one male subject was ambidextrous. No female subjects were left-hand-dominant or ambidextrous.

Subject anthropometrics

Table 5.3 presents descriptive statistics for subject anthropometrics. Female subjects were significantly shorter and lighter than male subjects (p=0.000). The average height and weight were 160.9 (7.8) cm and 57.2 (10.2) kg for female subjects and 177.1 (7.7) cm and 82.7 (10.8) kg for male subjects. Female subjects, on average, had "normal" BMI (22.0 kg/m^2), compared to male subjects with "overweight" BMI (26.3 kg/m^2) based on the

Table 5.2: Subject characteristics: physical activities and dominant-hand-side

		Female				**Male**				**Total**			
		N		**Percentage**		**N**		**Percentage**		**N**		**Percentage**	
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%	

classification system suggested by the world health organization (WHO) (refer to Chapter 3). Female subjects had an average of 25.6% body fat, which weighted 15.1 kg. Male subjects had significantly smaller body fat percentage (p=0.002, 19.4%) and hence significant heavier lean body mass (LBM) (p=0.000). Weights of the body fat were not statistically different between two gender groups (p=0.589). Female subjects had statistically smaller sitting height, shoulder width, head width, head circumference, head depth, chest breadth, and chest depth than male subjects (p=0.000).

Table 5.3: Descriptive statistics for subject anthropometric measurements

	Gender	**N**	**Mean**	**St.d.**	**Min**	**Max**	**t**	**df**	**Sig.**
Height (cm)	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 (kg)	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 (kg/m^2)	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 (kg)	Female	13	15.1	5.9	8.2	24.6	-.546	33	0.589
	Male	22	16.0	4.1	7.8	26.5			
Lean Body Mass (kg)	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 (cm)	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 (cm)	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 (cm)	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 (cm)	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 (cm)	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 (cm)	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 (cm)	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			

Table 5.4 presents descriptive statistics for subject anthropometrics of the upper and lower limbs from both sides for both gender groups. Compared to male subjects, female subjects had significantly smaller anthropometric measurements of the upper and lower limbs ($p<0.05$).

Table 5.4: Descriptive statistics for the anthropometric measurements from both sides

		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			

Table 5.4: Descriptive statistics for the anthropometric measurements from both sides

		Side	Gender	N	Mean	St.d.	Min	Max	t	df	Sig.
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			
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			

Table 5.4: Descriptive statistics for the anthropometric measurements from both sides

		Side	Gender	N	Mean	St.d.	Min	Max	t	df	Sig.
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			

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

Pairwise t tests revealed that there were significant differences between the right and left wrist circumference (p = 0.018), the right and left hand length (p = 0.008), the right and left hand width (p = 0.038), the right and left knee width (p = 0.034), and the right and left ankle width (p = 0.039). Since the differences were very small (approximately 1%) and had minimal biological plausibility for the purpose of this study, an average value for both sides was calculated. The average limb anthropometrics are presented in Table 5.4. All female limb anthropometric measurements were also significantly smaller than males. The main reason for averaging both sides was that the number of subject variables exceeded the number of observations, which may pose issues for statistical analyses.

Table 5.5 presents descriptive statistics of the average square thickness of bony structures (AST) and bony structure weight (SW) calculated with averaged limb

anthropometrics. AST and SW for female subjects were statistically smaller than males (p=0.000).

Table 5.5: Descriptive statistics for the average square thickness of bony structures (AST) and bony structure weight (SW)

	Gender	**N**	**Mean**	**St.d.**	**Min**	**Max**	**t**	**df**	**Sig.**
AST (cm^2)	Female	13	50.15	7.11	40.80	62.21	-8.024	33	***0.000****
	Male	22	66.64	5.03	57.00	75.69			
AST_{Turk} (cm^2)	Female	13	53.69	8.16	42.03	65.34	-6.980	33	***0.000****
	Male	22	70.82	6.27	59.55	84.95			
SW (cm^3)	Female	13	8919.10	1641.41	6884.62	12331.79	-8.130	33	***0.000****
	Male	22	12996.90	1300.30	10417.99	15677.67			

Measurements of the intervertebral disc (IVD) and vertebral endplate (EP)

Disc degeneration

Table 5.6 summarizes the overall disc degeneration status among all the subjects. At each lower lumbar spinal level, a majority of intervertebral discs were normal and no disc was in a severely degenerated condition. Therefore, no disc was excluded from the final analysis.

Table 5.6: Overall disc degeneration status

		Normal		Moderate		Severe
		Grade I	Grade II	Grade III	Grade IV	Grade V
L3/L4	Female	0	12	0	1	0
	Male	1	17	4	0	0
	Total	1	29	4	1	0
L4/L5	Female	0	12	1	0	0
	Male	4	14	4	0	0
	Total	4	26	5	0	0
L5/S1	Female	0	12	1	0	0
	Male	5	11	4	2	0
	Total	5	23	5	2	0

Cross-sectional areas (CSAs) of the intervertebral disc (IVD) and vertebral endplate (EP)

Table 5.7 presents the descriptive statistics for both genders and the overall sample for the cross-sectional areas (CSAs) of the intervertebral disc (IVD) and vertebral endplate (EP) at each lower lumbar spinal level measured on MR scans, including the mean, standard deviation and range of data. All figures illustrate means and 95% confidence intervals (CIs) with respect to each geometric dimension measured on MR scans.

Table 5.7: Cross-sectional areas (CSAs) of the intervertebral disc (IVD) and vertebral endplate (EP)

			N	Mean	SD	Min	Max
L3/L4	CrEP_CSA	Female	13	11.36	1.57	9.67	15.02
		Male	22	15.38	1.76	12.27	18.77
	IVD_CSA	Female	13	13.22	2.06	10.32	17.60
		Male	22	17.41	2.01	13.37	20.28
	CaEP_CSA	Female	12	13.53	2.16	11.39	18.04
		Male	22	17.71	1.92	13.04	20.57
L4/L5	CrEP_CSA	Female	13	11.38	1.64	8.51	15.58
		Male	22	15.33	1.64	11.34	17.77
	IVD_CSA	Female	13	13.14	2.01	9.77	18.03
		Male	22	17.87	2.05	13.14	20.90
	CaEP_CSA	Female	10	12.89	1.27	10.36	14.66
		Male	21	18.24	1.88	13.62	20.96
L5/S1	CrEP_CSA	Female	13	11.25	1.43	9.08	14.41
		Male	22	15.15	2.00	10.60	19.24
	IVD_CSA	Female	13	11.91	1.71	9.22	15.03
		Male	22	16.52	2.35	11.31	19.99
	CaEP_CSA	Female	13	12.06	1.76	8.69	15.67
		Male	19	16.30	1.90	11.46	19.42

Cross-sectional area of the intervertebral disc (IVD_CSA)

Statistics from SPF ANOVA (Table 5.8) indicated that the main effects for both gender (p=0.000) and spinal level (p=0.000) significantly influenced the IVD_CSA, but the main effect of their interaction was not significant (p=0.380).

Table 5.8: ANOVA summary table for the main and interaction effects of gender and spinal level on IVD_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	499.193	499.193	43.40	***0.000****
Subject(Gender)	33	379.559	11.502	17.16	
Within Subjects					
Spinal Level	2	33.641	15.929	23.76	***0.000****
Gender*Spinal Level	2	1.317	0.659	0.98	0.380
Spinal Level*Subject(Gender)	66	44.249	0.670		
Total	104	957.960			

Independent t tests (Table 5.9) revealed that the average male intervertebral discs were larger than female ones in IVD_CSAs across all three lower lumbar levels (p=0.000) with a 32% increase at the L3/L4 level, a 36% increase at the L4/L5 level, and a 39% increase at the L5/S1 level. Post-hocs analyses (Table 5.10) revealed that the difference in IVD_CSAs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, IVD_CSAs of the L5/S1 IVDs were 7% and 8% smaller than the L3/L4 and L4/L5 IVDs, respectively. Figure 5.7 illustrates the IVD_CSAs for both genders at each lower lumbar spinal level.

Table 5.9: Influence of gender on the IVD_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	-5.904	33	***0.000****	-4.190	-32%
L4/L5	-6.651	33	***0.000****	-4.735	-36%
L5/S1	-6.154	33	***0.000****	-4.610	-39%

Table 5.10: Pairwise comparisons of the IVD_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.026	0.469	N. S.	
L5/S1	L3/L4	-1.050	0.469	***Significant****	-7%
	L4/L5	-1.310	0.469	***Significant****	-8%

N. S.: not significant; Δ%= (I-J)/J× 100%

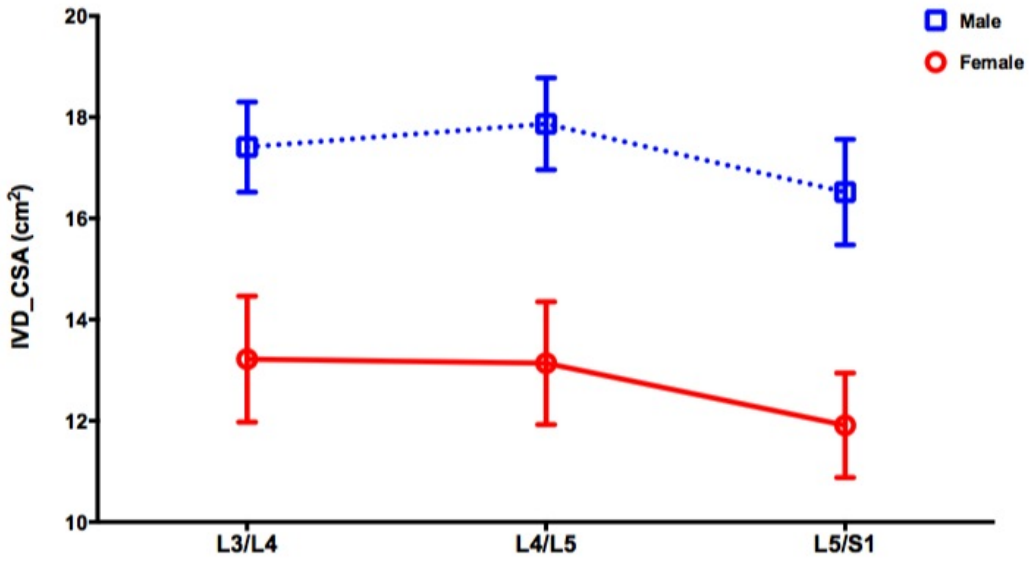


Figure 5.7: IVD_CSAs for both genders at each lower lumbar level

Cross-sectional area of the cranial endplate (CrEP_CSA)

Statistics from SPF ANOVA (Table 5.11) indicated that the main effect for gender (p=0.000) significantly influenced the CrEP_CSA, but the spinal level (p=0.575) and the interaction (p=0.943) were not significant.

Table 5.11: ANOVA summary table for the main and interaction effects of gender and spinal level on CrEP_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	383.973	383.973	49.33	***0.000****
Subject(Gender)	33	256.871	7.784	14.41	
Within Subjects					
Spinal Level	2	0.746	0.301	0.56	0.575
Gender*Spinal Level	2	0.063	0.032	0.06	0.943
Spinal Level*Subject(Gender)	66	35.651	0.540		
Total	104	677.305			

Independent t tests (Table 5.12) revealed that the average male intervertebral discs were larger than female ones in CrEP_CSAs across all three lower lumbar levels (p=0.000) with 35% increase for all levels. Post-hocs analyses (Table 5.13) revealed that all differences in CrEP_CSAs across the three lower lumbar spinal levels were less than the Tukey's HSD value and, therefore, were not statistically significant. Figure 5.8 illustrates the CrEP_CSAs for both genders at each lower lumbar spinal level.

Table 5.12: Influence of gender on the CrEP_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	-6.776	33	***0.000****	-4.020	-35%
L4/L5	-6.888	33	***0.000****	-3.956	-35%
L5/S1	-6.134	33	***0.000****	-3.900	-35%

Table 5.13: Pairwise comparisons of the CrEP_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	-0.022	0.474	N. S.	
L5/S1	L3/L4	-0.188	0.474	N. S.	
	L4/L5	-0.166	0.474	N. S.	

N. S.: not significant; Δ%= (I-J)/J× 100%

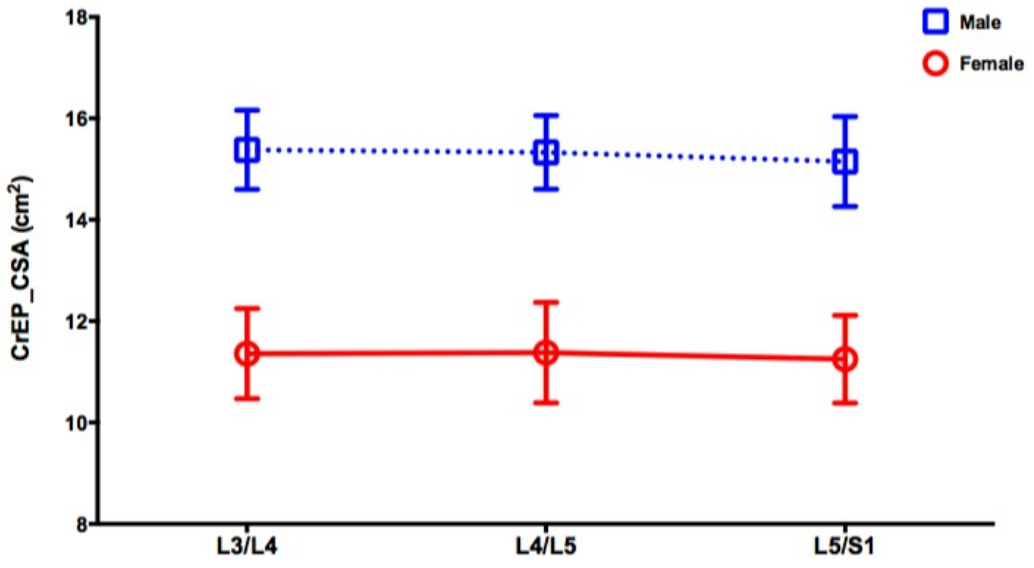


Figure 5.8: CrEP_CSAs for both genders at each lower lumbar level

Cross-sectional area of the caudal endplate (CaEP_CSA)

Statistics from SPF ANOVA (Table 5.14) indicated that the main effects for both gender (p=0.000) and spinal level (p=0.000) significantly influenced the CaEP_CSA, but the main effect of their interaction was not significant (p=0.388).

Table 5.14: ANOVA summary table for the main and interaction effects of gender and spinal level on CaEP_CSA

Source	df	SS	MS	F	P
Between Subjects					
Gender	1	428.381	428.381	60.35	***0.000****
Subject(Gender)	26	184.557	7.098	7.51	
Within Subjects					
Spinal Level	2	46.272	21.209	22.43	***0.000****
Gender*Spinal Level	2	1.824	0.912	0.96	0.388
Spinal Level*Subject(Gender)	52	49.177	0.946		
Total	83	710.212			

Independent t tests (Table 5.15) revealed that the average male intervertebral discs were larger than female ones in CaEP_CSAs across all three lower lumbar levels (p=0.000) with a 31% increase at the L3/L4 level, a 41% increase at the L4/L5 level, and a 35% increase at the L5/S1 level. Post-hocs analyses (Table 5.16) revealed that the difference in IVD_CSAs between the L5/S1 and L3/L4 IVDs exceeded the Tukey's HSD value and, therefore, was significant. So did the difference between the L5/S1 and L4/L5 IVDs. No significant difference was found between the L3/L4 and L4/L5 IVDs. On average, CaEP_CSAs of the L5/S1 IVDs were 9% and 11% smaller than the L3/L4 and L4/L5 IVDs, respectively. Figure 5.9 illustrates the IVD_CSAs for both genders at each lower lumbar spinal level.

