Determination of Safe Guidelines for One-Hand Lifting

by

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WAR EAGLE

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Introduction

1.1 Work Related Musculoskeletal Disorders

1.1.1 Work Related Musculoskeletal Disorders in General Industry

Bones, ligaments, and muscles are the structures that form levers in the body to enable human movement. Simply stated, a joint forms the fulcrum, and the muscles crossing the joint apply the force to move a weight or resistance. Levers are typically classified as first class, second class, or third class. All three types of levers are found in the body, but most levers in the human body are third class. Having a body comprised mostly of third class levers, allows humans the ability to move quickly and have a large range of motion. These attributes were quite useful in the early days of mankind to assist in hunting and gathering tasks. As society became more industrialized, there was an increase in manual material handling (MMH) activities, especially lifting. To be good at lifting, the human body should comprise mostly of second class levers, but as stated above, the human body is comprised mainly of third class levers and therefore not designed optimally to accomplish many lifting tasks. Work activities that are repetitive, forceful, require non-neutral postures, and or are performed for long duration may result in a work-related musculoskeletal disorder (WMSD).

Work-related musculoskeletal disorders (WMSD's) also known as repetitive motion injuries, repetitive strain injuries, cumulative trauma disorders (CTD's), and overuse syndrome are a group of painful disorders of the muscles, tendons, and nerves that can occur in the neck, back, upper and lower extremities. WMSDs were first identified in the early 18th century as workers in similar occupations developed similar injuries [Ramazzini, 2001]. WMSD's almost certainly have been around since the onset of work. Historically, the issues surrounding WMSD's were not of particular interest due to workers self selecting themselves out of occupations they could no longer perform, poor or no laws in favor of workers' rights, women leaving the workforce early to focus on raising a family, and little costs borne by manufacturers to pay for a work injuries. For instance, consider the automotive industry in the United States. Tasks performed in the assembly of automobiles had long been associated with WMSDs [Punnett et al., 2004]. Henry Ford circa 1910 stated, "No worker must ever have to stoop to attach a wheel, a bolt, a screw or anything else to the moving chassis." [Burlingame, 1954]. Although not an ergonomist, Ford realized the importance of his workers being in an "optimal" posture when manufacturing automobiles. Yet over one hundred years later, Bennie Fowler of Ford Motor Company in an interview touting Ford Motor company‘s burgeoning ergonomics program stated "very few operators will need to work with their hands raised above their heads or stoop down to do a job below their knees' [Fowler, 2010].

These statements may be viewed as indicative of MMH progress in the past one hundred years such that WMSD's should be avoided but the willingness to pay for the controls needed to minimize WMSD impact is not necessarily given a high priority. Interestingly, by the end of the 20th century, WMSDs or as they were commonly referred to then, CTD's, were acknowledged as the occupational epidemic of the 1990's [Herington and Morse, 1995] and "the No. 1 occupational hazard of the 1990's" by Tom Lantos in his opening statement at a congressional subcommittee meeting of the 101^{st} Congress [Congress, 1989].

The lack of a proactive approach to minimize WMSD's and namely back injuries through poorly designed workstations has cost workers, taxpayers, consumers, and industry billions of dollars. The Department of Labor (1989), in a fact sheet citing the Bureau of Labor Statistics (BLS) states that preventing back injuries is a "major workplace safety challenge." BLS records show more than one million workers suffer back injuries each year and they account for one of every five workplace injuries or illnesses. Furthermore, one–fourth of all compensation indemnity claims involve back injuries, costing industry billions of dollars on top of the pain and suffering borne by employees. Moreover, though lifting, placing, carrying, holding and lowering are involved in manual materials handling (the principal cause of compensable work injuries) the BLS survey shows that four out of five of these injuries were to the lower back, and that three out of four occurred while the employee was lifting. In addition to their social costs, workplace injuries and illnesses have a major impact on an employer's bottom line [Bureau of Labor Statistics, 2015].

OSHA (2014) notes on their website that "It has been estimated that employers pay almost $1 billion per week for direct workers' compensation costs alone." The costs of workplace injuries and illnesses include direct and indirect costs. Direct costs include workers' compensation payments, medical expenses, and costs for legal services. "Examples of indirect costs include training replacement employees, accident investigation and implementation of corrective measures, lost productivity, repairs of damaged equipment and property, and costs associated with lower employee morale and absenteeism." [Department of Labor, 2016]. The most disabling workplace injuries and illnesses in 2014 amounted to more than $59 billion in direct workers compensation costs, averaging more than 1 billion dollars per week according to the Liberty Mutual Workplace Safety Index (2014). The safety index combines information from Liberty Mutual, the U.S. Bureau of Labor Statistics, and the National Academy of Social Insurance to identify the top causes of serious workplace injuries. Overexertion injuries remained the largest contributor to the overall burden, accounting for $15.1 billion, or 25.3%, of the total cost. Bernard and Fine (1997) declare the true cost of work–related overexertion injuries and disorders in the United States is not known. They did however provide conservative estimates of annual expenditures, based on workers compensation payments and other direct costs, ranging between $13 to 20 billion, which today would be equivalent to $19.4 to $29.8 billion [Saving.Org, 2016]. More recently the Liberty Mutual Research Institute for Safety (2014) reported that overexertion injuries cost businesses $15.1 billion. The total cost to society is unknown but believed to be substantially higher due to various indirect costs that are not included in these conservative estimates. The annual total overexertion injury cost has been estimated to be as low as 2 to 5 times direct costs [Michael, 2002] and as high as 20 times direct costs [McGrane, 2015]. In conclusion, back injuries occur frequently, are costly, and no approach has been found for completely eliminating back injuries caused by lifting. Though it is believed that a substantial portion of back injuries can be prevented by an effective control program and ergonomic design of work tasks.

MMH tasks are associated with high WMSD incidence rates. MMH is a broad category, which encompasses many tasks such as lifting, lowering, carrying, pushing, pulling, or holding. Virtually all workplaces include tasks that involve MMH. This is notable because if a work task exceeds a worker's physical capabilities, then injuries can result with the back being the body part "most" likely to be injured. MMH and in particular lifting has been of interest to industry, researchers, and lifters since the 1950's [Golding 1952), (Whitney 1958) and (Davis 1959)]. Even though there has been an effort to train workers on safe lifting procedures since the 1950's, the injury rates associated with lifting have not appreciably changed over the past 40 years. Stevens (1996) proposed that rather than training, an emphasis should be made on engineering controls to reduce injury rates associated with lifting. BLS data indicates lower overexertion injury rates involving days away from work have decreased. They accounted for 15.6 percent of all injuries involving days away from work in private industry in 1999 [Bureau of Labor Statistics, 2001] but only 10.1 and 10.3 percent in 2013 [Bureau of Labor Statistics, 2014] and 2014 [Bureau of Labor Statistics, 2015] respectively. It is unknown if this decrease can be attributed to primarily administrative controls, engineering controls or a combination of both. Figure 1.1 is a pie chart that illustrates the breakdown of activities resulting in a sprain, strain, or tear.

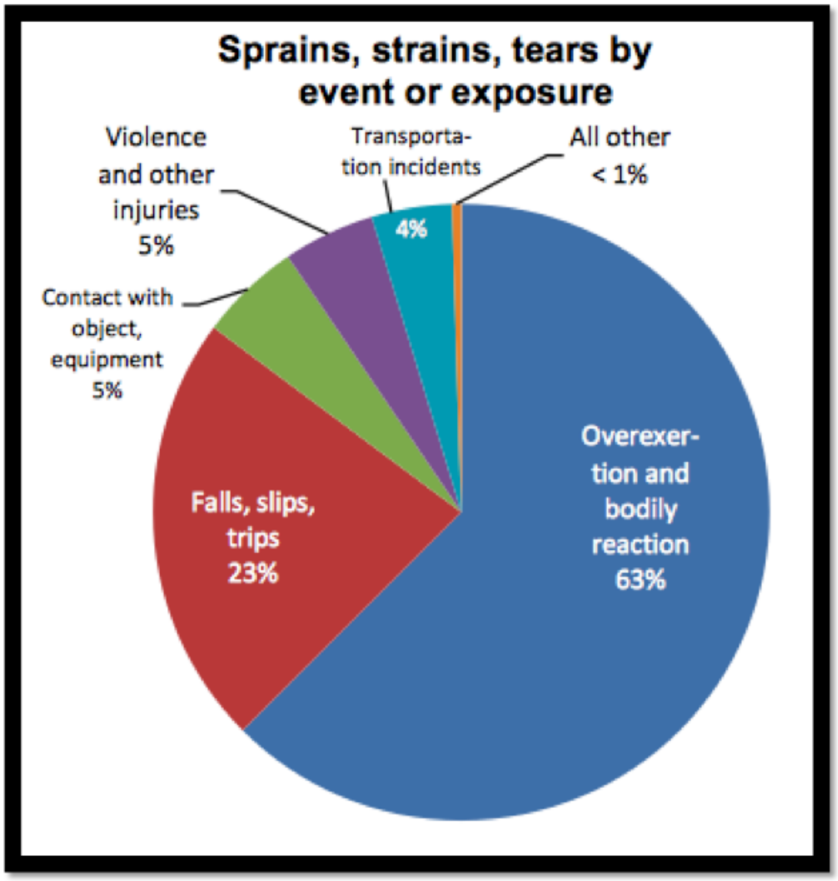

Figure 1.1: Sprain, strain, and tear cases by selected event or exposure, all ownerships, 2012 [Bureau of Labor Statistics, 2014]

Note: Ownership is the designation as to who controls firms and other organizations and agencies. Ownership can be private, or part of Federal, state, tribal, or local government.

The back is particularly vulnerable to a WMSD through lifting tasks and has long been known to be the most costly body part to injure. Americans spent $85.9 billion in 2005 looking for relief from back and neck pain [Martin et al., 2008]. These costs include surgery, doctor's visits, X–rays, Magnetic Resonance Imaging (MRI) scans and medications. This is an increase of approximately 65 percent since 1997 when these costs were $52.1 billion [Martin et al., 2008]. That expense has not helped reduce the number of sufferers; in 2005, 15 percent of U.S. adults reported back problems, up from 12 percent in 1997 [Springen, 2008]. While low back pain does not result in death, it may result in long term disability, reduced quality of life, or prevent people from partaking in recreational activities as well as the basic activities of daily life. Figure 1.2 is a pie chart that illustrates the breakdown of body parts suffering a sprain, strain, or tear.

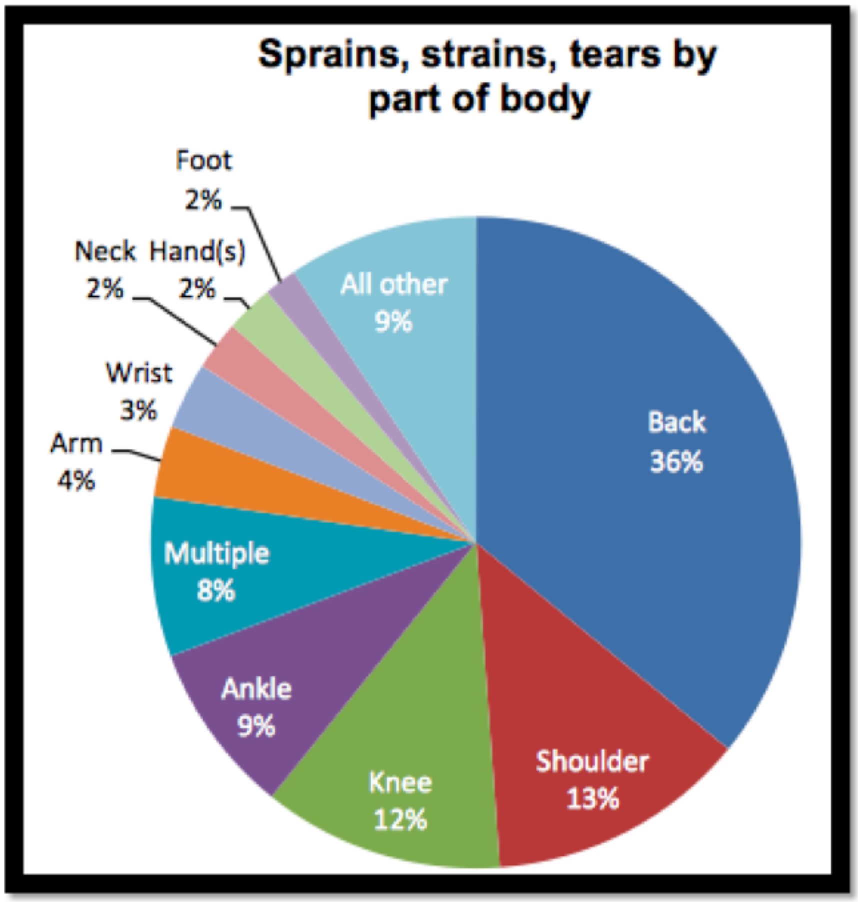

Figure 1.2: Sprain, strain, and tear cases by selected event or exposure, all ownerships, 2012 [Bureau of Labor Statistics, 2014]

Deyo et al., (2006) reported the annual prevalence of low back pain in the United States has been estimated at more than one–quarter of the U.S. population whereas Rubin (2007) noted the lifetime prevalence of low back pain has been reported at 80 percent. The costs associated with work–related low back pain are high. Webster and Snook (1994) reported that, on average, low back pain costs over $8,000 per claim in direct costs, and accounts for one third of workers' compensation costs even though they make up only 16 percent of all claims. Liberty Mutual Research Institute for Safety (2014) estimates that overexertion, which includes injuries related to lifting, pushing, pulling, holding, carrying, or throwing costs $13.6 billion dollars in direct costs to businesses. Figure 1.3 illustrates the 10 leading causes and direct costs of workplace injuries in 2014 as reported by Liberty Mutual (2014). Katz (2006) reported the annual national bill for the care of low back problems has been estimated to be $100 billion.

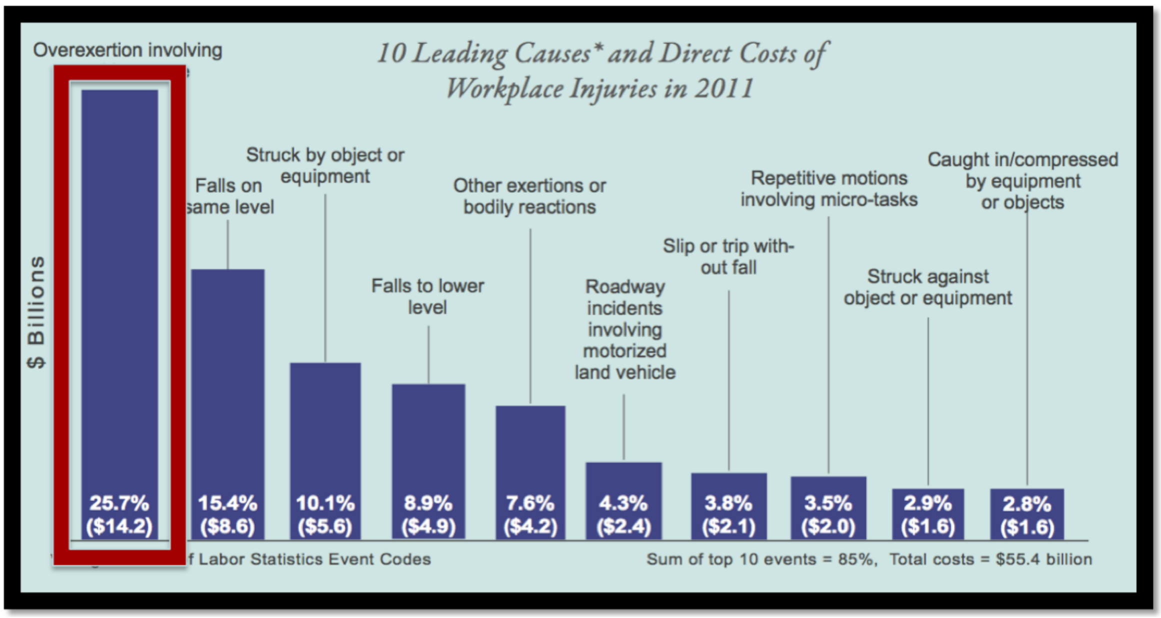

Figure 1.3: Sprain, strain, and tear cases by selected event or exposure, all ownerships, 2012 [Liberty Mutual Research Institute for Safety, 2014]

Back pain associated with lifting has been reported across a wide spectrum of industries throughout the years [(Brown 1975) and (Bigos et al., 1991). The hazards of lifting are known and the direct and indirect costs of lifting injuries are well documented; yet there is still an acceptance of risk as this is an easier solution than mitigating lifting risk through sound engineering controls.