Table 5.15: Influence of gender on the CaEP_CSA

	t	df	Sig.	Mean Diff. (M - F)	Δ (%)
L3/L4	-5.827	32	***0.000****	-4.187	-31%
L4/L5	-8.112	29	***0.000****	-5.350	-41%
L5/S1	-6.376	30	***0.000****	-4.237	-35%

Table 5.16: Pairwise comparisons of the CaEP_CSA across the three lower lumbar spinal levels

Spinal Level		Post-hocs tests			
(I)	(J)	Mean Diff. (I-J)	Tukey HSD	Sig.	Δ%
L4/L5	L3/L4	0.284	0.627	N. S.	
L5/S1	L3/L4	-1.409	0.627	***Significant****	-9%
	L4/L5	-1.699	0.627	***Significant****	-11%

N. S.: not significant; Δ%= (I-J)/J× 100%

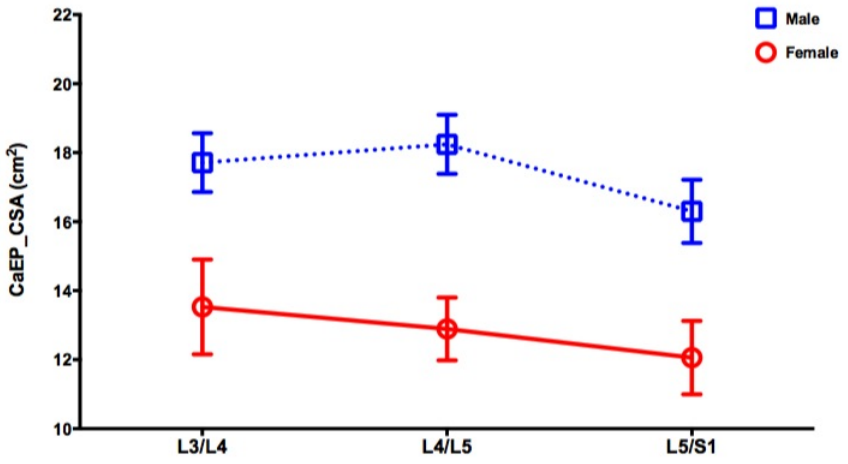


Figure 5.9: CaEP_CSAs for both genders at each lower lumbar level

Craniocaudal differences in the cross-sectional areas (CSAs)

Paired sample t tests were used to compare the size of these structures rather than independent t tests, since for each subject, these dimensions may be related to each other in some way (e.g., the same spinal level or vertebral body). Figure 5.10 illustrates the cross-sectional areas of the intervertebral discs and vertebral endplates measured at each lower lumbar spinal level.

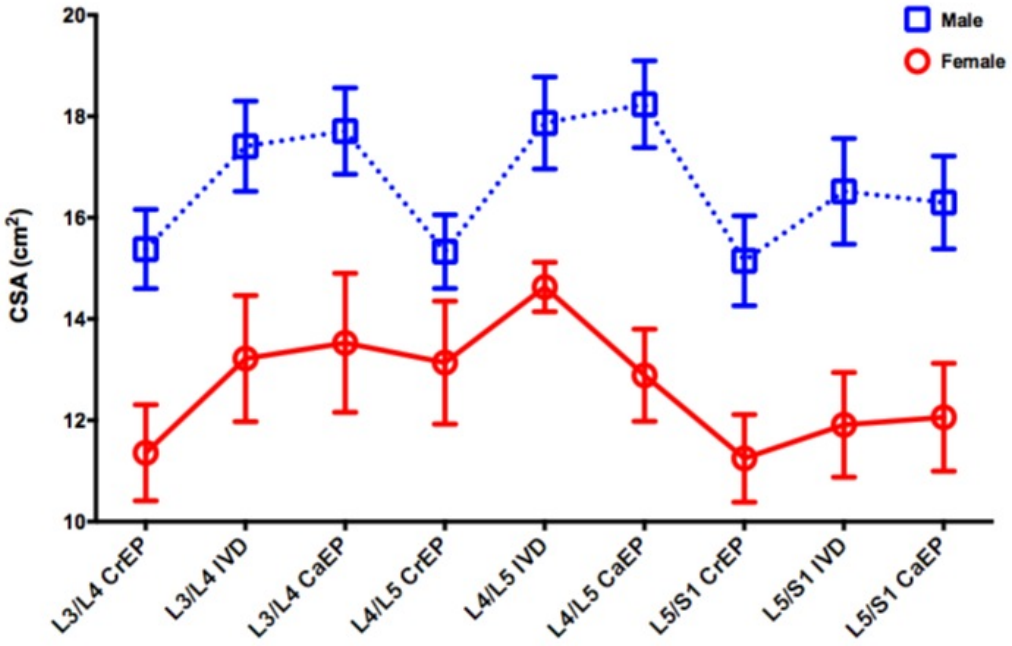


Figure 5.10: Complete distribution profiles of CSAs across the three lower lumbar levels

Single level lumbar motion segments

Paired sample t tests (Table 5.17) indicated that the cranial endplate had significantly smaller cross-sectional area (CSA) than the intervertebral disc and caudal endplate in both male ($p=0.000$) and female subjects ($p<0.05$) at all three lower lumbar levels. The differences were most pronounced at the L3/L4 and L4/L5 levels. Caudal endplates had significantly larger CSA than the intervertebral disc at both the L3/L4 and

L4/L5 levels ($p<0.05$) for both female subjects (on average 4%) and male subjects (3%), but no significant difference was found at the L5/S1 level.

Table 5.17: Differences in CSAs between the intervertebral discs and the adjacent vertebral endplates

			t	df	Sig.	Mean	SD	Δ%
Ca_EP - Cr_EP	Female	L3/L4	9.971	11	***0.000****	2.187	0.760	19%
		L4/L5	6.947	9	***0.000****	2.028	0.923	19%
		L5/S1	4.653	12	***0.001****	0.812	0.630	7%
	Male	L3/L4	8.339	21	***0.000****	2.333	1.312	15%
		L4/L5	10.729	20	***0.000****	2.946	1.258	19%
		L5/S1	5.612	18	***0.000****	1.336	1.038	9%
IVD - Cr_EP	Female	L3/L4	8.274	12	***0.000****	1.859	0.810	16%
		L4/L5	7.033	12	***0.000****	1.759	0.902	15%
		L5/S1	5.042	12	***0.000****	0.656	0.469	6%
	Male	L3/L4	9.784	21	***0.000****	2.031	0.973	13%
		L4/L5	11.353	21	***0.000****	2.537	1.048	17%
		L5/S1	5.884	21	***0.000****	1.370	1.092	9%
IVD - Ca_EP	Female	L3/L4	-2.781	11	***0.018****	-0.391	0.487	-3%
		L4/L5	-3.608	9	***0.006****	-0.521	0.456	-4%
		L5/S1	-1.153	12	0.271	-0.156	0.489	
	Male	L3/L4	-2.279	21	***0.033****	-0.302	0.622	-2%
		L4/L5	-3.406	20	***0.000****	-0.500	0.670	-3%
		L5/S1	-0.848	18	0.408	-0.177	0.912	

Lower lumbar vertebrae

Paired sample t tests (Table 5.18) indicated significant decreases in the endplate cross-sectional areas of both the L4 and L5 vertebra from cranial to caudal, for male subjects ($p=0.000$), 13% and 17% decrease respectively. Female L4 vertebrae exhibited a significant decrease (16%) in the endplate cross-sectional area ($p=0.000$).

Table 5.18: Craniocaudal differences in EP_CSAs with respect to L4 and L5 lumbar vertebrae

		t	df	Sig.	Mean	SD	Δ%
Female	L4	-5.454	11	***0.000****	-2.164	1.352	-16%
	L5	-0.632	10	0.542	-2.468	-0.865	
Male	L4	-9.263	21	***0.000****	-2.378	1.204	-13%
	L5	-8.732	20	***0.000****	-3.175	1.666	-17%

5.3.2 Correlation analysis

Correlation analyses (Table 5.19) were performed to determine correlations between independent subject variables (subject characteristics and anthropometrics) and the cross-sectional areas (CSAs) of each lower lumbar intervertebral disc and the adjacent endplates at the L3/L4 to the L5/S1 level.

Correlations between subject variables and the CSAs

Subject age exhibited no significant correlation with the CSAs at all three levels. Subject characteristics also had no significant correlation with the CSAs, including weight lifting, cardio exercise, and handedness. Fat percentage was only negatively correlated with L4/L5_CrEP_CSA and L5/S1_IVD_CSA ($p<0.05$). All the other independent subject variables were significantly positively correlated with all CSAs at the lower lumbar levels (from L3/L4 to L5/S1) ($p<0.05$).

Table 5.19: Correlations among subjects variables and the CSAs of the lower lumbar IVDs and EPs

	L3/L4 level			L4/L5 level			L5/S1 level		
Variable	**CrEP**	**IVD**	**CaEP**	**CrEP**	**IVD**	**CaEP**	**CrEP**	**IVD**	**CaEP**
Gender	*0.763**	*0.717**	*0.718**	*0.768**	*0.757**	*0.833**	*0.730**	*0.731**	*0.759**
Age	0.081	0.072	0.036	0.160	0.149	0.140	0.262	0.212	0.203
Height	*0.858**	*0.858**	*0.846**	*0.881**	*0.863**	*0.869**	*0.855**	*0.834**	*0.856**
Weight	*0.713**	*0.739**	*0.749**	*0.745**	*0.791**	*0.833**	*0.758**	*0.704**	*0.751**
BMI	*0.447**	*0.463**	*0.500**	*0.445**	*0.538**	*0.617**	*0.477**	*0.417**	*0.490**
Fat (%)	-0.304	-0.290	-0.267	*-0.357**	-0.331	-0.348	-0.331	*-0.335**	-0.297
Lean Body Mass	*0.739**	*0.747**	*0.750**	*0.766**	*0.801**	*0.834**	*0.767**	*0.721**	*0.755**
Fat Weight	0.240	0.244	0.279	0.206	0.257	0.274	0.248	0.205	0.265
Lifting exercise	-0.134	-0.109	-0.097	-0.202	-0.137	-0.112	-0.180	-0.173	-0.108
Cardio Exercise	-0.058	-0.061	-0.029	-0.129	-0.121	-0.096	-0.189	-0.160	-0.026
Dexterity	0.120	0.193	0.215	0.180	0.252	0.298	0.240	0.311	0.224
Sitting Height	*0.806**	*0.813**	*0.818**	*0.819**	*0.827**	*0.804**	*0.784**	*0.781**	*0.833**
Shoulder Width	*0.711**	*0.739**	*0.740**	*0.764**	*0.803**	*0.819**	*0.730**	*0.737**	*0.793**
Head Width	*0.541**	*0.504**	*0.505**	*0.570**	*0.553**	*0.558**	*0.517**	*0.479**	*0.602**
Head Circumference	*0.545**	*0.577**	*0.602**	*0.600**	*0.614**	*0.604**	*0.630**	*0.605**	*0.725**
Head Depth	*0.701**	*0.695**	*0.685**	*0.683**	*0.723**	*0.743**	*0.722**	*0.727**	*0.739**
Chest Breadth	*0.583**	*0.551**	*0.556**	*0.588**	*0.618**	*0.652**	*0.618**	*0.550**	*0.613**
Chest Depth	*0.426**	*0.462**	*0.480**	*0.409**	*0.488**	*0.523**	*0.486**	*0.418**	*0.537**
Elbow Width	*0.617**	*0.618**	*0.656**	*0.639**	*0.662**	*0.674**	*0.575**	*0.546**	*0.646**
Elbow Circumference	*0.767**	*0.762**	*0.778**	*0.779**	*0.788**	*0.839**	*0.783**	*0.758**	*0.788**
Wrist Width	*0.799**	*0.835**	*0.848**	*0.839**	*0.849**	*0.838**	*0.836**	*0.821**	*0.849**
Wrist Circumference	*0.851**	*0.868**	*0.876**	*0.863**	*0.885**	*0.897**	*0.845**	*0.837**	*0.845**
Arm Length	*0.789**	*0.803**	*0.801**	*0.846**	*0.797**	*0.808**	*0.796**	*0.782**	*0.773**
Hand Length	*0.709**	*0.748**	*0.746**	*0.795**	*0.781**	*0.803**	*0.750**	*0.787**	*0.780**
Hand Width	*0.754**	*0.793**	*0.804**	*0.780**	*0.817**	*0.841**	*0.780**	*0.792**	*0.802**
Hand Circumference	*0.783**	*0.818**	*0.822**	*0.795**	*0.826**	*0.860**	*0.807**	*0.803**	*0.811**
Knee Width	*0.470**	*0.507**	*0.527**	*0.485**	*0.549**	*0.633**	*0.524**	*0.532**	*0.553**
Knee Circumference	*0.627**	*0.680**	*0.693**	*0.649**	*0.711**	*0.760**	*0.661**	*0.704**	*0.648**
AnkleWidth	*0.860**	*0.853**	*0.852**	*0.846**	*0.856**	*0.849**	*0.831**	*0.844**	*0.872**
Ankle Circumference	*0.802**	*0.843**	*0.845**	*0.790**	*0.845**	*0.849**	*0.825**	*0.817**	*0.836**
AST	*0.761**	*0.780**	*0.798**	*0.803**	*0.781**	*0.819**	*0.766**	*0.755**	*0.807**
AST_{Turk}	*0.699**	*0.724**	*0.748**	*0.728**	*0.772**	*0.805**	*0.713**	*0.695**	*0.758**
SW	*0.820**	*0.833**	*0.842**	*0.843**	*0.866**	*0.885**	*0.827**	*0.809**	*0.845**

Correlations among subject variables

Table 5.20 provides the results of correlation analyses among independent subject variables (subject characteristics and anthropometrics). Significant correlations were found among all subject anthropometrics ($p<0.05$). Subject age, weight lifting exercise, and cardio exercise did not significantly correlate with other subject variables, except that age was correlated with chest breadth and depth ($p<0.05$), and cardio exercise was correlated with weight lifting exercise ($p<0.05$).

High correlations among independent subject variables may result in multicollinearity problems, which inflate the variance of the regression coefficients and result in small t values and unstable regression coefficients. Since in the present study, multiple anthropometric measurements were taken at each major body joint (wrist, elbow, knee, and ankle) and body segment (head, chest, and hand), it is suggested that only one subject anthropometric measure (the "best" representer) be kept for each joint or segment and the other (highly correlated) subject variables be removed from further statistical analyses. This study presented the following approach to obtain the "best" representer. Subject anthropometrics corresponding to the same body joint or segment were combined into one **index** variable by multiplying all related anthropometric measures. For example, an elbow index was calculated by multiplying elbow width and elbow circumference. Table 5.21 presents calculation for each index regarding the corresponding body joint and segment.

Table 5.20: Correlations among subject variables

Variable	Age	Height	Weight	BMI	Fat (%)	Lean Body Mass	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
Lean Body Mass							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														

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Table 5.20 (Continue): Correlations among subject variables

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
Lean Body Mass	*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**

Table 5.21: Definitions of anthropometric index variables

Index		**Combining Variables**				
Head	=	Head Width (W_{head})	×	Head Circumference (C_{head})	×	Head Depth (D_{head})
Chest	=	Chest Breadth (B_{chest})	×	Chest Depth (D_{chest})		
Elbow	=	Elbow Width (W_{elbow})	×	Elbow Circumference (C_{elbow})		
Wrist	=	Wrist Width (W_{wrist})	×	Wrist Circumference (C_{wrist})		
Hand	=	Hand Width (W_{hand})	×	Hand Circumference (C_{hand})	×	Hand Length (L_{hand})
Knee	=	Knee Width (W_{knee})	×	Knee Circumference (C_{knee})		
Ankle	=	Ankle Width (W_{ankle})	×	Ankle Circumference (C_{ankle})		

With respect to subject characteristics regarding body composition, body fat percentage (BFP), lean body mass (LBM), and fat weight were highly correlated with each other, since LBM (or "fat free weight") is a function of body fat percentage and body weight. To minimize multicollinearity issues, lean body mass (LBM) was selected to represent subject body composition. LBM was not only most predictive, it better estimates the underlying construct of body composition that was hypothesized to be predictive of internal structures.

In the final regression analyses, index variables representing body composition, body joints and body segments, were used, rather than individual subject variables. The updated list of independent subject variables that were use in the regression analysis are given in Table 5.22, including subject characteristics (gender and lean body mass) and anthropometrics (sitting height, shoulder width, arm length, index variables of head, chest, elbow, wrist, hand, knee and ankle). All subject variables were significantly correlated with the cross-sectional areas of the intervertebral disc and vertebral endplate at the L3/L4, L4/L5, and L5/S1 levels ($p<0.50$).

Table 5.22: Correlations between the cross-sectional areas (CSAs) and subject variables used in regression analyses

	L3/L4			L4/L5			L5/S1		
Variable	**CrEP**	**IVD**	**CaEP**	**CrEP**	**IVD**	**CaEP**	**CrEP**	**IVD**	**CaEP**
Gender	*0.763**	*0.717**	*0.718**	*0.768**	*0.757**	*0.833**	*0.730**	*0.731**	*0.759**
Height	*0.858**	*0.858**	*0.846**	*0.881**	*0.863**	*0.869**	*0.855**	*0.834**	*0.856**
Weight	*0.713**	*0.739**	*0.749**	*0.745**	*0.791**	*0.833**	*0.758**	*0.704**	*0.751**
Lean Body Mass	*0.739**	*0.747**	*0.750**	*0.766**	*0.801**	*0.834**	*0.767**	*0.721**	*0.755**
Sitting Height	*0.806**	*0.813**	*0.818**	*0.819**	*0.827**	*0.804**	*0.784**	*0.781**	*0.833**
Shoulder Width	*0.711**	*0.739**	*0.740**	*0.764**	*0.803**	*0.819**	*0.730**	*0.737**	*0.793**
Arm Length	*0.789**	*0.803**	*0.801**	*0.846**	*0.797**	*0.808**	*0.796**	*0.782**	*0.773**
Head	*0.734**	*0.725**	*0.722**	*0.748**	*0.767**	*0.768**	*0.759**	*0.739**	*0.824**
Chest	*0.522**	*0.520**	*0.531**	*0.515**	*0.575**	*0.614**	*0.577**	*0.497**	*0.591**
Elbow	*0.700**	*0.698**	*0.729**	*0.720**	*0.740**	*0.772**	*0.690**	*0.657**	*0.714**
Wrist	*0.828**	*0.857**	*0.867**	*0.855**	*0.872**	*0.872**	*0.847**	*0.833**	*0.848**
Hand	*0.752**	*0.798**	*0.804**	*0.797**	*0.822**	*0.848**	*0.791**	*0.809**	*0.805**
Knee	*0.564**	*0.610**	*0.631**	*0.584**	*0.651**	*0.726**	*0.617**	*0.640**	*0.619**
Ankle	*0.850**	*0.868**	*0.866**	*0.836**	*0.870**	*0.866**	*0.850**	*0.851**	*0.871**
AST	*0.761**	*0.780**	*0.798**	*0.803**	*0.781**	*0.819**	*0.766**	*0.755**	*0.807**
AST_{Turk}	*0.699**	*0.724**	*0.748**	*0.728**	*0.772**	*0.805**	*0.713**	*0.695**	*0.758**
SW	*0.820**	*0.833**	*0.842**	*0.843**	*0.866**	*0.885**	*0.827**	*0.809**	*0.845**

5.3.3 Regression analyses

Selection of regression models

There are several methods to evaluate and select the "best" regression models, each is dependent on their underlying selection algorithm. It should be noted that no one method is unanimously accepted as superior to the others. An all-possible-regressions procedure, however, minimizes the disadvantages of the traditional model selection methods (e.g., forward, backward, and stepwise selection methods which add and/or delete one predictor during each iteration and fail to address the possible improvement in model performance by selecting a combination of individual predictors rather than each predictor itself. Advances in computing power allow large-scale data processing problems and it is, therefore feasible to process all-possible-regressions models cost-effectively. In addition, selection of the "best" model is a function of the end users of the final regression model.

Researchers may select the "best" model from all possible subsets by employing decision criteria for acceptance/rejection of potential models. Logistical considerations may also be considered. For exmaple, a simple model might be chosen over a complex one by practitioners, even though it may provide lesser performance. The coefficient of determination (R^2), adjusted R^2, residual mean square (MSE), Mallows' prediction criterion (C_P) and Akaike information criterion (AIC) are the most common model selection criteria to determine the "best" model.

This study presents the top five "best" subsets for each model size (number of parameters, P), using the statistics software package Minitab (version 15, Minitab Inc., State College, PA), from 2 parameters (one independent variable and one intercept) to 15 parameters in total (14 independent variables and 1 intercept) to predict the cross-sectional area of the intervertebral disc (IVD_CSA) and the cranial (CrEP_CSA) and caudal endplate (CaEP_CSA), respectively at each lower lumbar spinal level. All subset regression models are presented in Appendices D, E, and F. 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 displayed in **bold** and *italic* are the models selected in this study as the "best" models.

These subset regression models were then evaluated based on model statistics (e.g., Adjusted R^2, residual mean square, Mallows' C_P) and Akaike information criterion (AIC) to determine the "best" model(s). The primary model selection criteria used in this study was to select models with the largest Adjusted-R^2 since this provides information on how well a regression model fits the data. Adjusted-R^2 is preferred over R^2 since it removes the influence of degrees of freedom and allows for better comparisons of models involving different numbers of parameters. R^2 values typically increase with the addition of each new

variable even though these variables may not significantly improve model performance. Solely based on maximum R^2, the subset with all independent variables will always be the "best" model. On the contrary, Adjusted-R^2 penalizes models with unnecessary variables. This study preferred the simplest model (number of parameters) with the largest Adjusted-R^2 or near the largest Adjusted-R^2.

Mallows' C_P was used to assess the goodness of fit of a regression model and/or measure the prediction error (or bias). Based on the assumptions that the model with all independent variables has adequate terms to eliminate signficant bias, the Mallows' C_P is used to search for a simpler model with little bias. The Mallows' C_P theory suggests choosing subsets of each number of parameters with 1) the smallest C_P value and 2) the C_P value closest to the number of parameters. Models with large C_P values are susceptible to substantial bias and lack of fit for the data. It should be noted that the Mallows' C_P performs poorly when the difference between the numbers of obervations and parameters is small (≤ 10) compared to the suggested value (>40). In this study, the minimum difference is 20 (35 observations and 15 parameters including intercept), which is above the minimum but below the suggested value.

Akaike information criterion (AIC) was also used to analyze the regression models. Similar to Mallow's C_P, AIC also assess the relative difference between two regression models. However, it has superior capability to explain negative values, since it only characterizes the relative difference between two models and selects the smaller value. For example, two regression models have two different AIC values (e.g., 115.2 vs. 98.7, and -109.1 vs. -92.9). In this case, the model with lower value (98.7 and -109.1) were prefered over the other model.

In addition to these quantitative criteria, this study also subjectively preferred "best" models with predictors that had higher frequency (predictor appeared in multiple regression models) as indicated by the regression results, based on the purpose of this study to investigate the biological plausibility of regression models and provide general models for all the CSAs. Therefore, instead of providing only one regression model for each CSA, two alternative models were provided in this study. After the selection of the "best" subsets, the enter method of regression in SPSS was performed to determine the coefficients and regression equations.

Regression analyses for the cross-sectional area of the intervertebral disc (IVD_CSA)

Best subsets regression analyses were performed to determine prediction equations for the cross-sectional area of the intervertebral disc (IVD_CSA) (Appendix D). Table 5.23 lists two regression models for each lower lumbar intervertebral disc after applying the selection criteria. ANOVA tests revealed that all regression models were significant ($p \leq 0.05$). For each model, significant predictor(s) and the intercept were highlighted with italic and bold font.

At the L3/L4 level, subject height, elbow index, and ankle index were significant predictors in both size-4 (3 independent variables and one intercept, P=4) and size-5 (4 independent variables and one intercept, P=5) "best" subset regression models. Subject sitting height was not a significant predictor in the size-5 subset model. R^2 and Adjusted-R^2 values increased from 0.862 to 0.872 and from 0.848 to 0.855. Standard error decreased from 1.12 to 1.09. At the L4/L5 level, subject sitting height and ankle index

were significant predictors in both size-3 and size-4 "best" subset regression models. Subject hand index was not a significant predictor by itself but was included in the size-4 subset model. R^2 and Adjusted-R^2 values increased from 0.850 to 0.866 and from 0.841 to 0.853. Standard error decreased from 1.22 to 1.17. At the L5/S1 level, subject sitting height, ankle index, elbow index, and hand index were significant predictors in both size-5 and size-6 "best" subset regression models. Subject height was not a significant predictor by itself but included in the size-6 subset model. R^2 value increased from 0.863 to 0.867, while Adjusted-R^2 remained as 0.844 as well as standard error (1.22).

Table 5.23: Regression models for the CSA of the intervertebral disc (IVD_CSA)

Level	P	Equations for the IVD_CSA	ANOVA p-value	R^2	Adj.R^2	S.E.	C_P	AIC
L3/L4	4	= -18.124 + 0.160* ***Ht*** - 0.022* ***Elbow*** + 0.065* ***Ankle***	***0.000****	0.862	0.848	1.12	-0.3	11.52
	5	= -24.434 + 0.110* ***Ht*** - 0.020* ***Elbow*** + 0.063* ***Ankle*** + 0.115*Sitting Ht	***0.000****	0.872	0.855	1.09	-0.2	10.83
L4/L5	3	= -26.782 + 0.253* ***Sitting Ht*** + 0.058* ***Ankle***	***0.000****	0.850	0.841	1.22	1.0	17.00
	4	= -25.356+ 0.248* ***Sitting Ht*** + 0.037* ***Ankle*** + 0.001*Hand	***0.000****	0.866	0.853	1.17	-0.3	15.00
L5/S1	5	= - 26.736 + 0.254* ***Sitting Ht*** + 0.054* ***Ankle*** - 0.029* ***Elbow*** + 0.002* ***Hand***	***0.000****	0.863	0.844	1.22	3.4	18.52
	6	= - 26.591 + 0.180* ***Sitting Ht*** + 0.057* ***Ankle*** - 0.032* ***Elbow*** + 0.001* ***Hand*** + 0.062*Ht	***0.000****	0.867	0.844	1.22	4.5	19.36

Regression analyses for the cross-sectional area of the cranial endplate (CrEP_CSA)

Best subsets regression analyses were performed to determine prediction equations for the cross-sectional area of the cranial endplate (CrEP_CSA) (Appendix E). Table 5.24 lists two regression models for the cranial endplate of each lower lumbar intervertebral disc after applying the selection criteria. ANOVA tests revealed that all regression models were significant ($p \leq 0.05$). For each model, significant predictor(s) and intercept were highlighted with italic and bold font.

At the L3/L4 level, both size-6 and size-7 "best" models included subject gender, height, chest index, ankle index, and hand index as the significant predictors. Subject elbow index was not a significant predictor independently but was included in the size-7 subset model. R^2 and Adjusted-R^2 values increased from 0.880 to 0.887 and from 0.860 to 0.863, respectively. Standard error decreased from 0.97 to 0.96. At the L4/L5 level, subject gender, height, chest index, and ankle index were significant predictors in both size-5 and size-6 "best" models. Subject sitting height was not significant independently but was included in size-6 models. R^2 value increased from 0.864 to 0.880. Adjusted-R^2 value decreased from 0.846 to 0.859. Standard error decreased from 0.99 to 0.95. At the L5/S1 level, subject height, elbow index, and ankle index were significant predictors in both size-4 and size-5 "best" subset regression models. Subject wrist index was not a significant predictor independently but was included in the size-5 model. R^2 and Adjusted-R^2 values increased from 0.841 to 0.850 and from 0.825 to 0.830. Standard error decreased from 1.09 to 1.08.

Regression analyses for the cross-sectional area of the caudal endplate (CaEP_CSA)

Best subsets regression analyses were performed to determine prediction equations for the cross-sectional area of the caudal endplate (CaEP_CSA) (Appendix F). Table 5.25 lists two regression models for the caudal endplate of each lower lumbar intervertebral disc after applying the selection criteria. ANOVA tests revealed that all regression models were significant ($p \leq 0.05$). For each model, significant predictor(s) and intercept are highlighted with italic and bold font.

At the L3/L4 level, both size-4 and size-5 "best" models had subject sitting height and ankle index as the significant predictors. Subject chest index was not a significant predictor in either the size-4 or size-5 models. Subject wrist index was not significant alone but was included in the size-5 subset model. R^2 and Adjusted-R^2 values increased from 0.858 to 0.873 and from 0.843 to 0.855, respectively. Standard error decreased from 1.12 to 1.08. At the L4/L5 level, subject gender, height, and knee index were significant predictors in both size-4 and size-5 "best" models. Subject chest index was significant in the size-5 model. R^2 and Adjusted-R^2 values increased from 0.851 to 0.864 and from 0.834 to 0.843, respectively. Standard error decreased from 1.24 to 1.21. At the L5/S1 level, subject sitting height, ankle index, and hand index were significant predictors in both size-4 and size-5 "best" subset regression models. Subject elbow index was a significant predictor and included in the size-5 model. R^2 and Adjusted-R^2 values increased from 0.861 to 0.884 and from 0.846 to 0.867, repsectively. Standard error decreased from 1.09 to 1.02.

Table 5.24: Regression models for the CSA of the cranial endplate (CrEP_CSA)

Level	P	Equations for the CrEP_CSA	ANOVA p-value	R^2	Adj.R^2	S.E.	C_P	AIC
L3/L4	6	= ***-17.630*** + 1.969****Gender*** + 0.176****Ht*** - 0.005****Chest*** + 0.049****Ankle*** - 0.002****Hand***	***0.000****	0.880	0.860	0.97	2.7	3.11
	7	= ***-18.718*** + 2.017****Gender*** + 0.185****Ht*** - 0.004****Chest*** + 0.052****Ankle*** - 0.001****Hand*** - 0.010*Elbow	***0.000****	0.887	0.863	0.96	3.2	3.03
L4/L5	5	= ***-13.845*** + 1.159****Gender*** + 0.148****Ht*** - 0.005****Chest*** + 0.026****Ankle***	***0.000****	0.864	0.846	0.99	2.0	4.00
	6	= ***-21.066*** + 1.312****Gender*** + 0.097****Ht*** - 0.005****Chest*** + 0.025****Ankle*** + 0.126*Sitting Ht	***0.000****	0.880	0.859	0.95	0.8	1.59
L5/S1	4	= ***-17.842*** + 0.153****Ht*** - 0.020****Elbow*** + 0.056****Ankle***	***0.000****	0.841	0.825	1.09	-2.8	10.02
	5	= ***-16.224*** + 0.136****Ht*** - 0.025****Elbow*** + 0.041****Ankle*** + 0.055*Wrist	***0.000****	0.850	0.830	1.08	-2.2	9.99

Gender: 0 for female, 1 for male

Table 5.25: Regression models for the CSA of the cranial endplate (CaEP_CSA)

Level	P	Equations for the CaEP_CSA	ANOVA p-value	R^2	Adj.R^2	S.E.	C_P	AIC
L3/L4	4	= ***-24.405*** + 0.248****Sitting Ht*** + 0.062****Ankle*** - 0.004*Chest	***0.000****	0.858	0.843	1.12	-1.5	11.72
	5	= ***-21.986*** + 0.222****Sitting Ht*** + 0.038****Ankle*** - 0.004*Chest + 0.063*Wrist	***0.000****	0.873	0.855	1.08	-2.1	9.84
L4/L5	4	= ***-10.812*** + 2.427****Gender*** + 0.126****Ht*** + 0.011****Knee***	***0.000****	0.851	0.834	1.24	1.0	17.18
	5	= ***-11.070*** + 2.929****Gender*** + 0.134****Ht*** + 0.014****Knee*** - 0.004*Chest	***0.000****	0.864	0.843	1.21	0.8	16.23
L5/S1	4	= ***-22.889*** + 0.224****Sitting Ht*** + 0.037****Ankle*** + 0.001****Hand***	***0.000****	0.861	0.846	1.09	0.3	9.47
	5	= ***-25.462*** + 0.249****Sitting Ht*** + 0.045****Ankle*** + 0.001****Hand*** - 0.018****Elbow***	***0.000****	0.884	0.867	1.02	-1.8	5.64

Gender: 0 for female, 1 for male

5.3.4 Further analyses regarding the regression models

Comparison with regression models reported in the literature

Table 5.26 compares the regression models using predictors reported in the literature. Compared to Colombini et al. (1989), the present models using bony structure weight (SW) had higher R^2 at the L3/L4 and L4/L5 levels, and a smaller value at the L5/S1 level. Colombini et al. (1989) reported that their model for L3/L4 IVD_CSA had the largest R^2 value, while their model for L4/L5 level had the lowest R^2. The present study reported that L4/L5 IVD_CSA model had the highest R^2 value and L5/S1 IVD_CSA model had the lowest. In the present study, models using average square thickness of bony structure (AST_{Turk}) had smaller R^2 values compared to the models using SW.

Table 5.26: Comparison with regression models reported in the literature

		Prediction Equation	R^2	Adj-R^2	S.E.	p-value
L3/L4	Colombini et al. (1989)	0.95 + 0.002*$\boldsymbol{SW}$	0.706	-	-	$\boldsymbol{<0.001}^*$
	Tang (2013)	$\boldsymbol{4.651}$ + 0.001*$\boldsymbol{SW}$	0.693	0.684	1.61	$\boldsymbol{0.000}^*$
L4/L5	Colombini et al. (1989)	2.7 + 0.002*$\boldsymbol{SW}$	0.624	-	-	$\boldsymbol{<0.001}^*$
	Tang (2013)	$\boldsymbol{3.657}$ + 0.001*$\boldsymbol{SW}$	0.749	0.742	1.56	$\boldsymbol{0.000}^*$
	Turk & Celan (2004)	2.11 + 0.29*$\boldsymbol{AST_{Turk}}$	-	-	-	-
	Tang (2013)	2.074 + 0.218*$\boldsymbol{AST_{Turk}}$	0.596	0.584	1.98	$\boldsymbol{0.000}^*$
L5/S1	Colombini et al. (1989)	2.57 + 0.002*$\boldsymbol{SW}$	0.672	-	-	$\boldsymbol{<0.001}^*$
	Tang (2013)	3.069 + 0.001*$\boldsymbol{SW}$	0.655	0.645	1.84	$\boldsymbol{0.000}^*$
	Turk & Celan (2004)	3.55 + 0.25*$\boldsymbol{AST_{Turk}}$	-	-	-	-
	Tang (2013)	2.078 + 0.197*$\boldsymbol{AST_{Turk}}$	0.483	0.467	2.26	$\boldsymbol{0.000}^*$

Comparison of the present regression models to the previous ones reported in Chapter 4

Easy-to-measure predictors included in this study are subject gender, height, weight, and age, which tend to be more frequently recorded than other subject characteristics and

anthropometric measures. Regression models with easy-to-measure subject variables may be preferred in occupational health practice. Unfortunately, a smaller number of parameters may result in a loss of prediction power. Table 5.27 lists the results of regression analyses to predict the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs).