The most recent information from the BLS shows that there were 356,910 musculoskeletal cases, which accounted for 31 percent of all injury and illness cases in 2015. Among the top six occupations that accounted for 26 percent of all MSD cases, three of the jobs required frequent manual material handling of items such as laborers, janitors and cleaners, and heavy truck and tractor trailer drivers. Another occupation associated with high MSD incidence rates involved patient handling (registered nurses and nursing assistants). Laborers accounted for the highest proportion of injuries and illnesses in private industry accounting for 6 percent of all cases (20,900 cases). The Bureau of Labor Statistics (2016) reported laborers in private industry had an incidence rate of 111 per 10,000 full time workers, more than three times greater than the rate for all private industry workers. These workers required a median of 11 days away from work to recuperate.

Over the years, three core methods to study the back and the maximum amount of weight that can be manually handled have been employed by researchers. Biomechanical models and laboratory studies are used to help determine how forces act on the body and how these exposures can result in physiological responses that may ultimately lead to a WMSD injury. Typical biomechanics studies will look at the magnitude and direction of forces exerted during manual handling tasks, exertion required to operate tools and equipment, the location where external forces act on the body and the posture required while performing these tasks. Psychophysical laboratory studies have been used to determine "acceptable levels" of work intensity by asking subjects to adjust their workload so that the resulting discomfort and fatigue is "acceptable" to them. Physiological studies as they relate to lifting consider repetitive handling to determine the effects the activity has on the subject's oxygen use and endurance. These studies are not focused on a one–time maximum lift but rather on how often a lift that is within the normal capacity of the subject can be performed before fatigue sets in.

Even with all the attention paid to back injury and lifting techniques, there is no consensus on how to prevent back injuries. Many have turned to worker training as a method to minimize the incidence of back injuries. Results of this approach do not seem encouraging. A study by Sharp and Legg (1998) demonstrated that training could be used as a means to increase the capacity of novice lifters. It is thought that this lifting improvement resulted from increased coordination and potential increase in muscular endurance.

Typical training elements focus on two-hand lifting where the lifter is instructed to: size up the object to be lifted; ask for help if the object is too heavy; stand close to the object to be lifted; take a deep breath; "bend with the legs and not the back"; grasp the object; keep the object close to the body; avoid twisting; and slowly raise the legs to lift the object. Roger Stephens, from the Department of Labor Office of Ergonomics (1996) noted in a symposium held by the U.S. Army that this training method has been used since the 1950's if not even earlier and no change in back injury rate has occurred. Burgess-Limerick (2003) stated, "Lifting training is generally ineffective, and there is unlikely to be a single "best" technique which is appropriate in all situations" and concluded that it may be preferable to provide education in general lifting guidelines. Stevens and Burgess–Limerick suggest points that help illustrate why the training method to lift with your legs has come under fire. van Poppel (1997) performed a literature search to gauge the effectiveness of lumbar supports, education, and exercise in the prevention of back pain in industry. The results of their investigation led them to conclude that there is limited evidence that training, be it from lifting techniques or back schools, has any substantial effect in the prevention of back pain. Simply put, the true effect of education is unknown and more high quality research is needed before any firm conclusions may be drawn.

Research has shown that the legs do not necessarily have the strength to lift using the "lift with your legs and keep your back straight posture" and this lifting technique is not suitable if the object cannot fit between the lifters knees or if it is bulky. Fundamentally, the back is engaged during lifting. The legs do not "take over for the back". Rather the purpose of this advice is to reduce back flexion and therefore reduce the moment arm that results from this activity [Garg and Herrin, 1979] and [Leskinen et al., 1983]. Others have developed different lifting techniques with the intent that their techniques be emphasized in training. Interestingly, Garg was involved in the early study of both the free style

[Garg and Saxena, 1985] and stoop [Garg and Herrin, 1979] lifting techniques. The use of different lifting techniques may be best summed up by Jones (1972) which still seems to hold true today, “there is no single lifting method that is best for all situations”. As noted, there are multiple methods reported in the literature on how to lift safely when performing a two-hand lift and there is debate over when to use one lifting technique over another. As opposed to the debate over which two hand lifting techniques workers should be trained to use, there is no such debate for one–hand lifting. No recommended one–hand lifting technique has been reported in the literature. A recent research article on one–hand lifting noted, “With a few exceptions, one-hand lifting has received no attention in the literature” [Kingma and van Dieën, 2004]. Little is known about safe lifting limits for one–hand lifting in the general work population. Unfortunately, even less is known about safe one–hand lifting limits for people with no or limited use of an upper extremity.

An epidemiological study on back injuries conducted by the OSHA [Department of Labor, 1982] presented a snapshot of the typical back injury. The study reported that: the majority of back injuries suffered were classified as a sprain or strain, 58 percent of the workers had at least a slightly bent back, and 52 percent of the time the location of the object being lifted was on the floor. Additionally, 59 percent of the weight handled was less than 60 pounds; in fact the weight of the object being lifted was less than 40 pounds in 20 percent of the incidents. OSHA has no specific regulations regarding lifting or any other ergonomic issue. The OSHA Salt Lake City technical office provides rule of thumb guidance for reducing back injury risk by stating that lifting loads heavier than about 50 pounds will increase the risk of injury and lifts over 50 pounds should be performed by two or more people. At best, OSHA may enforce its General Duty Clause to ensure a safe and healthy workplace is being provided. OSHA's expectation is that the employer evaluate safe lift limits and assure measures are taken to prevent injuries. If repeated injuries on a specific task are related to lifting tasks that could reasonably be considered to exceed the capabilities of the workforce, then OSHA is expected to issue a citation under the general duty clause. Nonetheless, this is a reactionary approach to worker safety. The state of California, which has an ergonomics standard, is similar to all other states in that neither have created a more stringent lifting standard than federal OSHA. The National Institute for Occupational Safety and Health (NIOSH) has long recognized that effective ergonomic interventions can lower the physical demands of MMH tasks. These interventions result in the lowering of the incidence and severity of the musculoskeletal injuries. In support of reducing WMSDs, NIOSH (1981) developed a lifting equation in 1981 and later revised it in 1991 [Waters et al., 1993] in order to evaluate two–handed lifting tasks as well as to assist in the identification of solutions to reduce the physical stress associated with manual lifting.

Lastly, there has been an emphasis to incorporate stretching programs as a means to reduce musculoskeletal injury risk. Laboratory studies indicate that stretching can cause changes in the body, namely making the body less stiff and more flexible due to the altering of the viscoelasticity of muscle tendon units. Proponents of stretching claim that the increase in worker flexibility will make them less likely to suffer a WMSD. Hess and Hecker (2003) conducted a literature search to determine if there was a positive correlation between stretching at work and injury prevention. They identified 8 articles that met their inclusion criteria from 1977-1998. They concluded that the few stretching studies they evaluated "fail to definitively prove the case for or against stretching". van Poppel(1997) performed a literature search to gauge the effectiveness of lumbar supports, education and exercise in the prevention of back pain in industry. Stretching was considered to be part of exercise. However, results of the review suggested "limited evidence for a positive effect of exercise". The authors also considered the studies reported in the literature to be of low quality. There is more information in the literature on stretching as an injury prevention measure when considering athletes. The Centers for Disease Control and Prevention reported in a review of the literature, that people who stretched were no more or less likely to suffer injuries such as pulled muscles, which the increased flexibility that results from stretching is supposed to prevent [Thacker et al., 2004]. Others have noted that many injuries athletes suffer result from a muscle reacting suddenly to control a movement. This could explain why lifting an item with shifting weight might result in a worker suffering a back injury, even if they participate in a stretching program. Witvrouw et al., (2004) looked at stretching and injury prevention in athletes. They concluded the literature reports conflicting findings. The authors feel "far greater attention should be given to an examination of the type of activity in which the athlete participates when one considers the merits of stretching to reduce injury".

1.1.2 Work Related Musculoskeletal Disorders in the U.S. Army

The U.S. Army in many ways lags behind the occupational safety efforts of major employers in the United States. The Army has emphasized injury reduction in different ways over the past fifteen years but has made no sustainable changes impacting leading or lagging metrics. In 2003, the Secretary of Defense initiated the Mishap Reduction Initiative [Rumsfeld, 2003] based in large part on the injury reduction efforts initiated by then Secretary of the Treasury, Paul O'Neill in 2002. This directive charged the armed forces with reducing preventable accidents by 50 percent, noting, "World-class organizations do not tolerate preventable accidents." Unfortunately, the Army has not met its goal. In 2001, The Department of Defense (DoD) enacted the Employee Work Safety Demonstration Program [Congress, 2001]. The program consisted of pilot studies at DoD military installations and DoD agency sites to determine if implementation of private sector best safe work practices could reduce civilian worker lost workday injury rates and the associated direct and indirect costs. The safe work practices included elements of performance–based safety programs, behavior–based safety programs, metric based safety programs, and integrated safety management programs. The program ended in 2003 with no appreciable change in Army injury rates. Today, back injuries account for over 25 percent of all injuries in the Army just as they had in the past.

The use of MMH equipment as a means to reduce worker and soldier musculoskeletal stress has changed little in the past twenty years. Health Hazard Assessments (HHA's) of systems entering the Army procurement process reveal a reliance on MMH, especially lifting, in order to move and assemble the system in question. A survey of recent Army job openings revealed applicants are asked to routinely handle weights over 75 pounds and up to 100 pounds even though the military standard for lifting dictates the maximum weight to lift under ideal conditions is 87 pounds [Department of Defense, 2012]. Army depots that have manufacturing missions often overlook ergonomics in their lean six sigma initiatives resulting in processes that may be faster but do not necessarily reduce MMH. Ergonomic surveys from 2006 to 2007 conducted at an Army depot that had gone through a lean six sigma transformation revealed many missed opportunities to reduce worker musculoskeletal exposures associated with MMH. It was observed that areas that underwent a"Lean" event did not address all ergonomic concerns. The end result was workers being exposed to an increase in repetition at workstations that were not well designed [Pentikis, 2007].

As mentioned previously, little is known about safe one–hand lifting limits in the general work population and, unfortunately, even less is known about safe one–hand lifting limits for people with no use of an upper extremity. This is significant as there are many jobs and activities within industry and the Department of Defense where one handed lifting is regularly performed. Also, within the DoD community, one handed lifting and MMH tasks may become more prevalent in the future as service members return from active duty disabled, potentially with little or no use of an upper extremity as a result of combat activities. As of September 1, 2010, over 1,600 American service members had lost at least one limb [Service, 2010]. Furthermore, there is a segment of the population, about one tenth of one percent that does not have use of at least one upper extremity limb. From the 2000 census [U.S Census Bureau, 2005], 12.0 million families or 16.6 percent, reported one or more members with a condition that substantially limited one or more basic physical activities such as walking, climbing stairs, reaching, lifting, or carrying. This disabled population may also be of interest to manufacturers of consumer goods in that providing a product that can be easily handled by a disabled person may provide an advantage over a competitor.

As far as one-hand lifting guidance is concerned, MIL STD 1472G mentions but does not account for it. Unfortunately, however, this standard does not differentiate between one–hand and two–handed lifting. From paragraph 5.8.6.3.7 on carrying limits, states "The maximum permissible weight for carrying also applies to an object with a handle on the top, such as a tool box, which usually is carried at the side with one hand" [Department of Defense, 2012]. Although technically a carrying activity, this guidance is used as the de facto maximum design weight limit for one-hand lifting. From conversations with Army experts who were involved in the revision of MIL STD 1472, it was established that there have been no Army or DoD studies to validate the lifting and carrying standards published in MIL STD 1472G, nor are there any models for one–hand lifting limits. Additionally, the research data used to generate the values in MIL STD 1472G are no longer in a "usable format" [(Sharp 2010) and (Goddard 2010)] due to the data being saved in a program that is no longer supported. Finally, Army experts reported there has been no research within the Army or DoD to compare the MIL STD 1472G values for lifting with the RNLE to determine which lifting model better predicts a safe lift.

1.2 Research and Dissertation Organization

A manuscript format will be used in the presentation of this dissertation and it is organized in accordance with the Auburn University dissertation guide [Auburn University, 2015a]. This dissertation is comprised of six chapters. Chapter One discusses the impact and cost MMH has on industry and the U.S. Army. Chapter Two is a comprehensive review of existing literature, highlighting the different methods researchers have used to study lifting, discussing recognized lifting guidelines available to safety and health professionals, the guidance these guidelines provide for one–hand lifting and the use of MRI as a means of collecting low back and trunk muscle information. The next three chapters will discuss in depth the experiments that were conceived and executed to collect data. Each of these chapters will act as a separate manuscript and be formatted so they will be ready for publication in a peer-reviewed technical journal. They will contain an introduction, methods, results, discussion, limitations, conclusions, and acknowledgments. Chapter 3 focuses on how to determine the relative muscle contribution of each low back and trunk muscle when performing a one–hand lateral lift. Chapter 4 compares and discusses back compressive forces when laterally lifting with either two or one hand. Chapter 5 considers the development of a regression model using easily measured gross anthropometric characteristics to predict an individual's back muscle size and location. Finally Chapter 6 will provide a synopsis of the overall findings and interpretations of these studies.

1.3 Closing Statement

For years, manual material handling activities, especially lifting tasks have been common throughout a wide spectrum of industries and the Department of the Army. Lifting tasks that are repetitive, forceful and require non–neutral postures place the lifter at increased risk of suffering a back injury, with the likelihood of injury increasing as the duration of activity increases. The cost of back injuries to workers, taxpayers, consumers, and industry is staggering with estimates topping a billion dollars per week. Control measures such as training, on–site stretching programs or use of specific lifting techniques have been ineffective in controlling back injuries. The dynamic nature of lifting, the effect it can have on the body, and the costs associated with back injuries are daunting. Additionally, there are no national standards on safe lifting and thus there remain many unanswered questions. Based on the lack of academic research studies pertaining to one–hand lifting, a questionable study design that is the basis for the current DoD one–hand lift limits, and a sizable segment of the population that is without use of at least one upper extremity indicates that research on safe one–hand lift capacity would be appropriate to research. This research could have benefits to both healthy and disabled workers, consumers, and special populations. The goals of the proposed research project are twofold: the first is to develop a methodology that will determine the relative muscle contribution of each back and trunk muscle during a one-hand lifting task and to determine the most accurate way to estimate back compressive forces when performing a one–hand lift. The second is to improve the one–hand lifting guidance proposed by the DoD by developing an easy to use model that can modify current government and industry two–handed lifting weight limit guidance to appropriate levels. The long term goal is to influence new one–hand lifting guidance for use in a future version of MIL STD 1472.