Table 5.27: Regression models using easy-to-measure predictors

		Prediction Equation	R^2	Adj-R^2	S.E.	p-value
CrEP_CSA	L3/L4	***-10.047*** + 0.152****Ht*** + 1.839****Gender*** - 0.119****Age***	0.808	0.789	1.19	***0.000****
	L4/L5	***-13.823*** + 0.157****Ht*** + 1.417****Gender***	0.813	0.801	1.13	***0.000****
	L5/S1	***-21.073*** + 0.203****Ht***	0.731	0.723	1.38	***0.000****
IVD_CSA	L3/L4	***-22.394*** + 0.224****Ht***	0.736	0.728	1.50	***0.000****
	L4/L5	***-16.525*** + 0.184****Ht*** + 1.750****Gender***	0.782	0.769	1.47	***0.000****
	L5/S1	***-16.959*** + 0.179****Ht*** + 1.700****Gender***	0.730	0.713	1.66	***0.000****
CaEP_CSA	L3/L4	***-10.709*** + 0.176****Ht*** + 1.723****Gender*** - 0.159****Age***	0.784	0.763	1.38	***0.000****
	L4/L5	***-12.581*** + 0.159****Ht*** + 2.634***Gender**	0.827	0.815	1.31	***0.000****
	L5/S1	***-14.807*** + 0.167****Ht*** + 1.608****Gender***	0.772	0.756	1.38	***0.000****

CSA (cm^2); Gender (0 for female, 1 for male); Ht: height (cm); Age: age (years)

ANOVA revealed that all regression models were significant (p=0.000). Subject height was a significant predictor in all models, compared to weight which was not significant and was not included in any models. Gender was also significant predictor, except for L5/S1 CrEP_CSA and L3/L4 IVD_CSA. Age was only significant in models for CrEP_CSA and CaEP_CSA at the L3/L4 level. In general, models for the L4/L5 spinal level had the largest R^2 and Adj-R^2, and smallest standard error, compared to models for L5/S1 level which had the smallest R^2 and Adj-R^2, and the largest standard error.

Compared to models in Chapter 4, the present regression models for the L4/L5 CrEP_CSA, L4/L5 IVD_CSA, and L5/S1 IVD_CSA had the the same predictors, as shown in Table 5.28. In general, subject height and gender were significant predictors that were frequently included in the regression models. In this study, age was a significant predictor

for the CrEP_CSA and CaEP_CSA at the L3/L4 level, contradicting to the findings of Chapter 4 in which age was not a significant predictor. The present study agrees with Chapter 4 that subject weight was not a significant predictor. Regression models in this study had higher R^2 and Adj-R^2 than the corresponding models in Chapter 4. However, in this study, models for the L5/S1 level had larger standard error compared to the ones in Chapter 4. While models for the L3/L4 and L4/L5 levels had smaller standard error relative to models in Chapter 4.

Table 5.28: Comparison of regression models in Study 1 and Study 2

		Study	Prediction Equation	R^2	Adj-R^2	S.E.	p-value
CrEP_CSA	L3/L4	1	***-6.115*** + 0.112****Ht*** + 0.996****Gender***	0.622	0.608	1.31	***0.000****
		2	***-10.047*** + 0.152****Ht*** + 1.839****Gender*** - 0.119****Age***	0.808	0.789	1.19	***0.000****
	L4/L5	1	***-4.565*** + 0.103****Ht*** + 1.041****Gender***	0.665	0.652	1.14	***0.000****
		2	***-13.823*** + 0.157****Ht*** + 1.417****Gender***	0.813	0.801	1.13	***0.000****
	L5/S1	1	***-1.157*** + 0.078****Ht*** + 1.285****Gender***	0.511	0.486	1.30	***0.000****
		2	***-21.073*** + 0.203****Ht***	0.731	0.723	1.38	***0.000****
IVD_CSA	L3/L4	1	***-9.453*** + 0.146****Ht*** + 1.096****Gender***	0.660	0.648	1.51	***0.000****
		2	***-22.394*** + 0.224****Ht***	0.736	0.728	1.50	***0.000****
	L4/L5	1	***-6.674*** + 0.129****Ht*** + 1.671****Gender***	0.644	0.631	1.60	***0.000****
		2	***-16.525*** + 0.184****Ht*** + 1.750****Gender***	0.782	0.769	1.47	***0.000****
	L5/S1	1	***-7.829*** + 0.129****Ht*** + 1.196****Gender***	0.637	0.624	1.44	***0.000****
		2	***-16.959*** + 0.179****Ht*** + 1.700****Gender***	0.730	0.713	1.66	***0.000****
CaEP_CSA	L3/L4	1	***-7.125*** + 0.129****Ht***	0.504	0.495	1.52	***0.000****
		2	***-10.709*** + 0.176****Ht*** + 1.723****Gender*** - 0.159****Age***	0.784	0.763	1.38	***0.000****
	L4/L5	1	***-8.661*** + 0.139****Ht***	0.522	0.514	1.60	***0.000****
		2	***-12.581*** + 0.159****Ht*** + 2.634***Gender**	0.827	0.815	1.31	***0.000****
	L5/S1	1	***-5.594*** + 0.116****Ht***	0.498	0.486	1.32	***0.000****
		2	***-14.807*** + 0.167****Ht*** + 1.608****Gender***	0.772	0.756	1.38	***0.000****

CSA (cm^2); Gender (0 for female, 1 for male); Ht: height (cm); Age: age (years)

Comparison of model performance

Regression models developed in Chapter 4 were validated using a subset of morphometric data reported in Chapter 3. In this study, these models were also used to predict the cross-sectional areas (CSAs) for the present sample of subjects. Table 5.29 lists the statistical results of paired sample t tests and analyses of absolute error. It was found

that the regression models of Chapter 4 significantly underestimated the CSAs of the L3/L4 caudual endplates (p=0.000), the L4/L5 caudal endplates (p=0.000), and the L5/S1 cranial endplates (p=0.013). Absolute errors between the predicted value and the measured value were on average 9.8% for the intervertebral disc, 8.6% for the cranial endplates, and 11% for the caudal endplates.

Table 5.29: Error analysis of the differences between the "measured" and "predicted" value

				Paired Sample T Tests					Absolute Error				
			Mean	Diff.	SD	t	df	Sig.	Mean	SD	Min	Max	%
L3/L4	CrEP_CSA	Measured	13.89	0.21	1.38	0.920	34	0.364	1.16	0.75	0.00	2.64	8.4
		Predicted	13.67										
	IVD_CSA	Measured	15.85	-0.36	1.49	-1.426	34	0.163	1.29	0.81	0.07	3.26	8.7
		Predicted	16.21										
	CaEP_CSA	Measured	16.23	1.26	1.79	4.082	33	***0.000****	1.82	1.19	0.00	4.68	10.7
		Predicted	14.98										
L4/L5	CrEP_CSA	Measured	13.86	0.15	1.32	0.696	34	0.491	1.09	0.74	0.05	2.78	8.1
		Predicted	13.71										
	IVD_CSA	Measured	16.11	-0.33	1.57	-1.254	34	0.218	1.40	0.74	0.04	3.73	9.5
		Predicted	16.44										
	CaEP_CSA	Measured	16.52	1.34	1.91	3.903	30	***0.000****	1.94	1.26	0.08	4.49	11.2
		Predicted	15.18										
L5/S1	CrEP_CSA	Measured	13.70	0.70	1.59	2.626	34	***0.013****	1.33	1.09	0.00	5.06	9.4
		Predicted	12.99										
	IVD_CSA	Measured	14.80	-0.19	1.78	-0.627	34	0.535	1.55	0.84	0.27	3.26	11.2
		Predicted	14.99										
	CaEP_CSA	Measured	14.58	0.42	1.83	1.310	31	0.200	1.56	1.02	0.13	3.90	11.1
		Predicted	14.15										

On the other hand, the present regression models were also used to predict the morphometry of the same subset of subjects as in Chapter 4. Table 5.30 lists the statistical results of paired sample t tests and the analyses of absolute error. It was found that the present models significantly overestimated the CSAs of the L4/L5 caudal endplates (p=0.005) and the L5/S1 cranial endplates (p=0.008). Absolute errors between the predicted value and the measured value were on average 7.0% for the intervertebral discs, 6.1% for the cranial endplates, and 9.1% for the caudal endplates.

Table 5.30: Error analysis of the differences between the "measured" and "predicted" value

				Paired Sample T Tests					Absolute Error				
			Mean	Diff.	SD	t	df	Sig.	Mean	SD	Min	Max	%
L3/L4	CrEP_CSA	Measured	13.97	0.48	1.33	1.624	19	0.121	1.05	0.92	0.08	3.39	7.4
		Predicted	13.49										
	IVD_CSA	Measured	16.10	-0.17	1.67	-0.445	19	0.661	1.40	0.87	0.18	3.29	9.1
		Predicted	16.27										
	CaEP_CSA	Measured	15.21	-0.47	1.71	-1.226	19	0.235	1.37	1.08	0.12	3.64	9.4
		Predicted	15.68										
L4/L5	CrEP_CSA	Measured	13.81	-0.40	0.89	-1.906	17	0.074	0.64	0.73	0.01	2.16	4.8
		Predicted	14.21										
	IVD_CSA	Measured	16.73	0.22	1.42	0.671	18	0.511	0.97	1.04	0.07	4.11	5.6
		Predicted	16.51										
	CaEP_CSA	Measured	15.58	-1.01	1.36	-3.236	18	***0.005****	1.43	0.89	0.02	3.05	9.4
		Predicted	16.59										
L5/S1	CrEP_CSA	Measured	13.33	-0.90	1.13	-3.094	14	***0.008****	1.03	1.01	0.04	2.76	6.2
		Predicted	14.23										
	IVD_CSA	Measured	15.07	0.25	1.10	0.961	16	0.351	0.94	0.58	0.20	2.10	6.3
		Predicted	14.82										
	CaEP_CSA	Measured	14.58	-0.35	1.15	-1.141	13	0.274	0.84	0.83	0.02	2.68	8.6
		Predicted	14.93										

Comparison of subject variables and morphometric data between Chapter 5 and Chapter 4

As shown in Table 5.31, independent t tests revealed that in the present study female subjects were significantly younger (p=0.009) than in the previous study. Female subjects also had significantly smaller body weight (p=0.007) and normal BMI level (p=0.025), but the same height (p=0.101). No significant difference was found between male subjects.

Comparisons of the cross-sectional areas (CSAs) measured in two studies are presented in Table 5.32. At the L3/L4 level, previous study reported significantly larger CrEP_CSA (p=0.038) and IVD_CSA (p=0.036) of female subjects and significantly smaller CaEP_CSA of male subjects (p=0.010). At the L4/L5 level, the present study reported significantly smaller IVD_CSA of female subjects (p=0.021) and significantly larger CaEP_CSA of male subjects (p=0.004). At the L5/S1 level, the present study reported

significantly larger CrEP_CSA of male subjects (p=0.047) and significantly smaller IVD_CSA (p=0.017) and CaEP_CSA (p=0.026) of female subjects.

Table 5.31: Comparison of the present study to the previous study (Chapter 4) regarding subject characteristics

			Age					Height					Weight					BMI				
Gender	**S**	**N**	**Mean**	**SD**	**t**	**df**	**Sig.**	**Mean**	**SD**	**t**	**df**	**Sig.**	**Mean**	**SD**	**t**	**df**	**Sig.**	**Mean**	**SD**	**t**	**df**	**Sig.**
Female	1	41	29.9	5.5	2.706	52	***0.009****	165.7	9.5	1.668	52	0.101	73.1	19.5	2.806	52	***0.007****	26.7	7.2	2.304	52	***0.025****
	2	13	25.5	3.6				160.9	7.8				57.2	10.2				22.0	2.6			
Male	1	38	30.1	5.5	1.744	58	0.086	178.3	9.3	0.527	58	0.600	86.1	20.4	0.733	58	0.467	27.0	5.6	0.560	58	0.578
	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 4); Study 2: Present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: kg/m^2

Table 5.32: Comparison of the present study to the earlier study (Chapter 4) regarding the CSAs of the lower lumbar intervertebral disc and vertebral endplate

			CrEP_CSA						IVD_CSA						CaEP_CSA					
Level	**Gender**	**S**	**N**	**Mean**	**SD**	**t**	**df**	**Sig.**	**N**	**Mean**	**SD**	**t**	**df**	**Sig.**	**N**	**Mean**	**SD**	**t**	**df**	**Sig.**
L3/L4	**Female**	1	40	12.5	1.6	2.130	51	***0.038****	40	14.5	1.8	2.153	51	***0.036****	40	13.8	1.6	0.539	50	0.592
		2	13	11.4	1.6				13	13.2	2.1				12	13.5	2.2			
	Male	1	38	14.7	3.0	-1.036	58	0.305	38	17.7	2.1	0.544	58	0.589	38	16.3	2.0	-2.680	58	***0.010****
		2	22	15.4	1.8				22	17.4	2.0				22	17.7	1.9			
L4/L5	**Female**	1	41	12.1	2.4	1.037	52	0.305	41	14.6	1.8	2.371	52	***0.021****	41	13.9	1.6	1.805	49	0.077
		2	13	11.4	1.6				13	13.1	2.0				10	12.9	1.3			
	Male	1	37	13.6	4.3	-1.764	57	0.083	37	18.1	2.1	0.493	57	0.624	37	16.6	2.1	-2.976	57	***0.004****
		2	22	15.3	1.6				22	17.9	2.0				21	18.2	1.9			
L5/S1	**Female**	1	29	11.7	1.4	0.998	40	0.324	41	13.4	1.9	2.475	52	***0.017****	29	13.5	1.9	2.306	40	***0.026****
		2	13	11.3	1.4				13	11.9	1.7				13	12.1	1.8			
	Male	1	28	14.1	1.6	-2.035	48	***0.047****	34	16.0	3.3	-0.661	54	0.511	27	15.2	1.7	-1.993	44	0.052
		2	22	15.1	2.0				22	16.5	2.4				19	16.3	1.9			

S: Study; Study 1: Previous study (Chapter 4); Study 2: Present study (Chapter 5); Age: years; Height: cm; Weight: kg; BMI: kg/m^2

5.4 Discussion

The present study explored the correlations between an individual's anthropometric measures and the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs) to develop more powerful regression models to predict the CSAs. Chapter 4 also suggested that regression models could provide satisfactory predictions of the CSAs. As discussed in Chapter 4, two primary assumptions are necessary and should be satisfied. First, it is assumed that the morphometric data are obtained precisely and accurately. In this dissertation, morphometric data regarding the CSAs of the lower lumbar IVDs and EPs were obtained using the research protocol developed in Chapter 3. The standardized protocol uses an advanced image processing software to perform the measurement on magnetic resonance (MR) scans, which provides "excellent" intra- and inter-observer measurement reliabilities. More importantly, the protocol has superior capability to handle the lumbar curvature and is able to measure the actual CSAs of the IVDs and EPs across the lower lumbar spine, particularly at the lumbosacral joint, rather than using a simple ellipsoid method to approximate (Farfan, 1973; Brinckmann et al., 1989; Colombini et al., 1989; Panjabi et al., 1992). The approximation may introduce an average of 9% systematic measurement error (Seidel et al., 2008). In addition, Chapter 3 reported that the measurement error varied across the lower lumbar levels, which was also dependent on the selection of the minor diameter in sagittal plane. The morphometric dataset is assumed to be a good representation of the adult population without spinal pathology and abnormality. Previous regression models (in Chapter 4) were developed using geometric data measured from the archived medical

magnetic resonance (MR) scans collected from a medical database at a healthcare institute. It should be noted that patients underwent an MRI scanning procedure to help medical doctors diagnose pathological alterations related to the lumbar region. Therefore, even with strict exclusion criteria, there are still possibilities that this sample of subjects may not be a good representation of a healthy population. To address such concerns, the present study employed several criteria to make the present sample a good representation. The present study recruited relatively young subjects (between 20 and 40 years old) with no medical conditions, no current episode of low back pain, and no previous low back injury. In addition, subjects with chronic leg or foot pain were excluded, since these symptom might be related to nerve damage in the lower lumbar region. All lower lumbar intervertebral discs were assessed to determine the degeneration status so that severely degenerated discs could be excluded from the morphometric analyses.

5.4.1 Regression models of the CSAs of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs)

Prior to this study, only a few studies in the literature have attempted to develop regression models to predict the CSAs of the lower lumbar IVD using subject variables and combinations of anthropometric measures (Colombini et al., 1989; Turk & Celan, 2004). Unfortunately, these regression models had only one predictor. Colombini et al. (1989) reported three significant regression models using subject weight, wrist diameter, and the bony structure weight (SW), respectively. Turk and Celan (2004) reported significant regression models using the average thickness of bony structures (AST) to predict the CSAs of the L4/L5 and L5/S1 IVDs. SW and AST, as anthropometric measures, have been

proposed to specifically characterize the overall development of the human skeletal system (Matiegka, 1921). Colombini et al. (1989) and Turk and Celan (2004) both reported that regression models using these anthropometric measures had better capability to explain the variance within the morphometric data, as indicated by larger R^2 and Adj-R^2 values.