Chapter 2

Review of the Literature

2.1 Problem Statement

It is believed that a subsection of lifting tasks that have not been studied in depth involve one-hand lifting. While there is an abundance of literature that has focused on two-handed MMH tasks [(Snook 1978), (Waters et al., 1993), (Maiti and Ray 2004) and (Mayer et al., 2013)], few studies have addressed the issue of one-handed lifting. For instance, Ayoub and Mital in their book noted that they were only able to identify eight studies which have addressed the problems of one–hand materials handling tasks [Ayoub, 1989]. A recent research article on one–handed lifting by Kingma and van Dieën (2004) noted, "with a few exceptions, one-hand lifting has received no attention in the literature".

Determining the percentage of one–hand lifting that takes place in industry is difficult to quantify as no government entity such as BLS, OSHA or DoD differentiates between one–hand and two–hand lifting injuries. Garg (1983) indicated that he has observed and also received anecdotal reports from others that one–handed lifts in industry are a common occurrence. Fifteen years later Marras and Davis (1998) agreed with Garg's assertion by noting that one–hand lifts commonly occur in industry. For example, Kingma and van Dieën (2004) observed that workers are often forced to lift an object with one hand because the object in question only has one handle. Cook et al., (1991), Ferguson et al., (2002), and Jones et al., (2013) all identified one–hand lifting taking place when removing items out of deep storage bins. Therefore, identifying challenges faced by one hand lifters and better understanding the individual back muscle contribution and back compressive forces during these lifts could provide an impetus for development of a one–hand lift standard.

A literature review was conducted to determine the extent previous research has focused on one–hand lifting, and to look in depth at current industry and government two–hand lift guidance and standards. An investigation was done to determine the types of lifting research studies conducted to better explain how much weight people can safely lift and if attempts have been made to expand current two-hand lift standards by modifying these existing guidance documents. A review of the literature was performed to understand how MRI technology has been incorporated into developing lifting models. Finally, a review of muscle co-contraction, how it influences low back and trunk muscle during asymmetric lifting tasks, and models used to quantify its effect was performed. It is anticipated that a solid basis of understanding of the study methods that have been used in the past will result in more opportunities to identify gaps in the literature.

2.2 One-Hand Lifting

The primary purpose of the one-hand lift literature search was to help answer the question "Has similar research been proposed?" Specifically, has a study considered a standing persons individual low back and trunk muscle force contribution while performing a one-hand lift in the lateral plane? These results of the literature search yielded 43 articles associated with one-hand MMH. The year of publication, author, title, and synopsis of all articles are listed in Appendix A. Figure 2.1 contains a breakdown of MMH activity and Figure 2.2 contains a breakdown of study approach.

2.3 Lifting Research Studies

Many methods are available to researchers when conducting a laboratory study to determine the stresses being placed on the body under different lifting conditions. During the development of the NIOSH Lifting Equation (NLE) and subsequent Revised NLE (RNLE), NIOSH used three criteria: biomechanical, physiological, and psychophysical, to define the

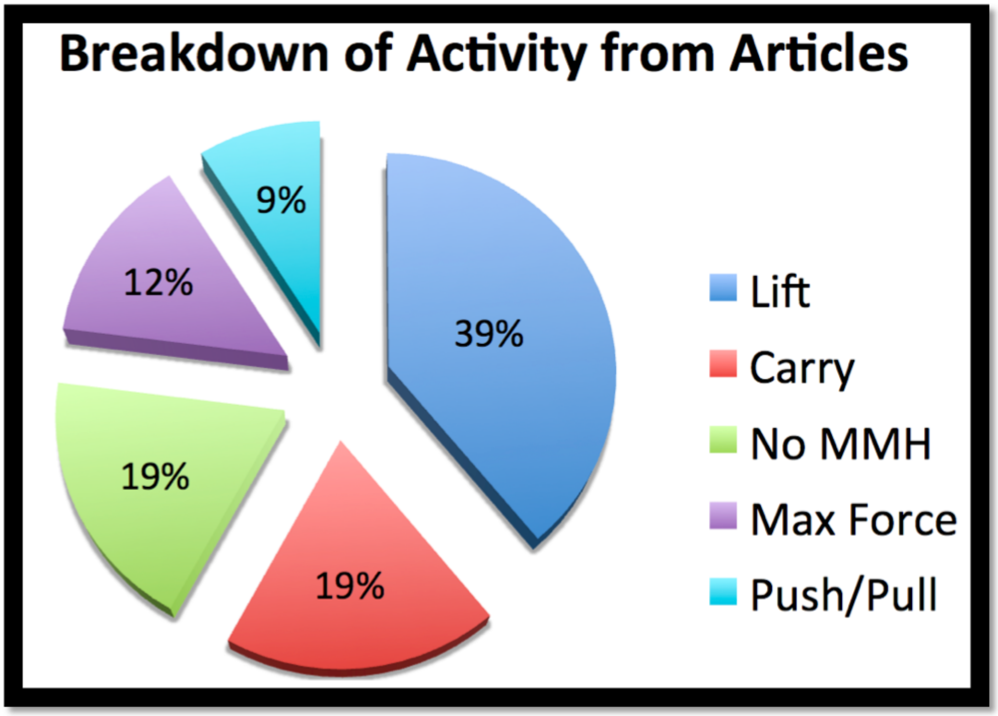

Figure 2.1: Literature Review Based on MMH Activity.

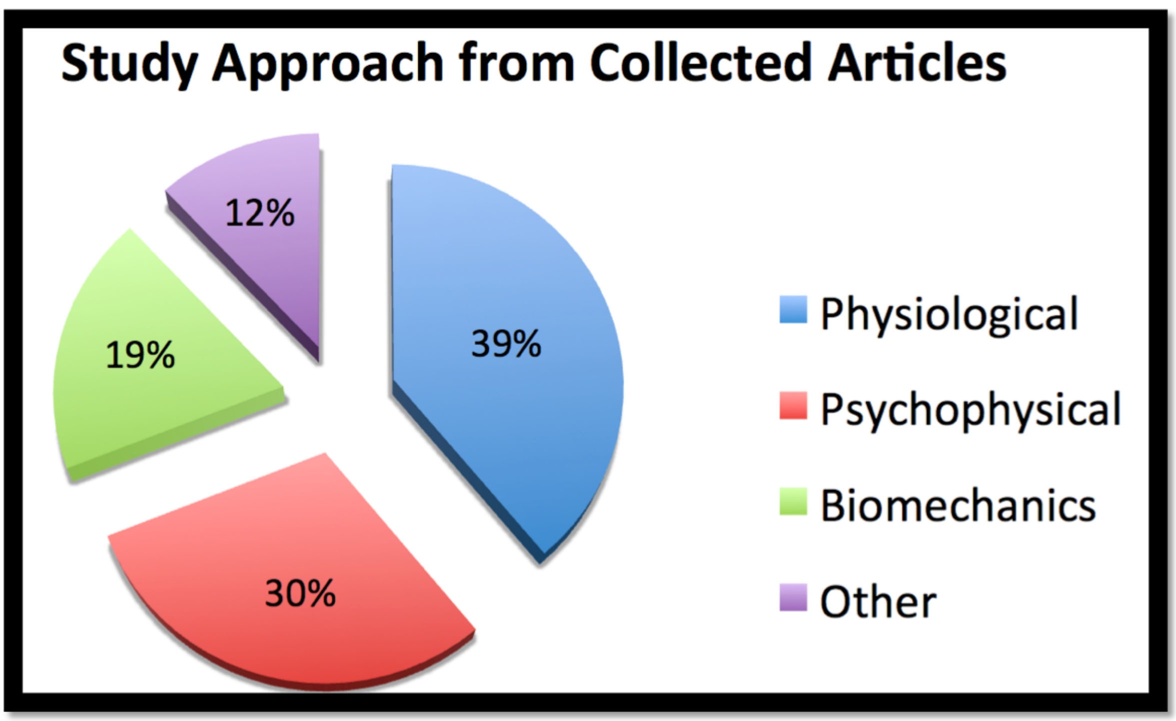

Figure 2.2: Literature Review Based on Study Approach.

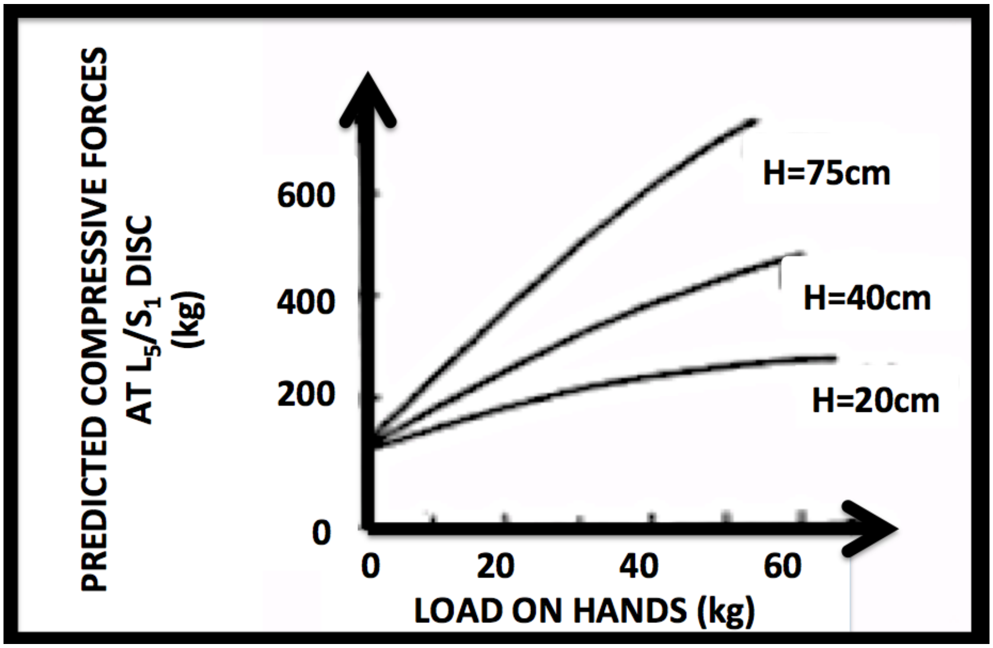

Figure 2.3: Predictive back compressive forces acting on the L5/S1 discPredictive back compressive forces acting on the L5/S1 disc. (Adapted from Chaffing, 1975). [NIOSH, 1981]

components of both the original and revised equations. A brief discussion of each criterion, their benefits and drawbacks follows.

Biomechanical studies use the laws of physics and engineering to describe motion of various body segments and the forces that act upon these body parts during normal daily activities. Considering an ergonomics perspective into the definition changes the emphasis. The purpose is to determine if the forces acting on the body exceed the physical limitations of the worker. If so, changes need to be made to the workstation or work practice to ensure worker safety. Many biomechanics studies of back injury risk during lifting focus on the the L5/S1 region of the back since "clinical and biomechanical data indicate the greatest problem to be at the lower lumbar spine" [NIOSH, 1981]. Others also consider this area to be the weak spot when performing MMH activities [(Chaffin, 1969) and (Andersson et al., 1985)]. Figure 2.3 illustrates how back compressive force at the L5/S1 disc increases as the horizontal distance between the hands and load increases.

When developing their biomechanical criterion, NIOSH selected “the L5/S1 as the site of greatest lumbar stress during lifting.” Other biomechanical criteria selected by NIOSH include “compressive force being the critical stress vector” and use of “3.4 kN as the compressive force that defines an increased risk of low-back injury.” In the case of one–hand lifting, the literature is beginning to come to consensus that when lifting an item with one–hand, the side opposite the lifting hand will be at greater risk of exposure. For instance, Allread et al., (1996) concluded that unsupported one–hand lifting, loads the spine more than two–hand lifting. Although the study did not quantify how much more spine loading occured, it did state that “back motion characteristics previously found to be associated with low back disorders were all significantly higher for one–handed lifts”. Marras and Davis (1998) noted that compressive forces in the back did not change, anterior-posterior shear decreased, while lateral shear increased when performing a one–hand lift with the hand on the same side of the body as the load. Wilke et al., (2001) inserted a pressure transducer into the L4/L5 region of a subject’s back . The transducer measured the pressure of a one–hand carry of 19.8 kg to a two–hand carry of 19.8 kg in each hand (39.6 kg total), Figure 2.4. Carrying the object asymmetrically (either in the right or in the left hand) leads to a pressure of 1.0 MPa where as carrying two symmetrically in each hand resulted in a lower pressure of about 0.9 MPa. McGill et al., (2013) conducted a one–hand carrying study with a subject population of six. The results of the study were similar to Wilke et al., (2001). Namely, carrying loads in one hand resulted in substantially more compressive load on the low back than when the load was split evenly between the hands. Dividing the load equally and using two hands reduces spinal load, and doubling the weight and carrying symmetrically did not increase spinal load. The authors also noted that the heavier the load, the larger the difference in spine loads between the hand conditions (one hand or two hand lift). Figures 2.4 [Wilke et al., 2001] and 2.5 [McGill et al., 2013] illustrate the difference in spinal compression between holding total weight in one hand and a two-handed lift while dividing weight with two hands.

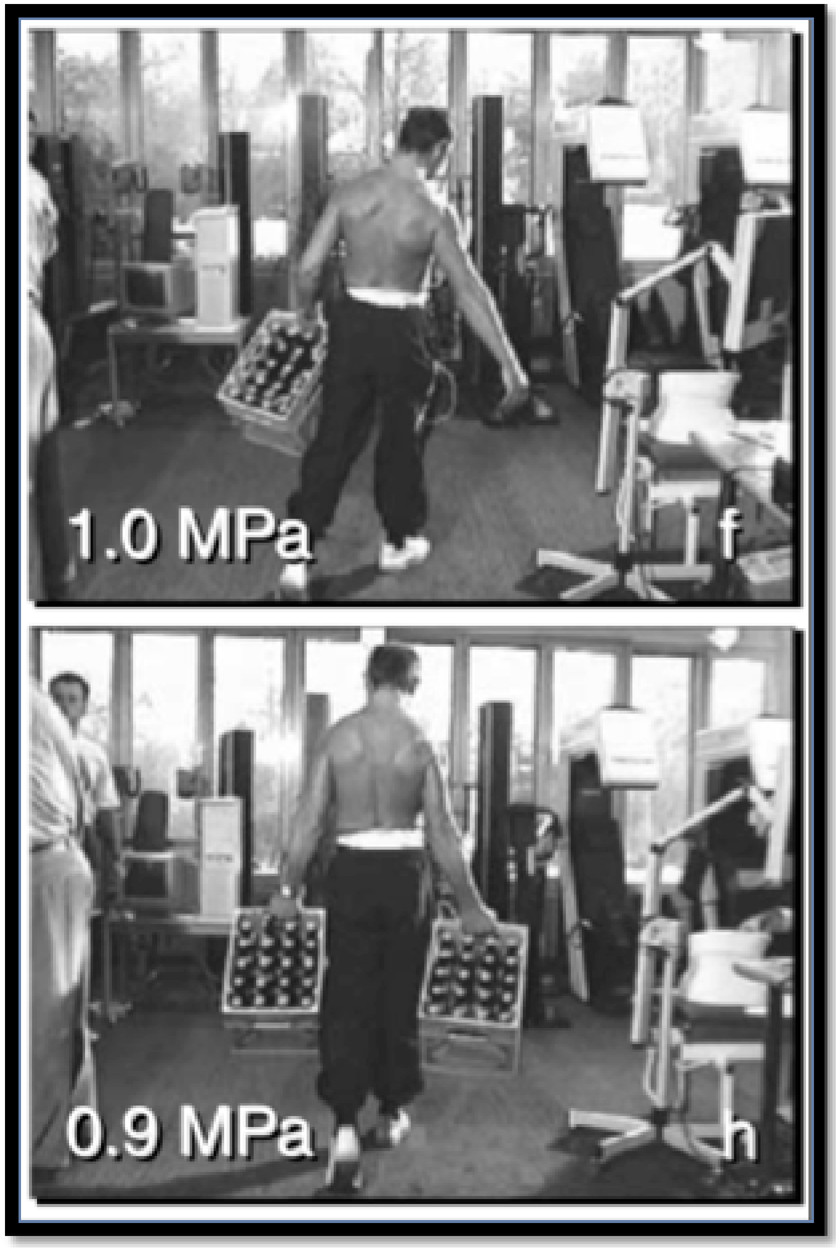

Figure 2.4: Differences in back compressive force when subject performs one-hand and two-hand lifts. [Wilke et al., 2001]

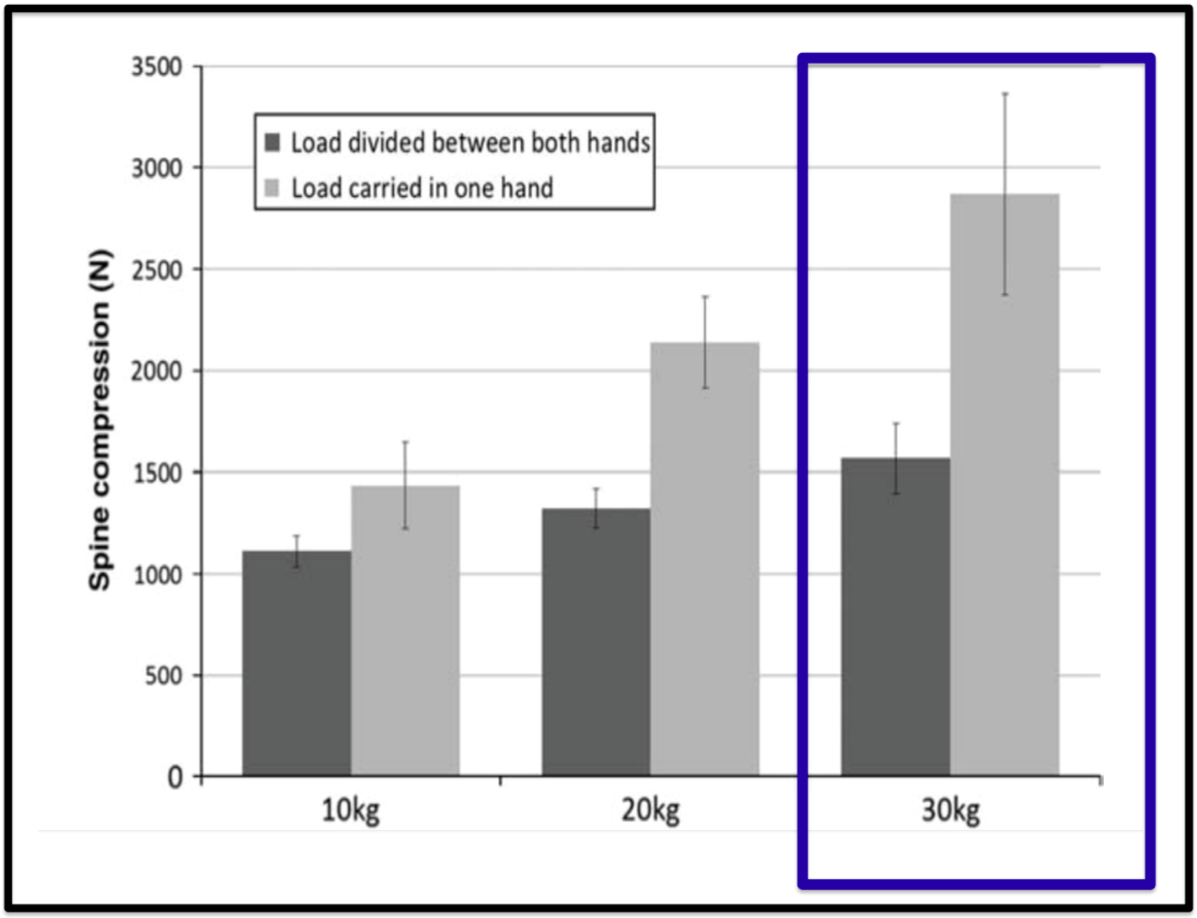

Figure 2.5: Difference in spinal compression when load is divided between both hands vs. being lifted by one hand. [McGill et al., 2013]

Remaining unknown factors include the location in the back that is most susceptible to injury, the critical injury vector, and the force likely to cause an injury when performing a one–hand lift. What may be preventing these questions from being answered is the unknown relative contribution of back muscle groups during one–hand lifts. For instance, Cholewicki and vanVliet IV (2002) noted that there were multiple muscle groups thought to be important for spine stability "but these conclusions were based on a variety on inconsistent data". This led them to theorize that "there is no one muscle or muscle group prevailing over other muscles in their spine stabilizing function under all loading conditions. On the contrary, the relative contribution of a muscle to spine stability will depend on the magnitude and direction of trunk loading".

Physiological methods used to understand the effects on the body when lifting focus on energy expenditure of the individual and the effects on the cardiovascular system. Measures typically used in physiological lifting studies include oxygen uptake/consumption, heart rate, blood pressure (systolic and diastolic), and endurance time. In ergonomics studies, the physiological approach can be used for static or dynamic lifting tasks. However it is primarily used to assess repetitive dynamic tasks since a worker's endurance is primarily limited by oxygen consumption rather than strength [Astrand and Rodahl, 1986]. Due to differences among workers, there are no standard values to determine if a worker is being overworked. The literature reports that age, gender, and physical conditioning can influence the ability to perform a lifting task. On average, older workers have lower lifting capacities than younger workers, females have a lower lifting capacities than males, and people with less physical conditioning (i.e. fitness) have lower lifting capacities than fitter people [Waters et al., 1993]. However, there seems to be some agreement in the literature that the maximum aerobic capacity for repetitive lifting should not exceed 33 percent of maximum aerobic capacity for lifting tasks of two hours or more [Asfour et al., 1988] and [Mital, 1984].

Specific to one-hand lifting, Garg (1983) set out to determine the physiological responses of female workers performing a one-hand lift in the horizontal plane so that an objective measure could be established for performing this type of work. Specifically, Garg tried to establish if permissible limits for one–hand lifts should be based on 33 or 50 percent of maximum work capacity. Garg concluded, "Physiological evaluation failed to support or refute that a work load equivalent to 50 percent of work capacity can be maintained without excessive fatigue". Garg also felt that psychophysical rather than physiological measures offered more potential to determine safe one–hand lifting guidance. Sevene et al., (2012) compared the physiological and psychophysical evaluations of one–hand and two hand lifting tasks and the authors observed that there were no significant differences in physiological or psychophysical stress when performing an identical lifting task with good couplings.

Psychophysical studies look at the relationship between people's sensations and physical stimuli [Fraser, 1989]. Specific to lifting, psychophysical studies focus on the workers' perceptions of physical strain, discomfort, and fatigue associated with different lifting tasks. This provides a clearer understanding of what a particular worker might be willing and able to accomplish in an 8 hour work day and how the body responds to this work can be estimated for populations. Perhaps the most famous psychophysical lifting data produced were the Snook Tables, [Snook, 1978]. These tables were later revised by Snook and Ciriello (1991) as part of their work for Liberty Mutual. As with physiological studies, researchers can study static or dynamic strength. Static tests involve the amount of force a subject can exert under certain postures, specified directions of force, and with "smooth" force application. Warwick et al., (1980) and Davis and Stubbs (1980) conducted one–hand lift studies. Warwick used 29 healthy adult males and measured isometric strength for each hand at two heights, three postures, and six directions, which yielded a table of the mean magnitudes of the forces exerted. Davis and Stubbs performed similar work looking at age, posture, and hand location. They also noted the lifting forces provided are for the dominant hand and if the non–dominant hand is used then a ten percent reduction in capacity should be made.

In a document used to validate their reasoning for an ergonomics standard, OSHA noted that doubts have been raised regarding whether maximum acceptable weights established during laboratory sessions of thirty minutes are valid for four or more hours of work. OSHA also noted that, Mital and Asfour (1983a) observed decreases in maximum acceptable weights [MAWs] at the end of an 8-hour experimental session when workers lifted at frequencies greater than six lifts/minute. Ciriello et al. (1990) observed stability in MAWs during 4-hour sessions as long as the lifting frequency was slower than 4.3 lifts/minute." Therefore caution is warranted for psychophysical values used to explain what is happening with the body for long periods of time and higher repetition rates [OSHA, 1999].

2.4 Timeline of Notable Lifting Guidance and Standards

The first lifting standards in the United States were developed for women and children entering the workforce. From the 1930's to 1950's almost all states had laws limiting the amount of weight women and children could lift [NIOSH, 1981]. Unfortunately, these lifting laws were not meant to protect women from injury but rather were exclusionary laws designed to minimize the types of jobs women could hold [Women's International Center, 2014]. For instance, women were prohibited in some states from lifting more than 15 pounds. Surprisingly, these exclusionary laws limiting the weights that women may lift were still in existence in 10 States and Puerto Rico as late as the 1970's as reported in a Senate Congressional meeting [History Matters, 2014].

During World War II the federal government issued the first federal lifting guidance from the Bureau of Labor Standard under the control of the U.S. Department of Labor. This guidance, Bulletin No. 11 – A Guide to the Prevention of Weight Lifting Injuries [Department of Labor, 1943], set maximum lifting guidelines for both men and women. The development of a lifting guideline by the Department of Labor may have been influenced by the number of women entering the workforce or the desire to ensure a minimum occurrence of injuries to maintain peak production levels. Within Bulletin No. 11, the Bureau of Labor Standards recommended maximum lifting weights of compact objects to 25 pounds for female workers and 50 pounds for male workers. The National Safety Council and other organizations soon adopted the limits specified in Bulletin No. 11 as the prevailing lifting standard for approximately the next 25 years.

The National Safety Council gradually began to raise the maximum amount of weight women could lift to 44 pounds by the 1960's. In the mid 1960s, the Bureau of Labor Standards updated their lifting guidance by publishing new lifting guidance in 1965 [Department of Labor, 1965]. The new guidance offered in Bulletin 110 Teach Them to Lift was centered on a technical report published by the International Labor Organization (ILO) in 1964. The ILO based its findings on a meeting convened by a panel of experts who considered the "physiological capacity of workers for weight carrying and the influence on it". Guidance was given for boys (15-20 kg) and girls (12-15 kg) between 16 and 18 years old, women (15-20 kg) and men (40 kg), [Scott, 1966]. A few years after the ILO proposed their standards Snook and Irvine published guidance of their own based on psychophysical information they collected on how much a male worker could lift [Snook and Irvine, 1967]. Later, this work became the source for the 1970 publication Ergonomics Guide to Manual Lifting [AIHA Ergonomics Committee, 1970]. Although not a standard it was made available to industrial hygienists and other occupational, safety, and health professionals to help them evaluate lifting tasks.

In 1968 the Department of Defense published Military Standard (MIL STD) 1472, Department of Defense Design Criteria Standard, Human Engineering, with six subsequent revisions. The original version of MIL STD 1472 specified how much weight male and female soldiers could lift individually in two different vertical region under ideal conditions. Factors such as frequency of lift, object depth, obstacles in the lifting path, could reduce the amount of weight a soldier could lift. The latest revision of MIL STD 1472, version "G", added an additional vertical lifting region for consideration [Department of Defense, 2012]. Other government agencies have used the information in MIL STD 1472 to create of their own lifting documents. Figure 2.6 contains the MIL STD 1472G maximum lift weights for three different heights for male and female soldiers.

TABLE XXXVIII. Maximum design weight limits.

Handling Function	Population	
	Male and female	**Male only**
Lift an object from the floor and place it on a surface equal to or greater than 152 cm (5.0 ft) above the floor	14 kg (31 lb)	21.9 kg (48 lb)
Lift an object from the floor and place it on a surface not greater than 152 cm (5.0 ft) above the floor	16.8 kg (37 lb)	25.4 kg (56 lb)
Lift an object from the floor and place it on a surface not greater than 91 cm (3.0 ft) above the floor	20 kg (44 lb)	39.5 kg (87 lb)
Carry an object 10 m (33 ft) or less	19 kg (42 lb)	37.2 kg (82 lb)

Figure 2.6: Table XXXVIII from MIL STD 1472G, Maximum Design Weight Limits. [Department of Defense, 2012]

The contributions of Snook do not end with his assistance in the development of the AIHAs Ergonomics Guide to Manual Lifting. Snook (1978) published results from a large psychophysical study for Liberty Mutual Insurance, which began in 1967. The data collected from the study were used to produce “maximum acceptable weight of load” (MAWL) tables for male and female workers that considered lifting, lowering, pushing, pulling and carrying. The tables, commonly referred to as the Snook Tables, provide a value for the maximum acceptable weight as judged by industrial workers for 10, 25, 50, 75 and 90% of the worker population tested for each activity. The results of this study were integrated into a series of tables that can be used to find the percentage of an industrial population capable of sustaining the efforts tabulated to lifting, lowering, pushing, pulling, and carrying. The maximum “acceptable” weight tables were later revised in 1991 by Snook and Ciriello (1991). In both cases, the psychophysical approach provided significant information about male and female worker capability and limitations and design of manual handling tasks to reduce injury risk. The Liberty Mutual Manual Materials Handling Tables were updated in 2008 and now provide “the male and female population percentages capable of performing MMH tasks without over exertion, rather than maximum acceptable weights and forces”.

During the early 1980s there was a flurry of activity related to lifting guidance being proposed by researchers. Warwick et al., (1980) measured the maximum voluntary isometric strengths (force) of 29 healthy adult males performing 120 activities that the authors considered to be representative of MMH tasks. The force measurements were performed using either one or two hands on a handle located at knee height (60 cm high) or shoulder height (142 cm high) and the forces were applied in six different directions using one or both hands. The study also considered participant age and grip location. Subject strength means varied from 74 to 386 N, depending on the task, with corresponding standard deviations from 24 to 157 N. However, the resulting lifting limits proposed have not been widely used by government or industry. Although not an American standard or guideline, The Materials Handling Research Unit of the University of Surrey produced a MMH guide [Davis and Stubbs, 1980] that was based on the intra–abdominal pressures of subjects reaching 90 mm Hg. The work of Davis and Stubb is widely cited in the literature and was an important document, as it considered lifting limits differently than previous research. First, it not only provided force limits when standing, it also included limits for other postures such as squatting, sitting, or kneeling. Second, it provided guidance for one–hand lifting as well as two–hand lifting. Third, the target population was the male 5^{th} percentile rather than previously studied male 50^{th} percentile. Figure 2.7 demonstrates a sample regression relationship developed by Davis and Stubbs and Figure 2.8 shows how the work of Davis and Stubbs is presented to practitioners in a table format.