The present study also found strong correlations between the average thickness of bony structures (AST) and the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs). It was also found that the bony structure weight (SW) had stronger correlations compared to the AST, which resulted in larger R^2 and Adj-R^2 associated with the corresponding regression models.

On the other hand, early attempts have failed to develop significant regression models to predict the cross-sectional areas (CSAs) of the lower lumbar vertebral endplates (Seidel et al., 2008). Seidel et al. (2008) reported poor correlations between the anthropometric measures and the CSAs of the lower lumbar endplates. It should be noted that previous morphometric data were measured on cadaveric specimens which may have been highly susceptible to post-mortem changes and, therefore, might not be a good representation of a healthy population. It has been supported in Chapter 4 that subject variables (gender and height) have strong correlations with the lower lumbar spinal morphometry and it is feasible to establish significant predictive relationships using them.

Regression models with easy-to-measure subject variables

Regression models in Chapter 4 and Chapter 5 both revealed that subject height and gender were the primary significant predictors. Although subject weight was significantly correlated with the cross-sectional areas (CSAs) of the lower lumbar intervertebral disc

(IVDs) and vertebral endplates (EPs), it was not a significant predictor in the regression model with the presence of other significant subject anthropometrics such as ankle index, sitting height, and elbow index. In the literature, regression models using subject weight were significant (Colombini et al., 1989). However, the relatively low R^2 values indicated that subject weight could only explain a small portion of the variance. In fact, the correlation between weight and lower lumbar spinal geometry may indeed be weak. Although one can speculate that the adult spinal structures may be adaptive to the mechanical stimulation introduced by body weight as suggested by Wolff's law (Chaffin et al., 2006), the changes could be very small since the spinal motion segment has very limited supply of nutrition through blood circulation (Raj, 2008). Therefore, it is very difficult to predict the actual size of the spinal structure based on weight alone, since an adult individual can easily change body weight (gain or lose). In addition, in the present study, lean body mass (LBM) did not appear in many regression models, despite the fact that it exhibited stronger correlation with the spinal geometry than body weight. On the other hand, the present study indicated that the geometric dimensions of bony structure, such as major joints and body segments might be more useful for estimating the size of the cross-sectional area of the lower lumbar intervertebral discs. In the literature, Colombini et al. (1989) reported wrist diameter as a significant predictor, superior to body weight. In the literature, some complex anthropometric measures have been proposed to characterize the overall human skeletal system, including the average square thickness of bony structures (AST) and bony structure weight (Matiegka, 1921). Regression models using these artificial measures were also reported in the literature (Turk & Celan, 2004), some of which exhibited superior performance (Colombini et al., 1989). The present study

supported that these anthropometric measures were significant predictors, however models using these measures exhibited smaller R^2 and Adj-R^2 values and larger standard error.

In agreement with Chapter 4, age was not significantly correlated with the CSAs of the lower lumbar intervertebral disc and vertebral endplate. However, it was noticed that age became a significant predictor in the regression models for L3/L4 CrEP_CSA and CaEP_CSA with the presence of gender and height. It may be due to the possible interactions between these three subject variables at the L3/L4 level or the uniqueness of the present geometric data. It was noted that the present regression models (Chapter 5) had greater R^2 and Adj-R^2, compared to the ones in Chapter 4, even though the present study had a smaller sample size, suggesting that the present models are capable to explain a greater proportion of the variance within the dataset in Chapter 5. It may be explained by the fact that in the present study, the differences between genders with respect to height, weight, and BMI were more pronounced (16.2 cm, 25.5 kg, and 4.3 in BMI) than the previous sample population (12.6 cm, 13.0 kg, and 0.3 in BMI), which might result in better spread of subject variables, particularly the height variable. Therefore, regression models in the present study had a smaller residual sum of squares using height as the predictor compared to the models in Chapter 4.

Regression models using "best" subset method

The present study may be the first attempt to characterize the predictive relationship between the subject anthropometrics and the lower lumbar spinal structure using "best" subset method, rather than traditional approaches using backward, forward, or stepwise methods. This method helps to address the possibility that certain combinations of subject

variables may better explain the variation than each single variable. It also provides the capability to evaluate the likelihood that a subject variable will be included in a model and help decide which predictors should be included. This paradigm of regression model development can provide better characterization of the spinal structure across the lower lumbar levels and provide cost-effective means to predict the cross-sectional areas by using fewer anthropometric measurements. Based on several criteria, the present study was able to provide regression models with satisfactory performance and reasonable effort to acquire additional anthropometric measurements.

With regard to the cross-sectional areas of the lower lumbar intervertebral disc (IVD_CSAs), across the three lower lumbar levels, ankle index was the most predictive subject variables, which was most likely to be included in a prediction model. Subject statue, measured by height and sitting height were also predictive in the models for the lower lumbar IVD_CSAs. Subject elbow index was significant and included in models for L3/L4 and L5/S1 IVD_CSAs but not for L4/L5 IVD_CSA. Subject hand index was only predictive in the model for the L5/S1 IVD_CSA. It should be noted that contradictory to the previous models reported in Chapter 4, gender was not included in any models for IVD_CSAs, since the frequency of including gender as a predictor was very low across all three lower lumbar levels.

With regard to the cross-sectional areas of the vertebral endplate (EP_CSAs), models for the cranial endplate and the caudal endplate also revealed that ankle index, subject stature (as measured by height or sitting height) were more predictive than other anthropometric variables. Subject hand index was predictive in models for the L3/L4 CrEP_CSA and L5/S1 CaEP_CSA. Differing from the models for IVD_CSA, the influence

of gender was evident for EPs, particularly for the CrEP_CSA. Subject elbow index was only predictive in the model for the L5/S1 CaEP_CSA.

It was noted that regression models using the bony structure weight (SW) and the average thickness of bony structures (AST) were less capable of explaining the variance within the morphometric data. Rather than combining anthropometric measures associated with different body joints, the measurement index variables, as proposed in this study, may have superior predictive relationships with the lower lumbar spinal morphometry.

Model selection

It should be noted that model selection is a trade-off between the model performance (as primarily measured by R^2 and Adj-R^2) and model complexity (as indicated by the number of predictors). Complex models are likely to provide better performance and accuracy to predict the CSAs of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs). However, they require more effort to obtain the additional anthropometric measurements. In the present study, although models using easy-to-measure subject variables exhibited smaller R^2 and Adj-R^2 values compared to the corresponding models using more comprehensive anthropometrics, the increase in time and effort to obtain the additional anthropometric measurements may be a barrier for some practitioners. The selection of appropriate regression models should a function of the end-users, given their time and resources available. For example, to an occupational health and ergonomics practitioner, a quick and easy equation may be more favorable to generate estimations of the cross-sectional area for 200 line workers in order to evaluate the associated risk of work-related musculoskeletal disorders (WMSDs). On the other hand, in

spinal surgery where an artificial implant of intervertebral disc is needed, the designer of the implant may prefer a comprehensive regression model to predict the size of the disc so that the implant could help the motion segment re-establish the intradiscal space.

Archived MR scans vs. Asymptomatic subjects

Another objective for this study was to determine the validity of using morphometric data measured on archived MR scans to develop regression models to predict the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs). In Chapter 4, regression models were validated using a subset of 20 subjects from the same sample, exhibiting no significant over- or underestimation. The paired sample t tests between the current morphometric data and the predicted value using regression models developed in Chapter 4 also revealed no significant difference for the CSAs of the lower lumbar IVDs. Absolute errors were very similar when predicting the IVD_CSAs for the subset of 20 subjects, on average 6.9% and 7% using regression models in Chapter 4 and Chapter 5 respectively. When predicting the IVD_CSAs for the asymptomatic subjects using regression models in Chapter 4, absolute errors were 9.8% on average. Therefore, there is no evidence that regression models in Chapter 4 are subjected to systematic error obtaining morphometric data on archived MR scans.

However, one CrEP model and two CaEP models in Chapter 4 significantly underestimated the CSAs by an average of 10.4% absolute error, compared to the corresponding measurements in Chapter 5. On the other hand, one CrEP model and one CaEP model in Chapter 5 significantly overestimated the CSAs, resulting in an average of 7.8% absolute error. For the same measurement, absolute error reported by the

corresponding regression models in Chapter 4 was on average 7.4%. In addition, overall average absolute errors associated with endplate models were on average 6.0% and 8.6%, and 6.1% and 9.1% when using regression models developed in Chapter 4 and Chapter 5 to predict the subset of 20 subjects, respectively. When predicting the asymptomatic subjects, models in Chapter 4 reported an average of 8.6% and an average of 11.0% absolute error for the CrEP and CaEP, respectively. Therefore, it remains unclear if regression models using archived MR scans will introduce systematic error in prediction. It was noted that in the present study, morphometric analyses revealed different patterns of cephalocaudal changes compared to the subjects associated with the archived MR scans. The present study reported that for both female and male subjects, caudal endplates at the L3/L4 and L4/L5 levels were significantly larger than the intervertebral discs, while no significant difference was found at the L5/S1 level, which contradicted to the findings of Chapter 4 where intervertebral discs had significantly larger CSAs. Therefore, further investigation is necessary to analyze the lower lumbar spinal morphometry with a large asymptomatic subject dataset and evaluate the predictability of the regression models.

5.5 Conclusion

The present study measured the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs) of a sample of young subjects without low back pain. Using magnetic resonance imaging (MRI) techniques and image processing software, precise and accurate morphometric data were obtained using the standardized measurement protocol. Differing from the previous studies, a comprehensive set of anthropometric characteristics were measured and included in the regression analysis

in order to develop more powerful prediction models to estimate the CSAs of the lower lumbar IVDs and EPs. The present study suggests that a number of anthropometric measures are strongly correlated with the CSAs of the lower lumbar IVDs and EPs. The present study proposed a new approach to develop the regression models using an all-possible-regressions procedure which would help develop alternative regression models for different model selection criteria. The present study allows a better understanding of statistical correlations between the subject anthropometric measures and the lower lumbar spinal morphometry. In addition, the present study found no evidence suggesting systematic errors associated with the regression models of the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) developed using archived MR scans, compared to the ones developed using asymptomatic subjects. Archived MR scans may be a reliable source to obtain morphometric data regarding the lower lumbar IVDs when proper exclusion criteria are employed. However, further investigations are needed to evaluate the performance of the prediction models for the lower lumbar vertebral endplates.

Chapter 6

CONCLUSION

The objective of this dissertation was to obtain accurate and reliable morphometric data regarding the lower lumbar motion segments, primarily the cross-sectional areas (CSAs) of the intervertebral discs (IVDs) and vertebral endplates (EPs), perform morphometric analyses of the spinal structures, and provide regression models that can accurately predict the CSAs of the lower lumbar IVDs and EPs. Biomechanical models of the human spine are highly dependent on the ability to accurately describe the complexity of the musculoskeletal structures and predict the spinal loading. Biomechanical models using simplified geometric representations of the human spine become less capable to accommodate the large variations in overall population and, therefore, characterize the risk of work-related low back pain for specific individuals. The cross-sectional area is a critical morphometric characteristic that contributes to the mechanical properties of a lumbar motion segment. In this dissertation, the CSAs of the lower lumbar IVDs and EPs were analyzed using magnetic resonance imaging (MRI) techniques.

A comprehensive literature review indicated that morphometric data regarding the lower lumbar motion segments were lacking, especially the CSAs of the lower lumbar IVDs and EPs. It was also noted that previous morphometric studies had some limitations. For example, some studies had very small sample sizes, subjects with different medical conditions, and simplified measurement protocols. Primarily, the measurement of

geometric dimensions involves three concerns: 1) how to prepare specimens (cadaver or *in vivo*), 2) how to access the structure (cadaver or scanned image), and 3) how to define the dimensions. In general, cadaver studies have difficulties addressing the limitations associated with post-mortem changes in soft tissues (e.g., the intervertebral discs, muscles, ligaments, etc.) and changes caused by storage conditions (e.g., freezing conditions, preservation methods, etc.) Measurements performed *in vivo* can improve the understanding of the living human spine. Medical imaging techniques vary in their capability to deliver comprehensive morphometric data. Radiographs provide good identifications of the bony landmarks, however, they can only measure the dimensions in the sagittal and frontal planes. Computed tomography (CT) scans can be used to measure the morphometric characteristics of the spinal motion segments in the transverse section, however, they are less capable of evaluating the disc degeneration status, compared to magnetic resonance imaging (MRI) techniques. MRI techniques have superior capability to accommodate the lumbar curvature by providing oblique slicing planes, and provide better resolution and contrast to help diagnose the health status of the disc.

To address the limitations found in previous morphometric studies, this dissertation obtained morphometric data for both genders using high resolution MR scans, advanced image processing software, and utilized a standardized measurement protocol with both archived medical MR scans (Study 1) and a sample of asymptomatic subjects (Study 2). With archived MR scans, a total of 109 subjects (55 females and 54 males) were included in the morphometric analyses in Chapter 3. Out of 109, 79 subjects (41 females and 38 males) were included for regression analyses in Chapter 4. Since archived MR scans were collected from a medical database, several criteria were employed to exclude presumed unhealthy

discs. Still, there is concern that this sample of subjects may not be a good representation of a healthy population, which may introduce systematic error into the regression models. Therefore, a total of 35 asymptomatic subjects (13 females and 22 males) were included in a second morphometric study, in which regression models were also developed.

Morphometric data of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs) were obtained using an advanced image processing software that can provide the measurement of the actual shape of the IVDs and EPs, particularly the cross-sectional areas (CSAs), rather than using simple linear dimensions to approximate shapes and sizes. This dissertation standardized the measurement protocol by employing clear definitions and illustrations of geometric dimensions. This helped to obtain accurate morphometric data with excellent intra- and inter-observer reliabilities. In Study 1, the influence of using an ellipsoid approximation method was investigated. The specific impact on measurement error was reported for each lower lumbar spinal level. Morphometric analyses in both Study 1 and Study 2 reported significant differences between genders. In general, male subjects had larger lower lumbar motion segment dimensions. Compared to the previous studies, morphometric data reported in this dissertation tended towards the lower end of the spectrum. Differences might be due to variations in subject characteristics and measurement protocols. It was also found that subject morphometric characteristics varied with respect to the patterns of cephalocaudal changes between the subjects in Study 1 and Study 2. At the L3/L4 and L4/L5 levels, the caudal endplates were significantly larger than the intervertebral discs for both genders in study 2. No significant differences were found at the L5/S1 level. This contradicted the findings of Study 1, in which the

intervertebral disc had the largest cross-sectional area within a lower lumbar motion segment.

Regression analyses in both Study 1 and Study 2 suggests that it is feasible to develop significant prediction models to provide satisfactory estimations for the cross-sectional areas (CSAs) of the lower lumbar intervertebral discs (IVDs) and vertebral endplates (EPs) using subject characteristics and anthropometric measures. In Study 1 (Chapter 4), subject height and gender were identified as better predictors of the CSAs compared to weight and age. In Study 2 (Chapter 5), more anthropometric measures were obtained with respect to an individual's body segments (e.g., head, chest, and arm) and joints (e.g., wrist, elbow, knee, and ankle). It was evident that many anthropometric measures had strong correlations with the CSAs of the lower lumbar IVDs and EPs, which provided the opportunity to explore many develop regression models. In order to provide better understanding of the regression models and the selection of predictors, Study 2 employed an all-possible-regressions procedure ("best" subset method) to help develop regression models with balanced complexity and predictability. It was evident that models with more anthropometric measures had better capability to explain the variance within the morphometric data. However, more time and effort is required to obtain these comprehensive anthropometric measures. Regression models using easy-to-measure subject variables also provided satisfactory estimations. This dissertation also shows that it is feasible to use morphometric data measured on archived MR scans and develop regression models to predict the CSAs of the lower lumbar IVDs with no apparent systematic error, compared to the ones developed with asymptomatic subjects. This finding can help future morphometric studies to obtain larger sample sizes and improved the understandings of

predictive relationships. In addition, this dissertation also suggests further investigations to analyze the difference in morphometric characteristics of the vertebral endplates in archived MR scans and asymptomatic subjects. The regression models developed in this dissertation also improve the understanding of the morphometric data reported in the literature. As indicated by the significant predictors, variations in previous morphometric data may be due to the different subject anthropometric characteristics, rather than the influence of gender alone. This dissertation also suggests that future morphometric studies should at a minimum report subject gross anthropometric characteristics, such as height, weight, and gender, in order to establish a general database of the human spinal morphometry for the development of biomechanical models, finite element models, and surgical applications.

This dissertation has several limitations. First, subjects in Study 1 and Study 2 had small range of age (from 20 to 40 years). Age was not significantly correlated with the lower lumbar spinal morphometry. Regression analyses also revealed minimal influence of age on the CSAs of the lower lumbar cranial endplates. In addition, the influence of disc degeneration was not fully investigated in this dissertation. Future studies should include more subjects with a wider range of age and disc degeneration status to investigate the influence of age, disc degeneration, and their interactions on the spinal morphometry. Future studies might also include subject symptom level and medical diagnoses related to low back pain. Secondly, all morphometric data were obtained while subjects were in supine position. This alters the spinal curvatures and the spinal loading, compared to a natural standing posture. Therefore, future studies should investigate possible means to help subjects resume the spinal curvature and the spinal loading with MRI-compatible techniques.

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Appendix A

Approval letter from the Institutional Review Boards (IRBs) at the University of Utah and Auburn University

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

Documentation of research protocol (Informed Consent and subject recruitment flyer) as approved by the Institutional Review Board (IRB) at Auburn University

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 # 11-292MR1111

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).

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____

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____

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

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.

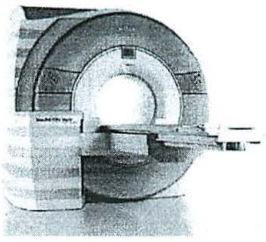
Participant's signature	Date	Investigator obtaining consent	Date

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.

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

Data collection form used in Study 2

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 D

Best subset regression models for the CSA of the intervertebral discs (IVDs)

Appendix - D.1: Best subset regression models for the L3/L4 IVD_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
												X		X	2	75.3	74.6	16.7	1.4459
	X													X	2	73.6	72.8	20	1.4955
										X				X	2	73.4	72.6	20.4	1.5021
			X											X	2	66.1	65.1	34.4	1.6942
						X								X	2	64.5	63.4	37.6	1.7345
			X									X		X	3	83.6	82.6	2.6	1.1958
	X											X		X	3	82.7	81.6	4.4	1.2292
			X							X				X	3	80.8	79.6	8.1	1.2952
						X						X		X	3	80.3	79.1	9	1.3116
			X										X	X	3	80.1	78.9	9.4	1.3187
	X								X			X		X	4	86.2	84.8	-0.3	1.1174
			X					X				X		X	4	85.9	84.5	0.3	1.1295
	X	X										X		X	4	85.7	84.3	0.6	1.1357
	X							X				X		X	4	85.3	83.9	1.4	1.1516
	X				X							X		X	4	85.1	83.7	1.7	1.1575
			X			X			X			X		X	5	87.4	85.7	-0.6	1.0852
	X		X					X				X		X	5	87.3	85.6	-0.4	1.0895
	X		X						X			X		X	5	87.2	85.5	-0.2	1.093
			X			X		X				X		X	5	87.2	85.4	-0.2	1.0945
	X	X							X			X		X	5	87	85.2	0.2	1.1021
	X		X					X	X			X		X	6	88.2	86.2	-0.2	1.0657
	X		X						X	X		X		X	6	88	86	0.1	1.0749
			X			X		X	X			X		X	6	87.9	85.9	0.3	1.0781
			X			X			X	X		X		X	6	87.9	85.8	0.4	1.0798
	X		X				X		X			X		X	6	87.9	85.8	0.4	1.0809
	X		X					X	X	X		X		X	7	89	86.6	0.3	1.049
			X			X		X	X	X		X		X	7	88.5	86.1	1.1	1.0698
	X		X				X		X	X		X		X	7	88.5	86.1	1.1	1.07
	X		X				X	X	X			X		X	7	88.5	86	1.2	1.0716
	X		X	X					X	X		X		X	7	88.5	86	1.2	1.0723
	X		X	X				X	X	X		X		X	8	89.2	86.4	1.9	1.0593
	X		X				X	X	X	X		X		X	8	89.2	86.4	1.9	1.0596
	X		X					X	X	X		X	X	X	8	89	86.2	2.2	1.0668
X	X		X					X	X	X		X		X	8	89	86.1	2.3	1.0678
	X	X	X					X	X	X		X		X	8	89	86.1	2.3	1.0681
	X		X	X				X	X	X		X	X	X	9	89.3	86	3.7	1.0739
	X		X				X	X	X	X		X	X	X	9	89.2	85.9	3.8	1.0759
	X		X	X			X	X	X	X		X		X	9	89.2	85.9	3.8	1.0761
X	X		X				X	X	X	X		X		X	9	89.2	85.9	3.8	1.0765
X	X		X	X				X	X	X		X		X	9	89.2	85.9	3.8	1.0774
	X		X	X			X	X	X	X		X	X	X	10	89.4	85.5	5.5	1.0907
	X		X			X	X	X	X	X		X	X	X	10	89.4	85.5	5.6	1.0909
	X		X	X		X		X	X	X		X	X	X	10	89.4	85.5	5.6	1.0913
	X	X	X	X				X	X	X		X	X	X	10	89.3	85.5	5.6	1.0928
	X		X	X	X		X	X	X	X		X		X	10	89.3	85.5	5.6	1.0929
	X		X	X		X	X	X	X	X		X	X	X	11	89.5	85.1	7.3	1.1056
	X		X	X	X		X	X	X	X		X	X	X	11	89.4	85	7.4	1.1097
	X	X	X	X			X	X	X	X		X	X	X	11	89.4	85	7.4	1.1099
X	X		X			X	X	X	X	X		X	X	X	11	89.4	85	7.4	1.1102
X	X	X	X	X			X	X	X	X		X		X	11	89.4	85	7.5	1.1117
X	X		X	X		X	X	X	X	X		X	X	X	12	89.6	84.6	9.1	1.1258
	X		X	X	X	X	X	X	X	X		X	X	X	12	89.6	84.6	9.2	1.127
	X	X	X	X		X	X	X	X	X		X	X	X	12	89.5	84.5	9.2	1.1279
	X		X	X		X	X	X	X	X	X	X	X	X	12	89.5	84.5	9.3	1.1291
X	X	X	X	X			X	X	X	X		X	X	X	12	89.5	84.4	9.3	1.131
X	X	X	X	X		X	X	X	X	X		X	X	X	13	89.6	84	11	1.1486
X	X		X	X	X	X	X	X	X	X		X	X	X	13	89.6	84	11.1	1.149
X	X		X	X		X	X	X	X	X	X	X	X	X	13	89.6	83.9	11.1	1.151
	X	X	X	X		X	X	X	X	X	X	X	X	X	13	89.6	83.9	11.2	1.1515
	X		X	X	X	X	X	X	X	X	X	X	X	X	13	89.6	83.9	11.2	1.1521
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	89.6	83.2	13	1.1742
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	89.6	83.2	13	1.1754
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	89.6	83.2	13.1	1.176
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14	89.6	83.1	13.1	1.1785
X	X	X	X	X	X		X	X	X	X	X	X	X	X	14	89.5	83	13.3	1.1822
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	89.6	82.4	15	1.2032

Appendix - D.2: Best subset regression models for the L4/L5 IVD_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s $(=\sqrt{MSE})$
										X				X	2	76	75.3	16.9	1.524
												X		X	2	75.6	74.9	17.7	1.5366
	X													X	2	74.5	73.7	20	1.5724
			X											X	2	68.4	67.5	32.1	1.7488
													X	X	2	67.5	66.6	33.9	1.7739
			X									X		X	3	85	84.1	1	1.2238
			X										X	X	3	83.9	82.9	3.2	1.2692
			X							X				X	3	83.7	82.7	3.6	1.2767
	X											X		X	3	83.4	82.3	4.3	1.2897
	X									X				X	3	80.8	79.6	9.4	1.3858
			X									X	X	X	4	86.6	85.3	-0.3	1.1741
			X			X						X		X	4	86	84.6	1	1.2023
			X							X		X		X	4	85.8	84.4	1.4	1.2109
			X	X								X		X	4	85.7	84.4	1.5	1.2132
	X		X									X		X	4	85.7	84.3	1.6	1.2147
			X						X			X	X	X	5	87.6	86	-0.2	1.1495
			X		X			X				X		X	5	87.5	85.8	0	1.1554
			X					X				X	X	X	5	87.5	85.8	0.1	1.156
			X	X				X				X		X	5	87.1	85.4	0.8	1.1736
			X				X					X	X	X	5	86.9	85.1	1.2	1.1821
			X						X	X		X	X	X	6	87.9	85.9	1.1	1.1529
			X		X			X				X	X	X	6	87.9	85.8	1.2	1.1549
			X					X	X			X	X	X	6	87.8	85.7	1.3	1.158
			X		X			X		X		X		X	6	87.8	85.7	1.4	1.1591
		X	X					X				X	X	X	6	87.8	85.7	1.4	1.1594
			X		X			X	X	X		X		X	7	88.6	86.2	1.8	1.1405
		X	X					X	X			X	X	X	7	88.5	86.1	1.9	1.144
		X	X					X	X	X		X		X	7	88.5	86.1	2	1.1451
			X		X			X	X			X	X	X	7	88.5	86	2	1.1465
			X		X		X		X			X	X	X	7	88.3	85.8	2.4	1.1559
		X	X					X	X	X		X	X	X	8	89.1	86.2	2.9	1.1385
X		X	X					X	X	X		X		X	8	89	86.1	3	1.1416
			X		X			X	X	X	X	X		X	8	88.9	86.1	3.1	1.1451
			X		X		X	X	X			X	X	X	8	88.9	86	3.2	1.1474
			X		X			X	X	X		X	X	X	8	88.9	86	3.3	1.149
		X	X			X		X	X	X		X	X	X	9	89.2	85.9	4.5	1.1508
X		X	X					X	X	X		X	X	X	9	89.2	85.9	4.5	1.1509
			X		X			X	X	X	X	X	X	X	9	89.2	85.9	4.6	1.1528
X		X	X				X	X	X	X		X		X	9	89.2	85.8	4.7	1.1552
			X		X	X	X	X	X			X	X	X	9	89.1	85.8	4.7	1.156
X			X		X		X	X	X	X	X	X		X	10	89.4	85.6	6.2	1.1639
X		X	X				X	X	X	X		X	X	X	10	89.4	85.6	6.2	1.164
		X	X			X	X	X	X	X		X	X	X	10	89.4	85.6	6.2	1.1648
X		X	X			X		X	X	X		X	X	X	10	89.4	85.6	6.2	1.1651
			X		X		X	X	X	X	X	X	X	X	10	89.4	85.6	6.2	1.1657
X		X	X			X	X	X	X	X		X	X	X	11	89.7	85.4	7.6	1.1715
			X		X	X	X	X	X	X	X	X	X	X	11	89.7	85.4	7.6	1.1724
		X	X		X	X	X	X	X	X		X	X	X	11	89.6	85.2	7.9	1.1797
X			X		X		X	X	X	X	X	X	X	X	11	89.5	85.2	7.9	1.1804
X			X		X	X	X	X	X		X	X	X	X	11	89.5	85.2	8	1.1818
X			X		X	X	X	X	X	X	X	X	X	X	12	89.9	85	9.3	1.188
X		X	X		X	X	X	X	X	X		X	X	X	12	89.8	84.9	9.4	1.192
X		X	X	X		X	X	X	X	X		X	X	X	12	89.8	84.9	9.5	1.1925
X	X	X	X			X	X	X	X	X		X	X	X	12	89.8	84.9	9.5	1.1926
			X	X	X	X	X	X	X	X	X	X	X	X	12	89.7	84.8	9.5	1.1941
X	X		X		X	X	X	X	X	X	X	X	X	X	13	89.9	84.4	11.1	1.2101
X			X	X	X	X	X	X	X	X	X	X	X	X	13	89.9	84.4	11.2	1.2111
X		X	X		X	X	X	X	X	X	X	X	X	X	13	89.9	84.4	11.2	1.2124
X	X	X	X		X	X	X	X	X	X		X	X	X	13	89.8	84.3	11.3	1.2152
X	X	X	X	X		X	X	X	X	X		X	X	X	13	89.8	84.3	11.3	1.2154
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	90	83.8	13	1.2351
X	X	X	X		X	X	X	X	X	X	X	X	X	X	14	90	83.7	13.1	1.2372
X		X	X	X	X	X	X	X	X	X	X	X	X	X	14	89.9	83.7	13.1	1.2375
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	89.9	83.6	13.2	1.2409
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	89.9	83.6	13.3	1.2426
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	90	83	15	1.2645

Appendix - D.3: Best subset regression models for the L5/S1 IVD_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
												X		X	2	72.4	71.6	25.9	1.6466
	X													X	2	69.5	68.5	32	1.7332
										X				X	2	69.4	68.5	32.2	1.735
													X	X	2	65.4	64.3	40.5	1.8463
						X								X	2	61.1	60	49.3	1.9559
			X									X		X	3	79.2	77.9	13.9	1.4527
	X											X		X	3	78.9	77.5	14.6	1.4647
			X										X	X	3	78	76.7	16.3	1.4925
						X						X		X	3	76.9	75.4	18.8	1.5323
			X							X				X	3	75.7	74.2	21.2	1.5702
	X								X			X		X	4	84.2	82.7	5.5	1.2846
	X	X										X		X	4	83.2	81.6	7.7	1.3265
	X				X							X		X	4	81.8	80.1	10.5	1.3795
	X							X				X		X	4	81.8	80	10.6	1.3806
			X					X				X		X	4	81.7	79.9	10.8	1.3841
			X						X			X	X	X	5	86.3	84.4	3.4	1.22
	X	X							X			X		X	5	85.3	83.4	5.3	1.2608
	X								X	X		X		X	5	85.1	83.2	5.7	1.2686
	X								X			X	X	X	5	85	83	5.9	1.2731
	X							X	X			X		X	5	84.8	82.8	6.4	1.2822
			X						X		X	X	X	X	6	86.8	84.5	4.3	1.2174
	X		X						X			X	X	X	6	86.7	84.4	4.5	1.2204
			X					X	X			X	X	X	6	86.7	84.4	4.5	1.2214
			X		X				X			X	X	X	6	86.5	84.2	4.8	1.2284
			X						X	X		X	X	X	6	86.5	84.2	4.9	1.23
	X				X	X			X			X	X	X	7	87.9	85.4	3.9	1.1824
	X	X				X			X			X	X	X	7	87.8	85.2	4.2	1.1894
		X	X						X		X	X	X	X	7	87.6	84.9	4.6	1.199
			X					X	X		X	X	X	X	7	87.5	84.8	4.8	1.2039
	X		X		X				X			X	X	X	7	87.4	84.6	5.1	1.2113
	X	X				X			X		X	X	X	X	8	89.2	86.4	3.2	1.1384
	X	X	X						X		X	X	X	X	8	88.4	85.4	4.9	1.1803
	X				X	X			X	X		X	X	X	8	88.4	85.4	5	1.1827
X	X				X	X			X			X	X	X	8	88.4	85.4	5	1.1827
	X		X		X	X			X			X	X	X	8	88.3	85.2	5.2	1.1873
	X	X				X			X	X	X	X	X	X	9	89.6	86.4	4.4	1.139
X	X	X				X			X		X	X	X	X	9	89.6	86.4	4.5	1.1412
	X	X	X			X			X		X	X	X	X	9	89.5	86.3	4.6	1.1436
	X	X				X	X		X		X	X	X	X	9	89.3	86	5.2	1.1583
	X	X			X	X			X		X	X	X	X	9	89.3	85.9	5.2	1.1586
X	X	X				X			X	X	X	X	X	X	10	90	86.4	5.7	1.1409
	X	X	X			X			X	X	X	X	X	X	10	89.8	86.2	6	1.1497
X	X	X	X			X			X		X	X	X	X	10	89.8	86.1	6.1	1.1528
	X	X				X	X		X	X	X	X	X	X	10	89.7	86	6.3	1.1577
	X	X		X		X			X	X	X	X	X	X	10	89.7	86	6.3	1.1584
X	X	X	X			X			X	X	X	X	X	X	11	90.1	86	7.4	1.1575
X	X	X		X		X			X	X	X	X	X	X	11	90.1	86	7.4	1.1576
X	X	X				X		X	X	X	X	X	X	X	11	90	85.9	7.6	1.1615
X	X	X				X	X		X	X	X	X	X	X	11	90	85.8	7.7	1.1644
X	X	X			X	X			X	X	X	X	X	X	11	90	85.8	7.7	1.1644
X	X	X	X	X		X			X	X	X	X	X	X	12	90.2	85.6	9.2	1.1748
X	X	X	X			X		X	X	X	X	X	X	X	12	90.2	85.5	9.3	1.1777
X	X	X		X		X		X	X	X	X	X	X	X	12	90.1	85.4	9.3	1.1794
X	X	X		X		X	X		X	X	X	X	X	X	12	90.1	85.4	9.4	1.1815
X	X	X	X		X	X			X	X	X	X	X	X	12	90.1	85.4	9.4	1.1822
X	X	X	X	X		X		X	X	X	X	X	X	X	13	90.3	85	11	1.1961
X	X	X	X	X	X	X			X	X	X	X	X	X	13	90.2	84.9	11.1	1.2
X	X	X	X	X		X	X		X	X	X	X	X	X	13	90.2	84.9	11.2	1.2011
X	X	X	X			X	X	X	X	X	X	X	X	X	13	90.2	84.8	11.3	1.204
X	X	X	X		X	X		X	X	X	X	X	X	X	13	90.2	84.8	11.3	1.2042
X	X	X	X	X	X	X		X	X	X	X	X	X	X	14	90.3	84.3	13	1.224
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	90.3	84.3	13	1.2242
X	X	X	X	X	X	X	X		X	X	X	X	X	X	14	90.2	84.2	13.1	1.2283
X	X	X	X		X	X	X	X	X	X	X	X	X	X	14	90.2	84.1	13.3	1.2323
X	X	X		X	X	X	X	X	X	X	X	X	X	X	14	90.2	84.1	13.3	1.2328
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	90.3	83.5	15	1.2542