NIOSH (1981) published the first of their two lifting equations. In the technical report titled Work Practices Guide for Manual Lifting , NIOSH cited over 600 literature citations used to better understand the scope of the problems associated with lifting. A 4-pronged approach using epidemiological, biomechanical, physiological, and psychophysical criteria was developed to establish the NIOSH lifting equation.

This equation consisted of:

The action limit (AL), an algebraic equation in which the maximum amount of weight that could be lifted under the specified lifting conditions could be calculated. The theoretical maximum amount of weight a worker could lift was 90 pounds under ideal conditions.

The maximum permissible limit (MPL), which was defined as 3 x AL. The MPL acts as a secondary boundary to consider lifting tasks and helps to create three different regions for how a lift can be considered.

Comparing the calculated AL and MPL with the actual weight of the item being lifted will determine lift safety. From the Work Practices Guide for Manual Lifting "Thus, properly analyzed lifting tasks may be of 3 types:

Those above the MPL should be viewed as unacceptable and require engineering controls.

For one-handed palmar thrusting when standing, the best fit (r^2 = .878, p<.05) relationship is:

$$FL\ (kgf) = (A)(F)(19.54 - .0336V' - .101H' - .1481L' - .00182V'^2 - .00096H'^2 + .00172H'L') \quad (14)$$

where:

$$A = \begin{cases} 1.0 \text{ for males} \leq 40 \text{ years old;} \\ 0.920 \text{ for males 41-50 years old; and} \\ 0.608 \text{ for males 51-60 years old.} \end{cases} \quad (15)$$

For one-handed pushing horizontally forward when standing, the best fit (r^2 = .798, p<.05) relationship is:

$$FL\ (kgf) = (A)(F)(25.28 - .0607V' - .066H' - .231L' - .00219V'^2 + .00165H'L') \quad (16)$$

where:

$$A = \begin{cases} 1.0 \text{ for males} \leq 40 \text{ years old;} \\ 0.934 \text{ for males 41-50 years old; and} \\ 0.745 \text{ for males 51-60 years old.} \end{cases} \quad (17)$$

Figure 2.7: Sample regression relationship developed by Davis and Stubbs, [Davis and Stubbs, 1980]

Position	Shoulder – Grip Distance	RWL
Standing/Squatting	65 cm (25.6 in)	4.1 kg (9 lbs)
	60 (23.6)	5 (11)
	50 (19.7)	5.9 (12.9)
	35 (13.8)	8.2 (18)
	20 (7.9)	10 (22)
	5 (2.0)	12.3 (27)
Sitting	65 (25.6)	3.6 (8)
	50 (19.7)	5.5 (12)
	40 (15.7)	7.3 (16)
	30 (11.8)	9.1 (20)
	15 (5.9)	11.1 (24.3)
	5 (2.0)	12.7 (28)
Kneeling on One Knee	65 (25.6)	4.1 (9)
	60 (23.6)	5 (11)
	55 (21.6)	5.5 (12)
	30 (11.8)	6.8 (15)
	25 (9.8)	8.2 (18)
	15 (5.9)	10 (22)

Figure 2.8: Sample one-hand lift table created from regression relationship developed by Davis and Stubbs [Davis and Stubbs, 1980]

Those between the AL and MPL are unacceptable without administrative or engineering controls.

Those below the AL are believed to represent nominal risk to most industrial workforces."

NIOSH published a revised lifting equation (Revised NIOSH Lifting Equation [RNLE]) with several significant changes including philosophical considerations for how it should be employed [Waters et al., 1993]. The philosophical differences refers to the new "permissible" limit as opposed to "recommended" maximums of the initial equation. This was the result of a conflict between OSHA and NIOSH over enforcement. Major changes to the revised NIOSH Lifting Equation (RNLE) included reducing the maximum amount a person could lift from 90 to 51 pounds, inclusion of two new lifting multipliers to consider twisting and object couplings, and replacing the MPL with the concept of the lifting index (LI).

Where

HM = Horizontal Multiplier, is measured from the mid-point of the line joining the inner ankle bones to a point projected on the floor directly below the mid-point of the hand grasps (ie. load center), as defined by the large middle knuckle of the hand.

VM = Vertical Multiplier, is measured vertically from the floor to the mid-point between the hand grasps, as defined by the large middle knuckle.

AM = Asymmetry Multiplier, is operationally defined as the angle between the asymmetry line and the mid-sagittal line.

DM = Travel Distance Multiplier, is defined as the vertical travel distance of the hands between the origin and destination of the lift.

CM = Coupling Multiplier, is the relationship between the hands and must be classified as good, fair, or poor depending on the nature and dimensions of the object and gripping method.

FM = Frequency Multiplier, is the average number of lifts per minute, as measured over a 15 minute period.

The RNLE yields two equations, the RWL and the LI. The Recommended Weight Limit (RWL) is the theoretical maximum weight that should be lifted under the given lifting conditions, it is stated algebraically as:

$$RWL = 51 \text{ lbs } (HM)(VM)(AM)(DM)(CM)(FM)$$

The RWL is then used to compute a LI. The LI is defined as the actual weight of the object being lifted divided by the RWL. The LI gives a relative indication of the risk of injury associated with the measured lifting tasks.

$$LI = \text{Weight of object}/RWL$$

The LI gives a relative indication of the risk of injury associated with the measured lifting tasks. NIOSH states that "it is not possible to quantify the precise degree of risk associated with increments in the lifting index." Many ergonomists and safety professionals will revert to the 1981 NLE lifting task definitions and apply them to the 1991 RNLE. For instance, lifts at or below the LI of 1.0 are similar to lifts below the action limit. Lifts with a LI over 1.0 and equal to 3.0 are treated similarly to lifts between the AL and MPL. Lifts with a LI over 3.0 are treated like lifts above the MPL [McCoskey, 2014]. The NIOSH perspective is that it is likely that tasks with a LI greater than 1.0 pose an increased risk of lifting related injury. Hence, the goal should be to design all lifting jobs for LI of 1.0 or less. Neither the NLE or RNLE provide guidance for one-hand lifting.

Finally, the American Conference of Governmental Industrial Hygienists (ACGIH) considers lifting in their Threshold Limit Value (TLV) publication. In their most recent publication [ACGIH, 2016] the TLVs consist of three tables which present lifting tasks defined by their duration time. These duration categories are either less than or greater than 2 hours per day, and frequency, expressed in number of lifts per hour. The TLVs represent weight limits for a two-handed, single-lift performed in front of the body in an upright (neutral) position. Maximum amount of weight that can be safely handled ranges from 5 to 70 pounds. The ACGIH does not provide tables for one-hand lifting, rather they defer to professional judgment to determine a safe one-hand lift.

2.5 Current Government and Industry Lifting Guidance

2.5.1 Military Standard 1472G

Military Lifting Guidance is provided in many DoD documents. The Department of Defense Instruction (DODI) for DoD Safety and Occupational Health Program [Department of Defense, 2014] identifies frequent or heavy lifting as an ergonomic workplace risk factor but it does not provide any guidance as to how to limit frequency nor provide suggestions on how to lessen the risk of lifting. Guidance from the Army safety program regulation is generic with no mention of standards to be used to control an occupational safety and health concern [Department of Defense, 2013]. The Army safety program pamphlet establishes procedures for safe material handling but it does not reference any safe manual material handling limits [Department of Defense, 2008]. The Army ergonomics pamphlet mentions that heavy lifting, especially in an awkward posture, can contribute to the development of a work–related musculoskeletal disorder, but there is no mention of safe handling limits [Department of Defense, 2003]. At best, Army guidance through regulations and pamphlets recognizes lifting as a contributor to injury but does not offer information on what is safe a safe lift nor does it direct the reader to the lifting guidance cited in DOD Military Standard 1472G [Department of Defense, 2012].

The maximum weight lifting values in MIL STD 1472G are believed to have been developed using information based on weight lifting and holding tests performed on Air Force basic trainees by McDaniel (1983). The Air Force volunteers incrementally lifted weights starting at 40 pounds six feet high. If a lift was successful another 10 pounds was added until either; the subject requested to stop, the subject was unable to raise the weight to a height of six feet, or the 200 pound weight capacity was exceeded. However, when discussing the basis for the maximum weight values listed in then version MIL STD 1472D with an Army researcher for the U.S. Army Research Institute for Environmental Medicine, I was told that "My understanding is that the limits were at least partly based on McDaniels work, but at a meeting several years ago, McDaniel himself really did not substantiate it very well." [Sharp, 2010].

At best, the guidance for maximum weight limits for lifting loads presented in MIL STD 1472G is based on research but institutional knowledge cannot determine the original work that acts as the foundation for the lifting standard. Within MIL STD 1472G is two–handed lifting guidance for male service members, female service members, single gender lifting teams, and mixed gender lifting teams. In addition to gender, MIL STD 1472G contains reductions based on start height of the lift, twisting, frequency of lift, depth of item being lifted, and obstacles in the lifting path. One-hand lifting is not considered in the MIL STD but one hand-carrying is considered. Interestingly, there is not a reduction factor when carrying with one–hand vs. two–hand. The MIL STD states "The (two-hand lift) weight limit shall be used as the maximum value . . . . .for carrying an object with a handle on top, such as a tool box, which usually is carried at the side with one hand. However, there is a reduction for one–hand carrying based on the distance the item is carried. Carries of up to 33 feet have a maximum weight limit of 82 and 42 pounds for male soldiers and female soldiers respectively. If carrying an object greater than 33 feet, the carry limit drops to 30 pounds for both male and female soldiers.

From conversations with Army experts who were involved in the revision of MIL STD 1472 from version F to version G, it was discovered that there have been no Army or DoD studies to validate the lifting and carrying standards published in MIL STD 1472, nor does the Army or DoD have any models to predict safe one–hand lifting limits. Also, during these conversations it was mentioned that if the lifting guidance contained in MIL STD 1472G was based on McDaniels work then the research data used to generate the values in MIL STD 1472G and previous versions are inaccessible since the data generated by McDaniel is no longer in a "usable format" [(Goddard, 2010) and (Sharp, 2010)]. Finally, Army experts reported there has been no research within the Army or DoD to compare the MIL STD 1472G values for lifting with the RNLE to determine which lifting model better predicts risk. Also, from conversations with the same Army experts MIL STD 1472 is a living document and can be updated if valid information is presented to warrant its inclusion in future versions.

2.5.2 Liberty Mutual Group Snook Tables

The MMH guidelines developed by Snook (1978) and later revised by Snook and Ciriello (1991) for the Liberty Mutual Group uses a psychophysical approach as part of a scientific investigation into the determination of safe lifting weights for MMH tasks. Specific measurements taken to develop the MMH guidelines included oxygen consumption, heart rate, and anthropometric characteristics. Additionally, the psychophysical methodology developed by Snook (1978), consisted of giving a worker control over the weight being lifted. The experimenter controlled other aspects like height and frequency of lift. Workers were instructed to adjust the weight so that they would be able to work all day as hard as possible on an "incentive basis" without straining or becoming unusually tired, weak, out of breath or over heated. Snook concludes that "a worker is three times more susceptible to low back injury if performing a materials handling task that is comfortable for less than 75% of the worker population". Snook noted that "In practical sense, the goal was to determine what a man will do, opposed to what a man can do" [Snook and Irvine, 1967].

The MMH guidelines designed by the Liberty Mutual Research Institute for Safety for Liberty Mutual Group specifically notes "The tables cannot be used to evaluate one-hand tasks. By nature, these tasks place uneven loads on the back and present a greater physical stress than two-handed lifts." [Liberty Mutual Research Institute for Safety, 2014]. A review of the literature did not reveal any articles by researchers who modified the Liberty Mutual Tables to expand its use to one–hand lifting.

2.5.3 Davis and Stubbs

Davis and Stubbs from the Materials Handling Research Unit of the University of Surrey provided recommendations for males performing one-hand lifting tasks while standing, squatting, sitting, or kneeling. The authors recommend reductions based on the age of the lifter, use of dominant vs. non-dominant hand, and acromial-grip distance [Davis and Stubbs, 1980].

2.5.4 American Conference of Governmental Industrial Hygienists Threshold Limit Values

American Conference of Governmental Industrial Hygienists (ACGIH) Lifting Threshold Limit Values (TLVs) are intended to control biomechanical risks to the back [ACGIH, 2016]. The lifting TLV is based on EMG–assisted biomechanical models, the RNLE, and historical risk data. The end goal was to develop guidance for workplace lifting conditions that are considered to be safe for virtually all workers continuously exposed to them on a daily basis. The maximum amount of weight the ACGIH Lifting TLV recommends is 70 pounds under ideal conditions. The ACGIH Lifting TLV consists of three tables with weight limits for two–handed mono–lifting tasks within 30 degrees of the sagittal (neutral forward) plane. The three tables consider different lifting frequency rates and each table considers 15 different lifting postures based on five different horizontal locations and three different vertical locations of the hands.

As far as one–hand lifting is concerned, there are no tables with specific guidance provided. A special note regarding one-hand lifts provides some clarification "As stated, ACGIH Lifting TLV tables provide weight limits for two-hand mono-lifting tasks and do not represent the lifting limits for one-hand lifting". However, the ACGIH Lifting TLV document states that "professional judgment [can] be used to reduce weight limits...for one-hand lifting...below those recommended in the TLVs" for two-hand lifting [ACGIH, 2016]. Summarizing the ACGIH guidance, an unacceptable two-handed lift would also be unacceptable if it were made into a one-hand lift. Also, professional judgment can be used to determine a safe one-hand lift but no guidance is provided within the TLV booklet on how to do so. Furthermore, no articles were identified by researchers who attempted to modify the ACGIH TLV in an effort to expand its use.

2.5.5 NIOSH Lifting Equation

NIOSH developed a lifting equation in 1981 [NIOSH, 1981] and later revised it in 1991 [Waters et al., 1993] in an effort to provide guidance on the physical stresses associated with lifting and to provide a simple to use tool that could help determine if a lift was safe or hazardous based on the physical characteristics of the lift. Comparing the 1981 NIOSH Lifting Equation (NLE) with the revised 1991 NLE (RNLE) illustrates major changes to the NLE: reduction of the load constant from 90 pounds to 51 pounds, elimination of lifting zones that designate if a lift is “Acceptable” or “Unacceptable” (Acceptable, Unacceptable for some individuals, or Unacceptable for most individuals), providing a relative estimate of the physical stress associated with manual lifting, and adding methods for; evaluating asymmetrical lifting tasks, lifting of objects with less than optimal hand-container couplings, and guidance for a wider range of work duration and lifting frequencies.