Appendix E

Best subset regression models for the CSA of the cranial endplates (CrEPs)

Appendix - E.1: Best subset regression models for the L3/L4 CrEP_CSAs

Variables																Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
	X													X	2	73.7	72.9	25.5	1.3442
												X		X	2	72.2	71.3	28.8	1.3829
										X				X	2	68.6	67.7	36.5	1.4691
			X											X	2	65	63.9	44.3	1.5522
						X								X	2	62.2	61.1	50.2	1.6117
	X											X		X	3	81	79.8	11.8	1.16
			X									X		X	3	81	79.8	11.9	1.1622
X	X													X	3	78	76.6	18.3	1.2492
			X							X					X	3	77.2	75.7	20.1	1.2725
X			X											X	3	77.1	75.7	20.1	1.2731
	X	X										X		X	4	84.1	82.6	7.2	1.0789
	X								X			X		X	4	83.8	82.2	7.9	1.0897
	X				X							X		X	4	83.5	81.9	8.5	1.0992
	X							X				X		X	4	83.2	81.6	9.1	1.1081
	X			X								X		X	4	82.8	81.1	10	1.1222
	X	X										X	X	X	5	85.5	83.5	6.2	1.0483
	X	X				X						X		X	5	85.1	83.1	7.1	1.0623
X	X				X							X		X	5	85.1	83.1	7.1	1.0626
	X							X				X	X	X	5	84.9	82.9	7.4	1.0671
	X	X	X									X		X	5	84.9	82.9	7.4	1.0682
X	X							X				X	X	X	6	88	86	2.7	0.96761
X	X	X										X	X	X	6	87.6	85.5	3.6	0.98348
X	X			X					X			X		X	6	86.9	84.6	5.2	1.0137
X	X								X			X	X	X	6	86.7	84.4	5.6	1.0207
X	X				X				X			X		X	6	86.6	84.2	5.9	1.0254
X	X							X	X			X	X	X	7	88.7	86.3	3.2	0.95583
X	X			X				X				X	X	X	7	88.4	86	3.9	0.9682
X	X							X			X	X	X	X	7	88.4	85.9	3.9	0.96922
X	X	X						X				X	X	X	7	88.4	85.9	4	0.97081
X	X				X			X				X	X	X	7	88.3	85.8	4.2	0.97412
X	X			X				X	X			X	X	X	8	89.2	86.4	4.2	0.9518
X	X							X	X		X	X	X	X	8	89.1	86.3	4.4	0.95626
X	X							X	X	X		X	X	X	8	89.1	86.3	4.4	0.95643
X	X						X	X	X			X	X	X	8	88.9	86.1	4.8	0.96462
X	X					X		X	X			X	X	X	8	88.9	86	4.9	0.96689
X	X			X				X	X	X		X	X	X	9	89.7	86.5	5.1	0.94755
X	X			X				X	X		X	X	X	X	9	89.7	86.5	5.2	0.95026
X	X							X	X	X	X	X	X	X	9	89.4	86.1	5.8	0.96155
X	X			X		X		X	X			X	X	X	9	89.4	86.1	5.9	0.96344
X	X		X	X				X	X			X	X	X	9	89.4	86.1	5.9	0.96365
X	X			X				X	X	X	X	X	X	X	10	90	86.4	6.4	0.95142
X	X			X		X		X	X	X		X	X	X	10	89.9	86.3	6.7	0.95733
X	X			X		X		X	X		X	X	X	X	10	89.8	86.2	6.8	0.96056
X	X		X	X				X	X		X	X	X	X	10	89.8	86.1	6.9	0.96274
X	X		X	X				X	X	X		X	X	X	10	89.8	86.1	7	0.96303
X	X			X		X		X	X	X	X	X	X	X	11	90.2	86.2	8	0.96023
X	X		X	X				X	X	X	X	X	X	X	11	90.1	86	8.3	0.96741
X	X	X		X				X	X	X	X	X	X	X	11	90.1	86	8.3	0.96761
X	X			X		X	X	X	X		X	X	X	X	11	90.1	85.9	8.4	0.96925
X	X			X			X	X	X	X	X	X	X	X	11	90	85.9	8.4	0.97024
X	X	X		X	X			X	X	X	X	X	X	X	12	90.4	85.8	9.6	0.97316
X	X			X		X	X	X	X	X	X	X	X	X	12	90.4	85.8	9.7	0.97427
X	X	X		X		X		X	X	X	X	X	X	X	12	90.3	85.7	9.9	0.97857
X	X			X	X	X		X	X	X	X	X	X	X	12	90.3	85.6	9.9	0.97986
X	X		X	X		X		X	X	X	X	X	X	X	12	90.3	85.6	9.9	0.98023
X	X	X		X	X	X		X	X	X	X	X	X	X	13	90.6	85.5	11.2	0.98481
X	X	X	X	X	X			X	X	X	X	X	X	X	13	90.5	85.3	11.5	0.99178
X	X	X		X		X	X	X	X	X	X	X	X	X	13	90.4	85.2	11.6	0.99332
X	X		X	X		X	X	X	X	X	X	X	X	X	13	90.4	85.2	11.6	0.99404
X	X	X		X	X		X	X	X	X	X	X	X	X	13	90.4	85.2	11.6	0.99492
X	X	X		X	X	X	X	X	X	X	X	X	X	X	14	90.7	84.9	13.1	1.0043
X	X	X	X	X	X	X		X	X	X	X	X	X	X	14	90.6	84.8	13.2	1.0077
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	90.5	84.7	13.4	1.0116
X	X	X	X	X	X		X	X	X	X	X	X	X	X	14	90.5	84.6	13.4	1.0134
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	90.4	84.5	13.6	1.0174
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	90.7	84.2	15	1.0275

Appendix - E.2: Best subset regression models for the L4/L5 CrEP_CSAs

Variables																Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
	X													X	2	77.7	77	13.3	1.2114
										X				X	2	73.1	72.2	22.5	1.3305
						X								X	2	71.5	70.7	25.5	1.3676
												X		X	2	69.9	69	28.7	1.4066
			X											X	2	67	66	34.5	1.473
	X											X		X	3	82.4	81.3	6	1.0927
X	X													X	3	81.3	80.1	8.1	1.1259
	X									X				X	3	81.1	79.9	8.5	1.1315
			X							X				X	3	81	79.8	8.7	1.134
			X			X								X	3	80.9	79.7	8.9	1.1374
			X			X						X		X	4	85.1	83.7	2.5	1.0194
	X							X				X		X	4	85	83.5	2.8	1.0251
	X	X										X		X	4	84.8	83.4	3.1	1.0299
X	X							X						X	4	84.2	82.7	4.3	1.0499
	X								X			X		X	4	84.1	82.5	4.6	1.0555
			X			X		X				X		X	5	86.8	85	1.3	0.97796
X	X							X				X		X	5	86.4	84.6	2	0.99134
	X		X					X				X		X	5	86.2	84.4	2.4	0.99829
			X			X			X			X		X	5	86.1	84.3	2.5	1.0012
X	X		X					X						X	5	86.1	84.3	2.6	1.0021
X	X		X					X				X		X	6	88	85.9	0.8	0.94676
X			X			X		X				X		X	6	87.9	85.8	1.1	0.95232
X	X		X					X		X				X	6	87.7	85.5	1.5	0.96096
X	X							X				X	X	X	6	87.4	85.3	1.9	0.96907
X			X			X		X		X				X	6	87.3	85.1	2.3	0.97588
X			X			X		X				X	X	X	7	88.4	85.9	2	0.94668
X	X		X					X	X	X				X	7	88.4	85.9	2	0.94719
X	X		X					X	X			X		X	7	88.4	85.9	2	0.94727
X	X		X					X		X		X		X	7	88.2	85.7	2.3	0.95453
X	X		X					X				X	X	X	7	88.2	85.7	2.4	0.95589
X	X							X	X	X		X	X	X	8	89	86.2	2.8	0.93915
X	X		X					X	X	X		X		X	8	89	86.1	2.8	0.93993
X			X			X		X		X		X	X	X	8	88.9	86	3.1	0.9449
X	X		X					X	X	X			X	X	8	88.8	85.8	3.3	0.95031
X	X	X	X					X	X	X				X	8	88.7	85.8	3.3	0.95078
X	X		X					X	X	X		X	X	X	9	89.4	86.2	4	0.93847
X		X	X			X		X	X	X			X	X	9	89.3	86	4.3	0.94531
X			X			X		X	X	X		X	X	X	9	89.3	86	4.3	0.94608
X	X	X	X					X	X	X			X	X	9	89.1	85.8	4.6	0.95197
X	X		X			X		X		X		X	X	X	9	89.1	85.7	4.6	0.95359
X		X	X			X		X	X	X		X	X	X	10	89.8	86.1	5.3	0.94121
X	X		X			X		X	X	X		X	X	X	10	89.7	86	5.5	0.94636
X			X		X	X		X	X	X		X	X	X	10	89.6	85.9	5.6	0.9497
X	X	X	X					X	X	X		X	X	X	10	89.5	85.8	5.8	0.95274
X	X		X		X			X	X	X		X	X	X	10	89.5	85.7	5.9	0.95596
X	X	X	X			X		X	X	X		X	X	X	11	89.9	85.7	7.1	0.9558
X		X	X			X		X	X	X	X	X	X	X	11	89.8	85.6	7.2	0.95996
X		X	X	X		X		X	X	X		X	X	X	11	89.8	85.5	7.2	0.96023
X		X	X			X	X	X	X	X		X	X	X	11	89.8	85.5	7.3	0.96046
X		X	X		X	X		X	X	X		X	X	X	11	89.8	85.5	7.3	0.96056
X	X	X	X	X		X		X	X	X		X	X	X	12	89.9	85.1	9	0.9756
X	X	X	X			X		X	X	X	X	X	X	X	12	89.9	85.1	9	0.97597
X	X	X	X		X	X		X	X	X		X	X	X	12	89.9	85.1	9.1	0.97634
X	X	X	X			X	X	X	X	X		X	X	X	12	89.9	85.1	9.1	0.97635
X		X	X	X		X		X	X	X	X	X	X	X	12	89.8	84.9	9.2	0.97999
X	X	X	X	X		X		X	X	X	X	X	X	X	13	89.9	84.4	11	0.99691
X	X	X	X	X		X	X	X	X	X		X	X	X	13	89.9	84.4	11	0.99748
X	X	X	X	X	X	X		X	X	X		X	X	X	13	89.9	84.4	11	0.99751
X	X	X	X		X	X		X	X	X	X	X	X	X	13	89.9	84.4	11	0.99757
X	X	X	X			X	X	X	X	X	X	X	X	X	13	89.9	84.4	11	0.99787
X	X	X	X	X	X	X		X	X	X	X	X	X	X	14	89.9	83.7	13	1.0202
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	89.9	83.7	13	1.0204
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	89.9	83.7	13	1.021
X	X	X	X		X	X	X	X	X	X	X	X	X	X	14	89.9	83.7	13	1.021
X		X	X	X	X	X	X	X	X	X	X	X	X	X	14	89.8	83.5	13.2	1.0253
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	89.9	82.9	15	1.0454

Appendix - E.3: Best subset regression models for the L5/S1 CrEP_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
	X													X	2	73.1	72.3	9.8	1.3771
												X		X	2	72.3	71.5	11.1	1.3977
										X				X	2	71.8	70.9	11.9	1.411
						X								X	2	63.3	62.2	24.7	1.608
													X	X	2	62.6	61.4	25.9	1.6251
	X											X		X	3	80.7	79.5	0.3	1.1838
			X									X		X	3	79.3	78	2.5	1.2274
	X									X				X	3	77.8	76.4	4.8	1.2721
						X						X		X	3	77.7	76.3	4.9	1.2733
			X							X				X	3	77.5	76.1	5.2	1.279
	X								X			X		X	4	84.1	82.5	-2.8	1.0937
	X	X										X		X	4	82	80.2	0.4	1.1641
	X			X								X		X	4	81.6	79.8	0.9	1.1751
	X								X	X				X	4	81.6	79.8	0.9	1.1753
	X				X							X		X	4	81.6	79.8	1	1.1767
	X								X	X		X		X	5	85	83	-2.2	1.08
	X			X					X			X		X	5	84.4	82.4	-1.4	1.0989
	X		X						X			X		X	5	84.3	82.2	-1.1	1.1041
X	X								X			X		X	5	84.3	82.2	-1.1	1.1044
	X						X		X			X		X	5	84.2	82	-0.9	1.1085
	X			X					X	X		X		X	6	85.7	83.2	-1.2	1.0728
	X		X						X	X		X		X	6	85.2	82.7	-0.6	1.0886
	X					X			X	X		X		X	6	85.2	82.7	-0.5	1.0896
	X						X		X	X		X		X	6	85.2	82.6	-0.5	1.0911
X	X								X	X		X		X	6	85.1	82.5	-0.3	1.0941
	X			X			X		X	X		X		X	7	86.5	83.5	-0.4	1.0613
X	X			X					X	X		X		X	7	86	83	0.2	1.0777
	X			X		X			X	X		X		X	7	85.9	82.9	0.4	1.0828
	X		X	X					X	X		X		X	7	85.8	82.8	0.5	1.0847
	X			X				X	X	X		X		X	7	85.8	82.8	0.5	1.0854
X	X			X			X		X	X		X		X	8	86.6	83.1	1.3	1.0745
	X			X			X	X	X	X		X		X	8	86.5	83	1.5	1.0796
	X			X			X		X	X		X	X	X	8	86.5	83	1.5	1.0797
	X	X		X			X		X	X		X		X	8	86.5	83	1.5	1.0798
	X			X		X	X		X	X		X		X	8	86.5	83	1.5	1.08
X	X			X		X	X		X	X		X		X	9	86.7	82.6	3.2	1.0909
X	X	X		X			X		X	X		X		X	9	86.6	82.5	3.3	1.0933
X	X			X			X	X	X	X		X		X	9	86.6	82.5	3.3	1.094
X	X		X	X			X		X	X		X		X	9	86.6	82.5	3.3	1.0941
X	X			X			X		X	X	X	X		X	9	86.6	82.5	3.3	1.0941
X	X			X		X	X		X	X		X	X	X	10	86.8	82	5	1.1085
X	X	X		X		X	X		X	X		X		X	10	86.7	81.9	5.2	1.1118
X	X			X	X	X	X		X	X		X		X	10	86.7	81.9	5.2	1.1122
X	X			X		X	X		X	X	X	X		X	10	86.7	81.9	5.2	1.1123
X	X			X		X	X	X	X	X		X		X	10	86.7	81.9	5.2	1.1124
X	X	X		X		X	X		X	X		X	X	X	11	86.8	81.3	7	1.1308
X	X			X		X	X		X	X	X	X	X	X	11	86.8	81.3	7	1.1311
X	X			X		X	X	X	X	X		X	X	X	11	86.8	81.3	7	1.1311
X	X		X	X		X	X		X	X		X	X	X	11	86.8	81.3	7	1.1312
X	X			X	X	X	X		X	X		X	X	X	11	86.8	81.3	7	1.1314
X	X	X	X	X		X	X		X	X		X	X	X	12	86.8	80.5	9	1.1545
X	X	X		X	X	X	X		X	X		X	X	X	12	86.8	80.5	9	1.1547
X	X	X		X		X	X		X	X	X	X	X	X	12	86.8	80.5	9	1.1551
X	X		X	X		X	X	X	X	X		X	X	X	12	86.8	80.5	9	1.1551
X	X	X		X		X	X	X	X	X		X	X	X	12	86.8	80.5	9	1.1551
X	X	X	X	X	X	X	X		X	X		X	X	X	13	86.8	79.6	11	1.1803
X	X	X	X	X		X	X		X	X	X	X	X	X	13	86.8	79.6	11	1.1805
X	X	X	X	X		X	X	X	X	X		X	X	X	13	86.8	79.6	11	1.1805
X	X	X		X	X	X	X		X	X	X	X	X	X	13	86.8	79.6	11	1.1807
X	X	X		X	X	X	X	X	X	X		X	X	X	13	86.8	79.6	11	1.1807
X	X	X	X	X	X	X	X		X	X	X	X	X	X	14	86.8	78.7	13	1.2081
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	86.8	78.7	13	1.2081
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	86.8	78.7	13	1.2083
X	X	X		X	X	X	X	X	X	X	X	X	X	X	14	86.8	78.7	13	1.2084
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	86.8	78.7	13	1.2086
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	86.8	77.6	15	1.2379