The RNLE is comprised of two equations. The first equation, the Recommended Weight Limit (RWL) allows a user to determine the maximum amount of weight that can be safely lifted or lowered using two hands given the conditions of the lift. The RWL represents the load that 99 percent of the male work population and 75 percent of the female work population (90% of total work population) can safely accept. Based on data from studies of human capacities and endurance, such as biomechanical, physiological, psychophysical and epidemiological studies, a load constant and reference lifting point were established. The lifting constant was revised and lowered from 90 to 51 pounds and the standard lifting location was revised from 30 inches vertical and 6 inches horizontal to 30 inches vertical 10 inches horizontal, both points represent lifting in the sagittal plane. The second equation, the Lifting Index (LI) allows the user to “compare the lifting demands associated with different lifting tasks in which the load weights vary” [Waters et al., 1993]. The LI is a dimensionless value derived by dividing the actual weight of the object lifted by the RWL. The LI is a relative estimate of the physical stress associated with a manual lifting job. As the magnitude of the LI increases, the level of the risk for a given worker increases, and a greater percentage of the workforce is likely to be at risk for developing lifting-related low back pain. NIOSH considers that the goal should be to design all lifting jobs to achieve a LI of 1.0 or less [Ergoweb, 2002].

As was the case with the original NLE, the RNLE does not consider using a one-hand lift. "The 1991 lifting equation was not designed to assess tasks involving one-hand lifting" [Waters et al., 1993]. Unlike the other lifting guidance mentioned, there has been a history of modifying the RNLE to either make it more accurate or to increase its functionality.

2.6 Proposed Modifications to the Revised NIOSH Lifting Equation

As stated earlier, in an effort to provide guidance on the physical stresses associated with lifting and to provide a simple to use tool that could help determine if a lift was safe or hazardous based on the physical characteristics of the lift NIOSH developed the RNLE in 1991. Since its inception, others have made suggestions to modify the equation or multipliers used in the equation to improve its reliability, better estimate stressors faced by ethnic populations, expand the functionality, or to simplify the RNLE [Sesek et al., 2003]. Dempsey and Fathallah (1999) and Arjmand et al. (2012) take exception with how the RNLE asymmetric multiplier was derived. Dempsey and Fathallah assert that the asymmetric multiplier is not easy to use and cannot be applied in the workplace. They also feel that using qualitative categories such as the one proposed by Mital et al., (1987) in which the angle of asymmetry (A) could be categorized as:

$A = 0°$

$0° < A \leq 30°$

$30° < A \leq 60°$

$60° < A \leq 90°$

$A \geq 90°$

may decrease the variability associated with measuring asymmetry in the field [Mital et al., 2004].

Arjmand et al., (2012) take a biomechanical perspective to make their case for revision of the asymmetrical multiplier. In their study, they used a finite element biomechanical model to estimate spinal loads during one-hand and two-handed asymmetric lifting tasks. This yielded sixteen predictive equations for spinal loads at two disc levels, two postures, and two lifting styles. Based on the predictive equations, contour plots were constructed that yielded spinal loads beyond the RNLE RWL. The authors concluded that the RNLE asymmetrical multiplier should depend on the trunk posture and be defined in terms of the load vertical and horizontal positions.

When looking at spinal loading during asymmetric lifting, Marras and Davis (1998) proposed that the asymmetric multiplier should be revised to consider lifts performed to the left of the sagitaal plane. This type of lift should be considered differently than lifts performed to the right of the sagitaal plane and one–hand lifting with the weight on the same side of the body would not need an asymmetric discounting factor. Figure 2.9 illustrates the discounting factors for one-handed and two-handed lifts compared to the RNLE factor.

In a study looking at the maximum acceptable weight an experienced Chinese male manual material handler could lift, Wu (1997) observed that the most stressed body parts reported by the lifters were the back and wrist. It was suggested that the cause of this pain was due to the height of the table used in the lifting trials (760mm), which is 30 inches or the maximum VM value in the RNLE. It was concluded that the RNLE needed to be revised so that the standard reference height better matched the anthropometrics of the Chinese population.

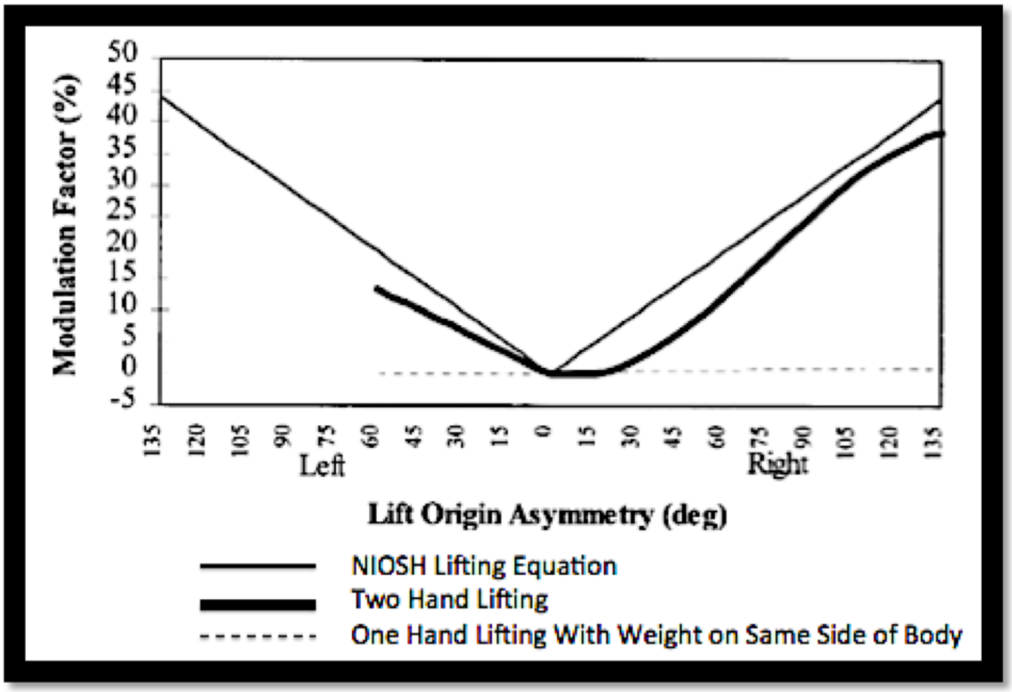

Figure 2.9: Asymmetric discounting factors for one-handed and two-handed lifts compared to the RNLE factor. [Marras and Davis, 1998]

In another instance where investigators feel a multiplier should be considered for modification, Adams et al, (2010) conducted a study looking at a lifting task in which two objects weighed the same, each at 12.5 kg but had different coupling factors (bag of dog food and milk crate with handles loaded with a solid fixed plate). The physiological and psychophysical stresses between the two lifting tasks were compared. The results of the study showed a significantly higher metabolic cost as well as a higher perceived exertion when subjects performed a paced two-handed lifting task with good coupling factors than when using an object with poor coupling factors.

Sesek et al., (2003) explored the idea of simplifying the RNLE to see if its predictive ability of determining workers who are at risk of suffering a low back injury could be maintained but with less work. In the study, data was analyzed from a database containing 667 manufacturing jobs collected from the automotive industry. The database had historical injury data, symptom interviews, basic medical exam information for approximately 1,100 people, and corresponding MMH ergonomics data. This information allowed the data to be analyzed from a biomechanical, physiological, and logically plausible basis. The authors explored if some aspects of the RNLE could be modified to produce a simplified lifting model that performs as well as the existing RNLE. Not only did the authors demonstrate that omitting use of three of the six multipliers (distance multiplier, asymmetry multiplier, and coupling multiplier) had little effect on the RNLE, they also demonstrated that one-hand lifts could be analyzed using the RNLE with good predictive performance.

Also in 2003, the European Committee for Standardization (CEN), which is a public standards organization of the European Union (EU) developed European Standard EN 1005-3, a MMH guide for the handling of machinery and their component parts, [European Committee for Standardization, 2005]. Notable differences between the RNLE and EN 1005–3 is the RWL is replaced by the Recommended Mass Limit (RML). LC is replaced by the Reference Mass M_{ref}, which considers field of application and the population lifting the item. There are seven reference masses ranging in weight from 5–40 kg. Unlike the RNLE population, the CEN population is not restricted to the general work population and includes children and the elderly. Additionally there are three new multipliers to be considered. One-handed lifting is designated by the multiplier OM and two-person lifting is designated by the multiplier PM. Additional environmental factors, which would be applied if the object being lifted is not very cold, hot, or contaminated or the moderate ambient thermal environment is normal, are designated by the multiplier AT. For two person lifts in which each lifter is only using one arm and an environmental factor is present, EN 1500-3 lifting equation is: RML = Mref x VM x DM x HM x AM x CM x FM x OM x PM x AT [European Committee for Standardization, 2005]

Maiti and Bagchi, (2006) proposed that due to the nature of risk factor interactions, the limits obtained from the RNLE might not be appropriate for all lifting tasks. The investigators examined the interactions of the lifting frequency multiplier, vertical lifting distance multiplier and the load weight. Their findings indicate that the contributions of interaction effects vary with different kinds of work environment, namely awkward and “complicated” postures. Therefore, lifting tasks should consider more than just the multiplication factors presented in the RNLE. Finally, it is concluded that in order to improve the current recommended weight limit estimated by the RNLE, the interaction effects between different lifting parameters must be considered.

Maiti and Ray, (2004) took elements of the RNLE in order to develop a maximum load limit for Indian adult female workers. The researchers used multipliers to better understand the effects different elements had on a lifting task. The authors modified the RNLE because they felt the use of the American biomechanical data was not appropriate for an Indian population. Citing previous research the authors opted to use heart rate for the evaluation of workload and based their multiplier equation on physiological measures rather than biomechanical criteria. The result is a lifting standard based on physiological measures specific to the female Indian workforce.

Waters et al., (2014), adapted the RNLE to develop provisional guidelines to accommodate pregnant workers. Empirically based lifting criteria established by NIOSH to reduce the risk of overexertion in the general U.S. working population were evaluated for application to pregnant workers. In an effort to make the provisional guidelines practical and feasible, the authors made simplifying assumptions, notably the multipliers for vertical travel distance, angle of asymmetry, and coupling were all set to 1. Similar to the ACGIH TLVs, the provisional lifting guidelines define the workspace into three vertical and three horizontal regions to produce nine lifting zones. Additionally, to help direct the practitioner to the correct lifting value a graphically based version of the guideline was created. Figure 2.10 shows recommended weight limits for early and late pregnancy for three lift frequency patterns. The authors conclude that adaption of the RNLE will produce lifting thresholds that most pregnant workers should be able to perform.

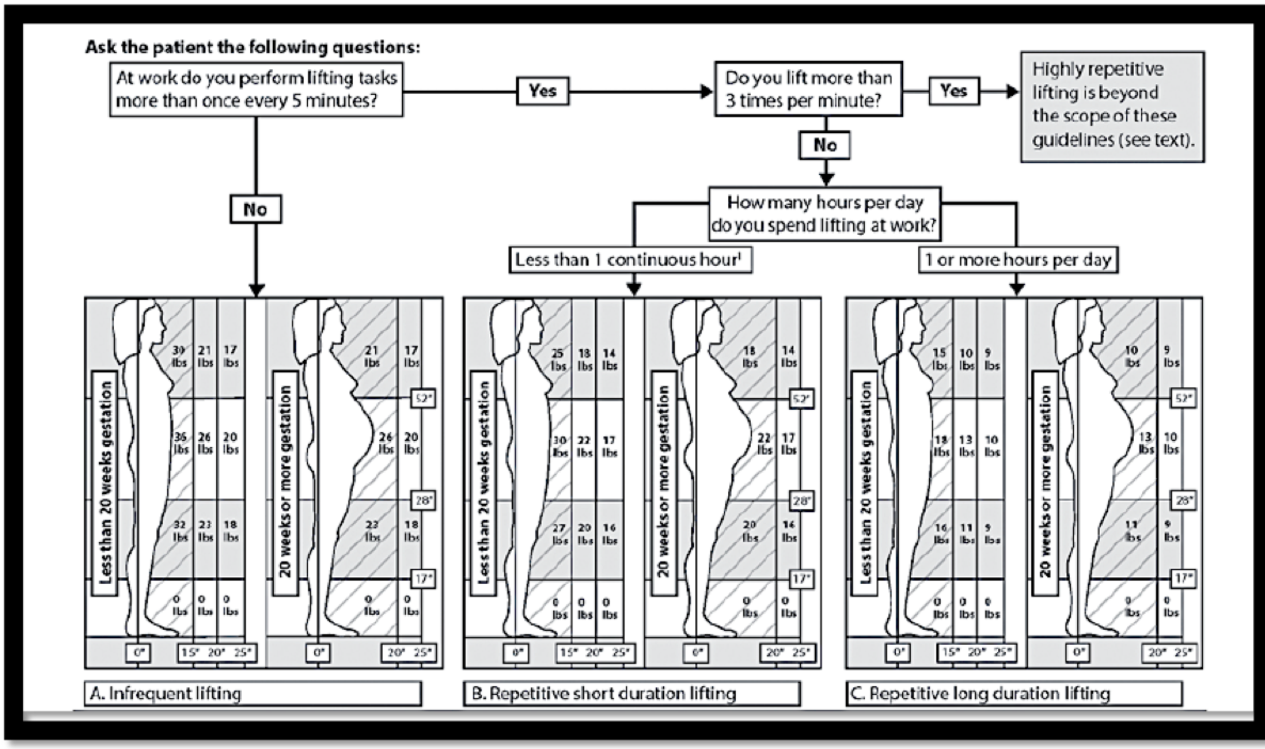

Figure 2.10: Recommended weight limits for early and late pregnancy for three lift frequency patterns. [Waters et al., 2014]

Garg et al., (2014) used an epidemiological approach to evaluate the relationships between the RNLE and risk of low–back pain (LBP). Their rationale was that the RNLE is commonly used to quantify physical stressors to the low back when investigating lifting and or lowering jobs. Their prospective study on the relationship between RNLE and LBP indicated that physical stressors are associated with increased risk of LBP. Data suggests that the physical exposure to on the job stressors such as the lifting index can be a useful metric for estimating exposure to biomechanical stressors and potentially predict jobs that will lead to LBP.

2.7 One-Hand Lifting and Carrying

After searching multiple electronic library databases using keywords one–hand, one–handed, and lifting capacity as well as reviewing textbooks and research articles it became apparent that there is minimal research devoted to one–handed lifting. In the textbook Manual Materials Handling, the authors noted that they "were only able to identify eight studies which have addressed the problems of one-hand materials handling tasks" [Ayoub, 1989]. Since then, more studies have been conducted but not enough to adequately address the issues surrounding one–hand lifting. When the keyword search was expanded to include the keyword terms asymmetric lifting and asymmetrical lifting, virtually all research articles located focused on twisting of the back rather than one–hand lifting [(Parikh et al., 1997), (Wu, 2000), (Dolan et al., 2001), (Bobick et al., 2001) and (Cheng and Lee, 2003)]. Based on these results, more work needs to be done to better understand the stresses placed on the body during one-hand lifting activities.

McConville and Hertzberg (1966) conducted a study for the U.S. Air Force to aid in establishing weight and size criteria for the design of industrial loads so that a design starting point for industrial or military equipment could be established. Figure 2.11 shows the regression line relating one–hand lift capability versus the width of the object being lifted. The study population consisted of 30 adult males who were considered to be a reasonable representation by height and weight of the U.S. Air Force population. In the study the interaction of two variables, weight and width of object, when lifting a symmetrical shaped container that was 30 inches high was considered. The investigation was limited to one–hand lifting. One handed carrying and two handed lifting were not considered. The shaped container width ranged from 6 to 32 inches and the maximum weight the subjects were able to lift increased as the shaped container width decreased. A linear equation of $Y = 60 - X$ was proposed where Y is the maximum weight in pounds of the object that 95 percent of the male population can lift and X is the width in inches of the shaped container being lifted. The numerical values of this formula were considered to be the upper limits of a lift performed under ideal conditions. Although not explicitly stated, lifting while twisting or lifting with a large horizontal distance were not considered. Interestingly, an organization within the DoD took the lead in trying to develop guidance for one–hand lifting yet the guidance document the DoD uses makes no mention of McConville and Hertzberg's work nor did the DoD ever try to increase the scope of McConville and Hertzberg's work.

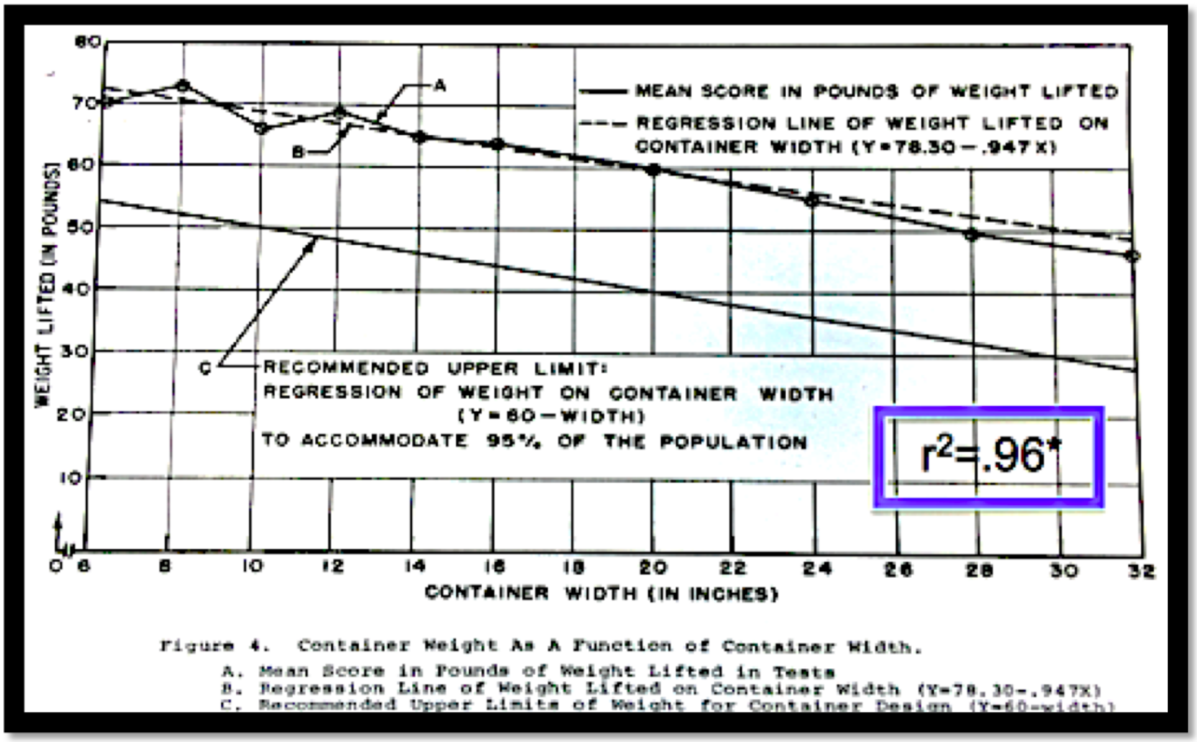

Figure 2.11: Regression line of weight lifted (pounds) vs. container width (inches) [McConville and Hertzberg, 1966]

Datta and Ramanathan, (1971) conducted a study comparing seven modes of carrying an identical load. The modes of carrying were: head, rucksack, double pack, rice bag, sherpa, yoke and hands. Analysis of variance on the data established a significant difference in energy cost, cardiac rate and pulmonary ventilation due to a change in the mode of carrying. Carrying by hands was observed to be the worst method.

Drury, (1975) expands on the unpublished work performed by two of his students in which they examined the relationship between carrying one item in one hand and two items in two hands. Six male students carried boxes that were fitted with handles and weighted 15.9, 20.5, and 25 kg under two conditions. In the first condition a single box is carried in the preferred hand and in the second two boxes of the same size and weight are carried in each hand. The results indicate that there is no difference in endurance between lifting a single weight with one hand (e.g. 1 x 25 kg) and lifting the same weight in each hand (e.g. 2 x 25 kg). The conclusion of this study indicates that for one-hand or two-handed carrying of equal loads the two arms can be considered as independent.

Warwick et al., (1980) noted "the data on maximum voluntary contraction strengths in manual handling task execution is far from comprehensive, particularly for asymmetric activities". The authors measured the maximum voluntary isometric strengths (force) of 29 healthy adult males performing 120 activities considered to be representative of manual materials handling tasks. The force measurements were performed using either one or two hands on a handle located at knee height (60 cm high) or shoulder height (142 cm high) and the forces were applied in six different directions using one or both hands. The authors observed that strength is dependent on posture, direction of force, and hand/s used to accomplish the task. "Even within the limited set of conditions examined here, these factors alone can account for a five-fold range of strengths." In a nod to engineering controls over administrative controls the authors observed that their data implies it may often be more efficient to redesign a task rather than select a stronger worker to perform it.

Garg, (1983) conducted a study to assess the physiological responses to one-hand lifts in the horizontal plane by female workers in an effort to provide an objective measure for determining acceptable maximum frequency of lift for the different weight-distance combinations. Ten female volunteers between the ages of 21-34 were chosen as subjects. The subjects were required to stand in front of a 91 cm high work table and with their dominant hand palm down lift three different weights 2.3, 4.5, and 5.7 kg a distance of 38 cm and also lift three different weights 1.1 kg, 2.3 kg, and 4.5 kg a distance of 63.5 cm. The lifting tasks lasted for one hour. The tasks as described were fatiguing to the shoulder and back but had little effect on physiological measures. The author observed that the degree of effort involved in a one-hand lift in the horizontal plane is not accurately reflected by physiological responses and the author also suggests that lactic acid build up in muscle and blood may be more useful as a possible index for fatigue from one-hand lifting tasks .

In the same year, Mital and Asfour, (1983a) added on to the work of Garg by using ten male test subjects who would stand and sit while lifting for two-hours rather than using females who would only stand while lifting for one-hour. The increase in duration time was done so that the results would better predict maximum acceptable frequencies for an eight hour work shift. Volunteers took part in an experiment designed to determine the maximum frequencies they could maintain for 2 hours while lifting in the horizontal–sagittal plane using the preferred hand. The psychophysical approach was used to determine the maximum acceptable frequencies of lift for sitting and standing postures at two reach distances. The study results showed that for two-hour lifting sessions the male subjects can maintain frequency of lifting equivalent to 51% of the maximum frequency acceptable to them for a 4 minute period .

Mital and Manivasagan, (1983) also conducted a study to determine the effects of container shape and volume on the weights people were willing to carry comfortably in one hand. Ten male and five female subjects carried loads of 8.5 and 12.3 liters that were packaged in four different shapes for 100, 200, and 300 feet. From a physiological standpoint, tasks where the arm was carrying the container were perceived as somewhat hard, but in terms of the whole body tasks were perceived as fairly light. Figure 2.12 illustrates how the rating of perceived exertion was higher in the arms and shoulders for both male and female subjects than it was for the back. The authors reported this was consistent with the findings of Garg and Saxena, (1982). Interestingly, the authors also compared their findings of the weight males were willing to carry in an 18 cm wide toolbox with what McConville and Hertzberg, (1966) suggested an acceptable lifting weight would be for an 18 cm wide object. The results were not close as¡ital and Manivasagan study participants carried 10.66 kg (23.5 lbs.) while the McConville and Hertzberg suggested weight based on their equation was approximately 23 kg (50.6 lbs.). Finally the authors noted that males comfortably carried 40 percent more weight than females 9.9 kg vs. 7.1 kg, some shapes due to their geometry are better suited for carrying, and ratings of perceived exertion for one-hand lifting tasks appear to be one-eighth of the heart rate rather than one-tenth of the heart rate which is the case for whole body tasks.

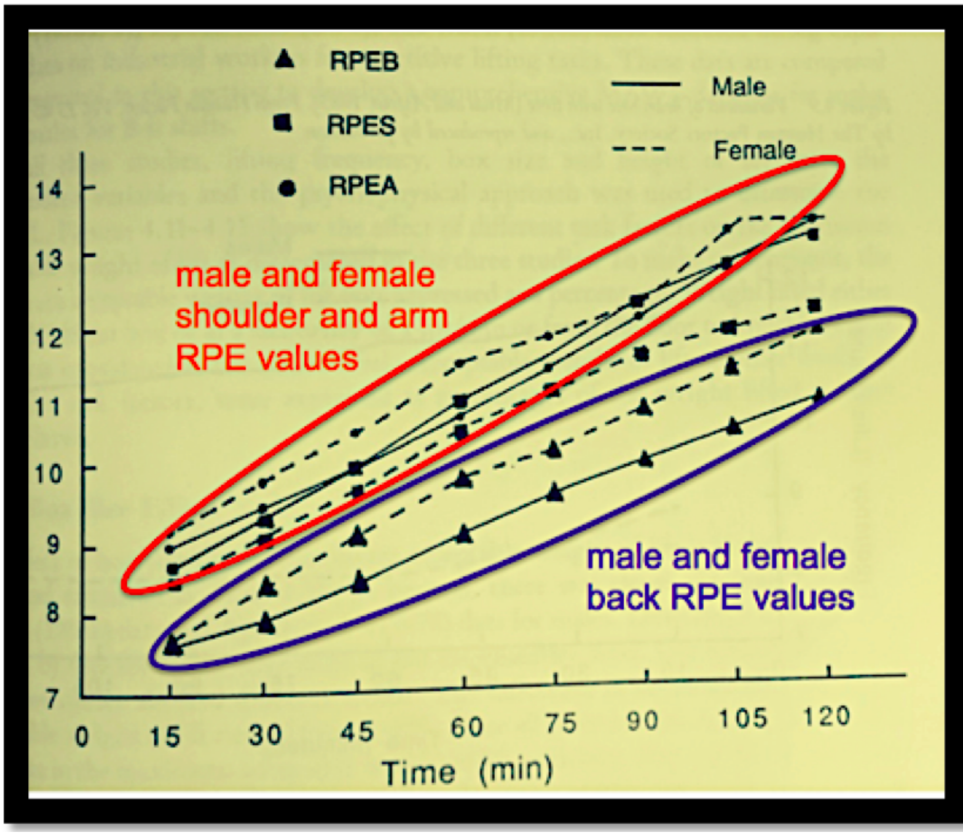

Figure 2.12: Rating of perceived exertion for the back, shoulders and arm vs. time [Mital and Asfour, 1983]

Legg, (1985) observed there are many different ways to carry loads and factors other than weight such as shape, size, and duration will influence the preferred method of carrying. Legg also observed from an energy expenditure perspective, that it is usually more difficult to carry loads in the hands or arms than to carry the load closely attached to the trunk as when using a backpack.

“Hand or arm carriage usually leads to local muscle fatigue rather quickly. Despite this, for convenience, over short distances or for intermittent load carriage, people will often choose to carry loads in their arms or hand”. Legg concluded his observations by noting that there is seldom a single ‘best’ way to carry a load.

Cook and Neumann, (1987) performed an EMG study of the lumbar paraspinal muscles during load carrying. Reported results showed that there was a significant difference between EMG activity and carrying position. With respect to one-hand carrying, EMG activity contralateral to the hand carrying the load was significantly increased. The authors observed that selection of carrying methods is important to reduce muscle activity in the back. The authors noted when comparing the results of an assisted one–hand lift versus the two–hand stoop lift technique the results of the study indicate that the assisted one–hand lift requires significantly less EMG activity than the two-hand stoop method when lifting loads out of deep containers. Results of this study seem to indicate that, under certain circumstances, the one-hand lift is a less stressful method of lifting than the two-hand stoop method.

Fothergill et al., (1991) described human strength capabilities during one–hand maximal voluntary exertions in the fore and aft plane in free–style postures. Twelve males and ten females participated in the study in which their free–style manual strength using their dominant hand was measured on a force bar set at heights of 1.0 and 1.75 meters. Twelve of the subjects also conducted two–handed exertions at the same handle heights. Results of the study showed that the ratios of one–hand to two–handed strengths ranged from 0.64 to 1.04. Two–handed strengths commonly exceeded one–hand strengths at the lower handle height, but showed fewer significant strength differences at 1.75 meters. The author‘s data showed regions in the fore and aft plane at both bar heights where the one–hand exertions actually exceeded the strength of two-handed exertions due to the greater freedom of postures available when applying force with only one hand.

Kilbom et al., (1992) looked at one-hand carrying and its effects on cardiovascular, muscular and subjective measures of endurance and fatigue. Figure 2.13 illustrates a fatigue relationship for men, plotting time vs. maximum voluntary contraction. The study population consisted of 5 women and 11 men who walked on a treadmill. Participants carried a weight in their right hand, which varied so that the participants experienced total exhaustion within 3, 5, 9, and 13 minutes. The authors concluded that cardiovascular and muscle criteria of fatigue in carrying coincided. Prolonged carrying in one hand of more than 6 kg for women and 10 kg for men should not be recommended.

Allread et al., (1996) investigated trunk kinematic differences of one–hand and two–handed lifts. Twenty–four right–handed male subjects performed every lifting condition which included lift technique, use of one or two hands, load asymmetry at the beginning of the lift (0, 45, 90, 135 degrees to the right of the mid–sagittal plane) and box weight (3.40, 6.80 and 10.20 kg). Data was collected via an electro-goniometer fitted to subjects' backs using a waist and shoulder harness. Figure 2.14 highlights the increased risk in suffering a back injury risk when there is increased asymmetry . The authors reported that one-hand lifting resulted in significantly higher ranges of motion in the lateral and transverse planes and greater flexion in the sagittal plane. Back motion characteristics observed to be associated with low back disorders were all significantly higher for one-hand lifts. The data suggests that unsupported one-hand lifting loads the spine more than two-handed lifts and can increase the risk of suffering a low back disorder.

Yoon and Smith, (1999) investigated the psychophysical and physiological response of study participants performing a combination of one–handed and two–handed tasks and applied these findings in order to develop prediction models for these tasks. In their experiment ten male participants were required to lift, carry, and lower an object with either one or two hands for three different frequencies (6, 1, and 0.2 handlings per minute) for one hour. Initial weights handled were up to 26 lbs. and 16 lbs. for two-handed tasks and one-hand tasks respectively. Results showed that the maximum acceptable weights of a one-handed task were 83, 75.2, and 76.3 percent of two-handed combined tasks at frequency rates of 6, 1, and 0.2 handlings per minute).