Appendix F

Best subset regression models for the CSA of the caudal endplates (CaEPs)

Appendix - F.1: Best subset regression models for the L3/L4 CaEP_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
										X				X	2	75.2	74.4	12.7	1.4323
												X		X	2	75	74.2	13.1	1.438
	X													X	2	71.6	70.7	18.9	1.5323
			X											X	2	66.9	65.9	26.9	1.6531
													X	X	2	64.7	63.6	30.7	1.7081
			X									X		X	3	83.8	82.8	-0.1	1.1756
			X							X				X	3	82.4	81.2	2.3	1.2265
	X											X		X	3	81.1	79.9	4.5	1.2691
			X										X	X	3	81	79.8	4.6	1.2722
						X						X		X	3	78.9	77.5	8.3	1.3422
			X					X				X		X	4	85.8	84.3	-1.5	1.1206
			X				X					X		X	4	84.8	83.3	0.1	1.1556
			X					X		X				X	4	84.8	83.3	0.2	1.158
			X									X	X	X	4	84.6	83.1	0.5	1.1643
			X							X		X		X	4	84.5	83	0.6	1.1679
			X					X		X		X		X	5	87.3	85.5	-2.1	1.0777
			X					X				X	X	X	5	86.9	85.1	-1.5	1.091
			X			X		X				X		X	5	86.4	84.6	-0.7	1.1121
	X		X					X				X		X	5	86.3	84.4	-0.5	1.1164
			X		X			X				X		X	5	86.2	84.3	-0.3	1.1198
			X					X		X		X	X	X	6	87.5	85.2	-0.5	1.0873
			X					X	X	X		X		X	6	87.4	85.2	-0.4	1.0887
		X	X					X		X		X		X	6	87.4	85.2	-0.4	1.089
			X				X	X		X		X		X	6	87.4	85.2	-0.4	1.0899
			X				X	X				X	X	X	6	87.4	85.2	-0.3	1.0905
		X	X					X	X	X		X		X	7	87.8	85.1	0.9	1.0912
			X	X				X		X		X	X	X	7	87.8	85	1	1.0946
			X				X	X		X		X	X	X	7	87.8	85	1.1	1.095
			X					X	X	X		X	X	X	7	87.7	85	1.1	1.0958
		X	X				X	X		X		X		X	7	87.7	84.9	1.2	1.0982
		X	X				X	X	X	X		X		X	8	88.1	84.9	2.4	1.099
		X	X	X				X	X	X		X		X	8	88.1	84.9	2.5	1.0998
			X	X				X	X	X		X	X	X	8	88	84.8	2.6	1.103
			X				X	X	X	X		X	X	X	8	88	84.8	2.6	1.1036
		X	X	X				X		X		X	X	X	8	88	84.8	2.7	1.1049
		X	X	X				X	X	X		X	X	X	9	88.6	84.9	3.7	1.0998
		X	X				X	X	X	X		X	X	X	9	88.4	84.7	4	1.1085
			X	X	X			X	X	X		X	X	X	9	88.2	84.5	4.3	1.1159
		X	X	X			X	X	X	X		X		X	9	88.2	84.5	4.3	1.116
			X		X		X	X	X	X		X	X	X	9	88.2	84.4	4.3	1.1185
		X	X	X			X	X	X	X		X	X	X	10	88.7	84.4	5.5	1.1163
		X	X			X	X	X	X	X		X	X	X	10	88.6	84.4	5.5	1.1187
		X	X	X		X		X	X	X		X	X	X	10	88.6	84.4	5.6	1.119
		X	X	X				X	X	X	X	X	X	X	10	88.6	84.3	5.6	1.1206
	X	X	X	X				X	X	X		X	X	X	10	88.6	84.3	5.6	1.1214
		X	X	X		X	X	X	X	X		X	X	X	11	88.9	84	7.1	1.131
		X	X	X			X	X	X	X	X	X	X	X	11	88.7	83.9	7.4	1.1373
	X	X	X	X			X	X	X	X		X	X	X	11	88.7	83.8	7.4	1.1378
X		X	X	X			X	X	X	X		X	X	X	11	88.7	83.8	7.5	1.1401
		X	X	X	X		X	X	X	X		X	X	X	11	88.7	83.8	7.5	1.1403
		X	X	X		X	X	X	X	X	X	X	X	X	12	88.9	83.4	9.1	1.1541
	X	X	X	X		X	X	X	X	X		X	X	X	12	88.9	83.4	9.1	1.1548
		X	X	X	X	X	X	X	X	X		X	X	X	12	88.9	83.3	9.1	1.1563
X		X	X	X		X	X	X	X	X		X	X	X	12	88.9	83.3	9.1	1.1564
	X	X	X	X			X	X	X	X	X	X	X	X	12	88.8	83.2	9.3	1.1603
	X	X	X	X		X	X	X	X	X	X	X	X	X	13	88.9	82.6	11	1.1798
		X	X	X	X	X	X	X	X	X	X	X	X	X	13	88.9	82.6	11	1.1808
X		X	X	X		X	X	X	X	X	X	X	X	X	13	88.9	82.6	11.1	1.1812
	X	X	X	X	X	X	X	X	X	X		X	X	X	13	88.9	82.6	11.1	1.1819
X	X	X	X	X		X	X	X	X	X		X	X	X	13	88.9	82.6	11.1	1.182
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14	89	81.8	13	1.2085
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	88.9	81.8	13	1.2089
X		X	X	X	X	X	X	X	X	X	X	X	X	X	14	88.9	81.7	13	1.2099
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	88.9	81.7	13.1	1.2111
X	X	X	X	X	X		X	X	X	X	X	X	X	X	14	88.8	81.5	13.2	1.2161
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	89	80.8	15	1.2398

Appendix - F.2: Best subset regression models for the L4/L5 CaEP_CSAs

Variables															Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s ($=\sqrt{MSE}$)
										X				X	2	76	75.2	11.6	1.5203
	X													X	2	75.6	74.7	12.3	1.5346
												X		X	2	75	74.1	13.2	1.5534
													X	X	2	72	71	18.1	1.6437
					X									X	2	69.6	68.6	21.8	1.7108
	X											X		X	3	83.2	82	2	1.2938
			X									X		X	3	83	81.7	2.4	1.3038
X	X													X	3	82.7	81.5	2.8	1.3127
			X										X	X	3	82.2	80.9	3.6	1.3321
			X							X				X	3	81.5	80.1	4.8	1.36
X	X										X			X	4	85.1	83.4	1	1.2426
			X									X	X	X	4	85	83.3	1.1	1.2462
			X	X								X		X	4	84.9	83.2	1.3	1.2502
			X								X		X	X	4	84.8	83.1	1.4	1.254
X	X											X		X	4	84.4	82.6	2.1	1.2712
X	X							X			X			X	5	86.4	84.3	0.8	1.2073
X		X	X					X						X	5	86.4	84.3	0.9	1.2088
X			X								X		X	X	5	86.1	84	1.3	1.2215
			X								X	X	X	X	5	86	83.9	1.5	1.2259
X	X	X						X						X	5	85.9	83.7	1.7	1.2328
X	X	X						X			X			X	6	87.3	84.8	1.4	1.1903
X		X	X					X		X				X	6	87.2	84.6	1.6	1.1956
X	X							X		X	X			X	6	87.2	84.6	1.6	1.1974
X		X	X					X			X			X	6	87.1	84.5	1.7	1.2007
X	X				X			X			X			X	6	87.1	84.5	1.7	1.2009
X		X	X					X		X	X			X	7	88	85.1	2.2	1.1798
X		X	X					X			X		X	X	7	87.9	84.9	2.4	1.1855
X			X		X			X		X	X			X	7	87.9	84.8	2.5	1.1884
X		X	X					X	X	X				X	7	87.8	84.8	2.6	1.1914
X			X		X		X	X			X			X	7	87.8	84.7	2.7	1.1937
X		X	X					X	X	X	X			X	8	88.5	85.1	3.4	1.1796
X	X	X						X	X	X	X			X	8	88.3	84.8	3.8	1.1914
X		X	X				X	X	X	X				X	8	88.3	84.7	3.8	1.1936
X		X	X				X	X		X	X			X	8	88.3	84.7	3.8	1.1937
X		X	X				X	X			X		X	X	8	88.3	84.7	3.9	1.1946
X		X	X				X	X	X	X	X			X	9	88.9	84.8	4.9	1.1893
X		X	X					X	X	X	X		X	X	9	88.7	84.7	5.1	1.1952
X	X	X				X		X	X	X	X			X	9	88.7	84.6	5.2	1.1985
X	X	X	X					X	X	X	X			X	9	88.6	84.5	5.2	1.2008
X	X					X		X	X	X	X		X	X	9	88.6	84.5	5.3	1.2016
X	X	X				X	X	X	X	X	X			X	10	89.1	84.4	6.5	1.2054
X		X	X				X	X	X	X	X		X	X	10	89.1	84.4	6.6	1.2056
X	X	X				X		X	X	X	X		X	X	10	89	84.3	6.6	1.2081
X	X		X		X	X	X	X			X		X	X	10	89	84.3	6.6	1.2087
X		X	X			X		X	X	X	X		X	X	10	89	84.3	6.7	1.2093
X	X	X				X	X	X	X	X	X		X	X	11	89.6	84.3	7.8	1.208
X	X	X	X			X	X	X	X		X		X	X	11	89.5	84.3	7.8	1.2096
X		X	X			X	X	X	X	X	X		X	X	11	89.5	84.3	7.9	1.2104
X	X		X		X	X	X	X	X		X		X	X	11	89.4	84.1	8.1	1.2175
X	X	X	X			X	X	X	X	X			X	X	11	89.3	84	8.1	1.22
X	X	X	X			X	X	X	X	X	X		X	X	12	90	84.2	9	1.2115
X	X		X		X	X	X	X	X	X	X		X	X	12	89.8	83.9	9.4	1.225
X	X	X				X	X	X	X	X	X	X	X	X	12	89.6	83.6	9.7	1.2361
X	X	X	X			X	X	X	X		X	X	X	X	12	89.6	83.6	9.7	1.2367
X	X	X	X		X	X	X	X	X	X			X	X	12	89.6	83.5	9.8	1.2381
X	X	X	X			X	X	X	X	X	X	X	X	X	13	90	83.4	11	1.2437
X	X	X	X	X		X	X	X	X	X	X		X	X	13	90	83.4	11	1.2437
X	X	X	X		X	X	X	X	X	X	X		X	X	13	90	83.4	11	1.2444
X	X		X	X	X	X	X	X	X	X	X		X	X	13	89.8	83	11.4	1.2573
X	X		X		X	X	X	X	X	X	X	X	X	X	13	89.8	83	11.4	1.2585
X	X	X	X	X		X	X	X	X	X	X	X	X	X	14	90	82.4	13	1.2794
X	X	X	X		X	X	X	X	X	X	X	X	X	X	14	90	82.4	13	1.2795
X	X	X	X	X	X	X	X	X	X	X	X		X	X	14	90	82.4	13	1.2796
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	89.8	82	13.4	1.2936
X	X	X	X	X	X	X	X	X	X		X	X	X	X	14	89.7	81.8	13.5	1.3007
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	90	81.3	15	1.3186

Appendix - F.3: Best subset regression models for the L5/S1 CaEP_CSAs

Variables																Statistics				
Gender	Height	Weight	Sitting	Shoulder Width	Lean Body Mass	Arm Length	Head	Chest	Elbow	Wrist	Knee	Ankle	Hand	Intercept	Parameters	R^2	Adj-R^2	Mallow's C_P	s $(=\sqrt{MSE})$
												X		X	2	75.9	75	14.1	1.3923
	X													X	2	73.3	72.4	18.6	1.4643
										X				X	2	71.9	71	21	1.5012
			X											X	2	69.3	68.3	25.5	1.5691
							X							X	2	67.9	66.8	28	1.6058
			X									X		X	3	85.1	84.1	0	1.113
			X										X	X	3	82.9	81.8	3.8	1.1903
	X											X		X	3	82.5	81.3	4.5	1.2058
			X							X				X	3	80.9	79.6	7.3	1.2585
X			X											X	3	79.9	78.6	9	1.2907
			X									X	X	X	4	86.1	84.6	0.3	1.0939
			X						X			X		X	4	85.7	84.2	0.9	1.1078
			X	X								X		X	4	85.7	84.1	1	1.1103
	X								X			X		X	4	85.6	84.1	1.1	1.1127
			X				X					X		X	4	85.6	84.1	1.1	1.1131
			X						X			X	X	X	5	88.4	86.7	-1.8	1.0169
	X						X		X			X		X	5	87.2	85.3	0.3	1.0685
	X		X						X			X		X	5	87.1	85.2	0.6	1.074
		X	X									X	X	X	5	87	85.1	0.6	1.0748
			X	X					X			X		X	5	87	85.1	0.6	1.0756
			X				X		X			X	X	X	6	89	86.9	-0.8	1.0098
			X	X					X			X	X	X	6	88.7	86.5	-0.3	1.0226
	X		X						X			X	X	X	6	88.5	86.3	0	1.0307
			X						X		X	X	X	X	6	88.5	86.3	0.1	1.0332
X			X						X			X	X	X	6	88.5	86.2	0.1	1.0338
			X			X			X			X	X	X	7	89.2	86.6	0.9	1.0202
	X		X				X		X			X	X	X	7	89.2	86.6	0.9	1.0211
			X				X	X	X			X	X	X	7	89.1	86.5	1	1.0249
		X	X				X		X			X	X	X	7	89.1	86.5	1	1.0249
			X				X		X		X	X	X	X	7	89.1	86.4	1.1	1.0263
	X		X		X		X		X			X	X	X	8	89.6	86.6	2.1	1.0216
	X				X	X	X		X			X	X	X	8	89.6	86.5	2.2	1.0229
			X	X	X		X		X			X	X	X	8	89.4	86.3	2.5	1.0305
	X	X	X				X		X			X	X	X	8	89.4	86.3	2.5	1.0317
	X		X			X	X		X			X	X	X	8	89.4	86.3	2.5	1.0326
	X		X		X	X	X		X			X	X	X	9	89.9	86.5	3.5	1.0259
	X		X	X	X		X		X			X	X	X	9	89.8	86.3	3.8	1.0328
	X			X	X	X	X		X			X	X	X	9	89.8	86.2	3.8	1.0342
	X	X	X			X	X		X			X	X	X	9	89.7	86.1	3.9	1.0377
	X	X	X				X		X		X	X	X	X	9	89.7	86.1	4	1.0398
	X		X	X	X	X	X		X			X	X	X	10	90.1	86.1	5.2	1.0389
	X	X	X			X	X		X		X	X	X	X	10	90	85.9	5.5	1.0472
	X		X		X	X	X		X		X	X	X	X	10	90	85.9	5.5	1.0473
X	X		X		X	X	X		X			X	X	X	10	90	85.9	5.5	1.0473
	X		X		X	X	X		X	X		X	X	X	10	89.9	85.8	5.5	1.0489
	X		X	X	X	X	X		X		X	X	X	X	11	90.2	85.5	7.1	1.0616
X	X		X	X	X	X	X		X			X	X	X	11	90.2	85.5	7.2	1.062
	X	X	X	X		X	X		X		X	X	X	X	11	90.2	85.5	7.2	1.0627
	X		X	X	X	X	X		X	X		X	X	X	11	90.1	85.4	7.2	1.0632
	X		X	X	X	X	X	X	X			X	X	X	11	90.1	85.4	7.2	1.0633
	X	X	X	X	X	X	X		X		X	X	X	X	12	90.2	84.9	9	1.0845
X	X		X	X	X	X	X		X		X	X	X	X	12	90.2	84.8	9.1	1.0861
	X		X	X	X	X	X	X	X		X	X	X	X	12	90.2	84.8	9.1	1.0873
	X		X	X	X	X	X		X	X	X	X	X	X	12	90.2	84.8	9.1	1.0877
X	X		X	X	X	X	X	X	X			X	X	X	12	90.2	84.8	9.1	1.088
X	X	X	X	X	X	X	X		X		X	X	X	X	13	90.3	84.1	11	1.1114
	X	X	X	X	X	X	X		X	X	X	X	X	X	13	90.2	84.1	11	1.1126
	X	X	X	X	X	X	X	X	X		X	X	X	X	13	90.2	84.1	11	1.1126
X	X		X	X	X	X	X	X	X		X	X	X	X	13	90.2	84	11.1	1.1135
X	X		X	X	X	X	X		X	X	X	X	X	X	13	90.2	84	11.1	1.1143
X	X	X	X	X	X	X	X		X	X	X	X	X	X	14	90.3	83.2	13	1.1418
X	X	X	X	X	X	X	X	X	X		X	X	X	X	14	90.3	83.2	13	1.1419
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14	90.2	83.2	13	1.143
X	X		X	X	X	X	X	X	X	X	X	X	X	X	14	90.2	83.2	13.1	1.144
X	X	X	X	X	X	X	X	X	X	X		X	X	X	14	90.2	83.1	13.1	1.1468
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	15	90.3	82.2	15	1.1749