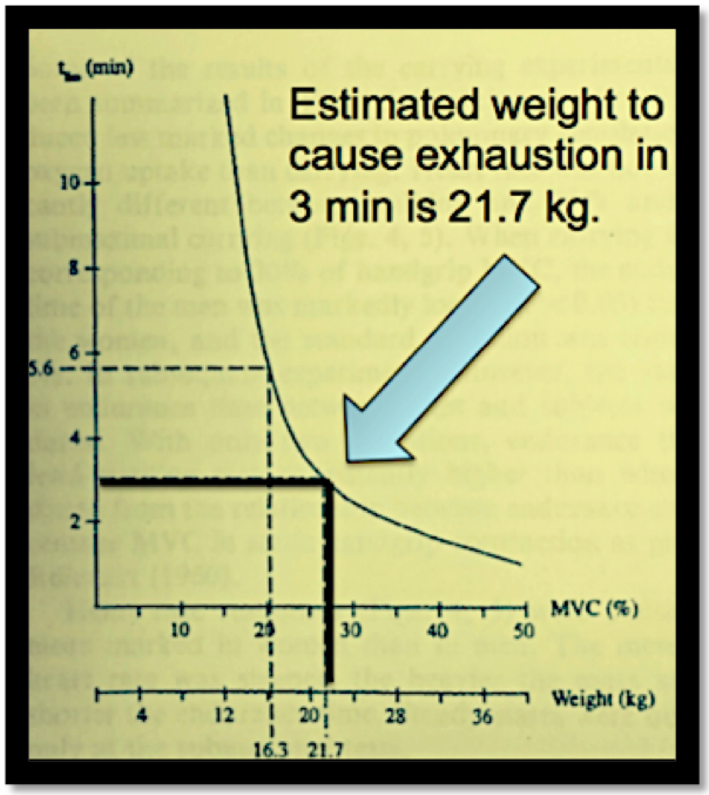

Figure 2.13: Fatigue relationship for men, plotting time vs. maximum voluntary contraction generated [Kilbom et al., 1992]

Marras and Davis, (1998) investigated how spinal loading develops during asymmetric lifting when the lift origin is to the left or right of the sagittal plane while using one or two hands to perform the lift. Ten male subjects lifted a 13.6 kg box in symmetric position in the sagittal plane (0 deg), 30 and 60 deg to the right of the mid-sagittal plane, and 30 and 60 deg to the left of the mid-sagittal plane. The results of the experiment showed that increased asymmetry corresponds to increased spinal loads when both hands are involved in the lift or if the lift was performed with one hand on the opposite side of the load reaching across the body. Lifting with the hand on the same side as the load did not increase loading significantly. Also, the authors observed that for a given asymmetry, lifting from the left of the sagittal plane resulted in greater mean peak spine compression.

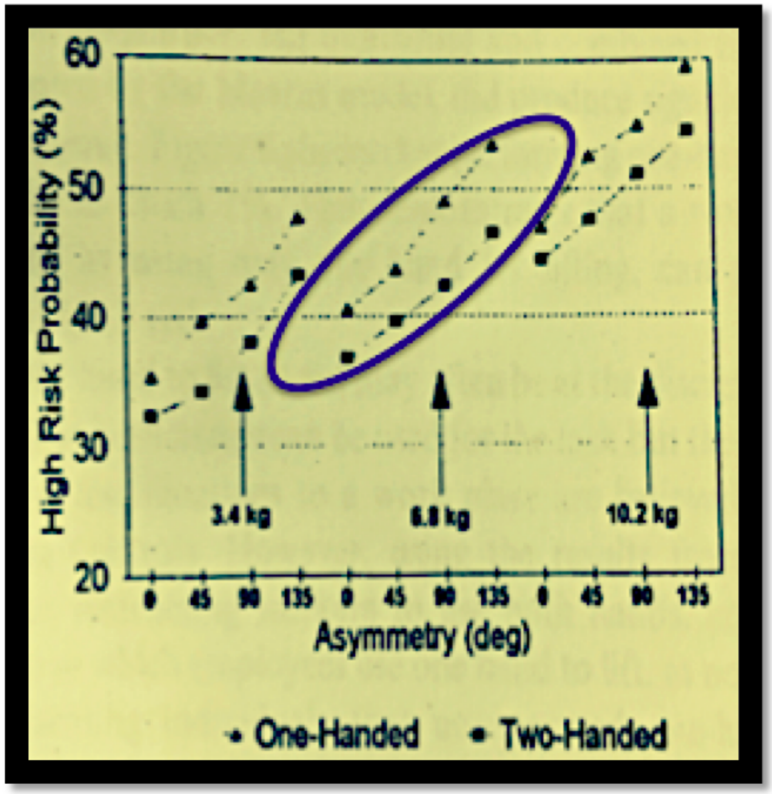

Figure 2.14: Increase in back injury risk probability vs. angle of asymmetry [Allread et al., 1996]

Ferguson et al., (2002) investigated spinal loading during lifting from an industrial bin. This study consisted of two phases. In Phase I, one hand versus two hand and standing on one foot versus two feet were examined when lifting an object out of a region in a bin. In Phase II, one–hand lifting styles with and without supporting body weight with the free hand on the bin, as well as the number of feet used when lifting and the region of the bin where the lift took place. Twelve male and twelve female subjects lifted an 11.3 kg box from the bin. It was observed that lifting from the lower regions or upper back region of a bin should be encouraged to use one–hand supporting lifting styles to minimize spinal loading.

Also, supporting body weight on the side of the bin with one hand reduces spinal loading by at least 15 percent therefore bin designs with a hand hold may facilitate workers using a supported lifting style that reduces spinal loading.

Kingma and van Dieën, (2004) also looked at one-hand lifting styles with and without the lifter supporting their body weight with the free hand. Ten males participated in the laboratory experiment in which they lifted a 15 kg load with one hand, two hands, lifting with one hand while bracing them self, or lifting with one hand while bracing themself while stretching one leg backwards over an obstacle. The results of the study show lifting technique significantly affected trunk kinematics for all three planes of motion. One–handed lifting resulted in more peak lateral flexion, more peak twisting, and less peak flexion as compared to two–handed lifting. The authors also observed that one-hand lifting, especially with hand support, reduces L5-S1 loading but increases asymmetry in movements and moments about the lumbar spine.

Jones et al., (2013) revisited the idea of bracing oneself when performing some type of exertion typically associated with manual material handling. Specifically they looked at the effects of kinematic constraints and associated bracing opportunities on isometric hand force. In the study, twenty–two right–handed men and women performed one–handed maximal push, pull and lift tasks in the forward, backward, and upward planes while being afforded bracing opportunities. Studied bracing options were no bracing, hand only bracing, thigh only bracing, and hand and thigh bracing. The results of the one–handed maximal push, pull, and lift tasks demonstrated that bracing surfaces available at the thighs and the free hand enabled study participants to exert an average of 43 percent more force. Figure 2.15 contains a timeline of pertinent one–hand lifting articles.

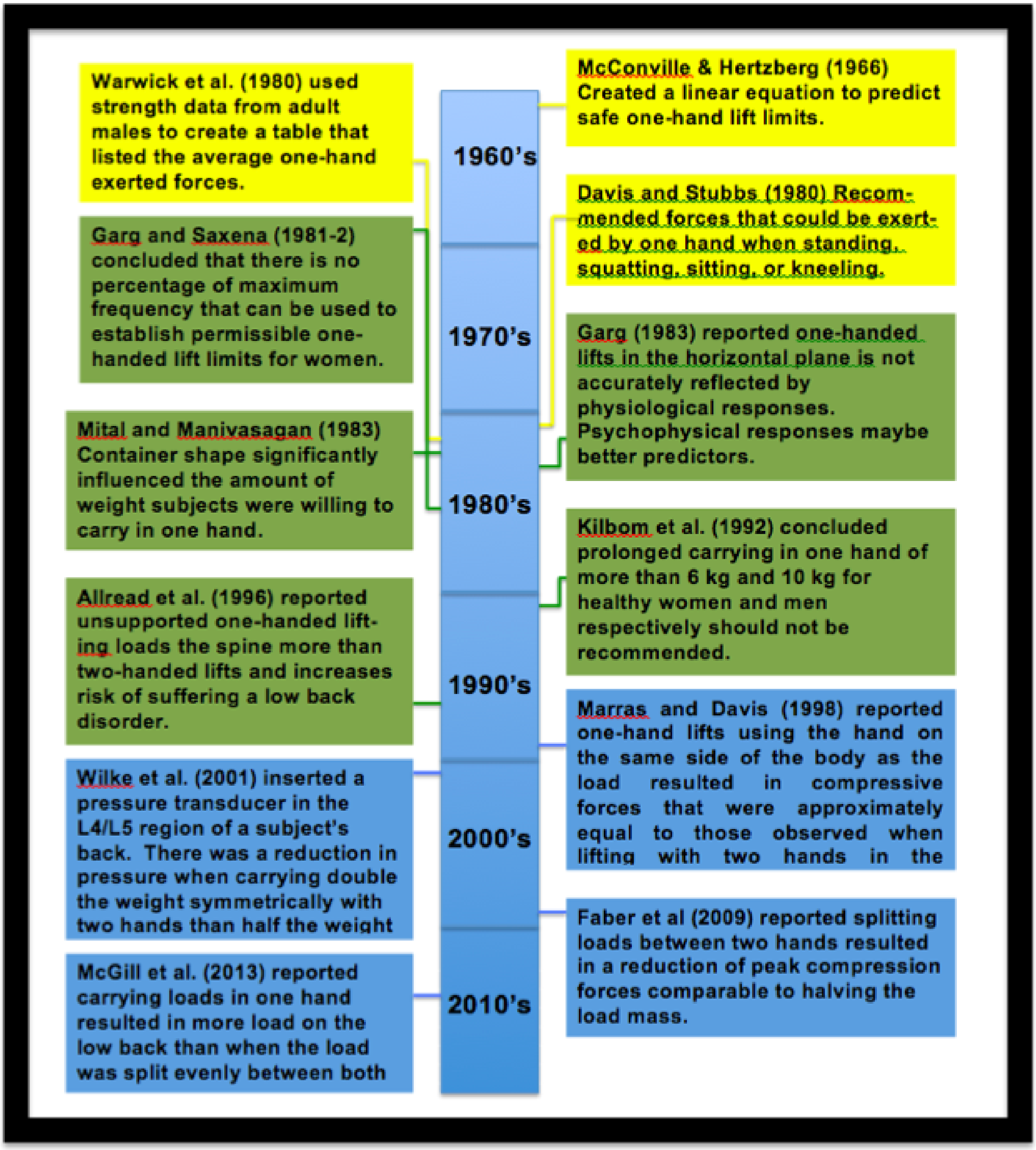

Figure 2.15: Timeline of selected one–hand lift research studies

2.8 Asymmetric Lifting

This section is not intended as a comprehensive literature review of asymmetric lifting but rather reports what was learned when conducting the initial one-hand lift literature search. Asymmetric lifting occurs when the hands are unable to share the weight of the object equally due to the object not being symmetrically shaped or the posture of the lifter is such that the hands cannot contribute equally to the lift. Based on this definition all one-hand lifts are asymmetric lifts. In the textbook Manual Materials Handling the authors feel asymmetric MMH tasks are the norm in industry and not the exception. They also report that; lifting asymmetrical objects is more stressful than lifting symmetrical objects and that the lifters inability to tolerate shear forces is the limiting factor to tolerate asymmetric MMH activities, [Ayoub, 1989]. Asymmetric lifting has been reported to increase the shear and compression loading on the intervertebral discs as well as low back and trunk muscle activity, [Anderson et al., 1985]. Anatomically speaking this makes sense since assuming a lifting technique that uses a neutral back posture will lessen the shear force on the spine.

A literature review focusing on one-hand asymmetric lifting yielded some interesting results, such as asymmetric lifting is not necessarily a bad thing. There has been some research focus on the benefits of lifting with one hand while bracing the body with the other hand. Cook et al., (1991) reports that under certain circumstances, the one-hand lift is a less stressful method of lifting than the two-hand stoop method. Ferguson et al., (2002) noted that a bin designed with a handhold might facilitate workers using a supported lifting style that reduces spinal loading. Kingma and van Dieën, (2004) compared two-handed lifting with one-handed supported and unsupported lifting. They observed that one-handed lifting, especially with hand support, reduces loading in the low back. This is similar to what Allread et al., (1996) reported, that increases in asymmetry increases the moments about the lumbar spine. Lastly, Jones et al., (2013) demonstrated that bracing surfaces available at the thighs and non-task hand enabled participants to exert an average of 43 percent more force.

However the majority of the literature reports that asymmetric lifting, via, hand or foot placement, twisting, or load distribution is detrimental to the health of the lifter. Marras and Granata, (1997a) looked at lateral lifting using an EMG-assisted model and observed that compressive loads on the spine were significantly influenced by lateral flexion angle and direction of motion. Compressive loads increased as the trunk was laterally flexed away from the direction of the applied lateral moment [Marras and Davis, 1998]. Another research article from the Ohio State University looked at one-hand and two-hand lift activities in three different asymmetric positions. For one-hand lifts the lifter had an increase in range of motion. This is not necessarily a desirable feature as the back motion characteristics known to put a lifter at greater risk for a back injury were higher for one-hand lifts [Allread et al., 1996].

Mital and Fard, (1986) investigated the effects of lifting symmetrical and asymmetrical objects symmetrically and asymmetrically. They collected psychophysical and physiological data including maximum acceptable weight of lift, heart rate, and oxygen uptake. They also interviewed subjects at the end of the experiment to get their opinion on preferred lifting style. Results indicate that subjects lifted 8.5 percent less weight when assuming asymmetrical postures and lifted 4 percent less weight when lifting asymmetrical loads offset by 10.16 cm (4 in) and 6.45 percent lesswhen offset by 20.32 cm (8 in). There was no difference in physiological costs when neither lifting symmetrically or asymmetrically nor was there a difference in physiological costs when lifting a symmetrically or asymmetrically balanced object. Of the eighteen research subjects none reported asymmetrical lifting was easier than symmetrical lifting. Also in the same year, Garg and Badger, (1986) considered maximum voluntary isometric strengths for two-hand asymmetric lifting. The maximum acceptable weights for asymmetric lifting were significantly lower when compared to sagittal symmetric lifts of different box sizes. Several years later Garg and Banaag, (1988) further investigated asymmetric lifting. Taking a physiologic approach the authors investigated the maximum acceptable weight, heart rate and RPE for repetitive lifting in the sagittal plane that took place in one hour. Maximum acceptable weight was significantly lower and heart rate and RPE were significantly higher in the asymmetric plane when compared to lifting in the symmetric plane. Also, not surprisingly, the authors observed that maximum acceptable weight was significantly lower and heart rate and RPE were significantly higher as asymmetry increased.

Mital, (1987) noted that the absolute effect of load asymmetry was smaller than other lifting effects such as lift height or frequency of lift. He concluded the effects of asymmetrical loads are small, yet they still need to be considered as an important element to reduce spinal stress and WMSD.

Wu, (2003) in an investigation of Chinese females, used a psychophysical approach looking at the effect asymmetric lifting has on maximum acceptable weight of lift. Heart rate, oxygen uptake and RPE were also measured. The maximum acceptable weight of lift decreased with the increase in the angle of asymmetry. However, the heart rate, oxygen uptake and RPE remained unchanged. Lee and Cheng, (2011) investigated the effects of asymmetric lifting on maximum acceptable weight lifted. Their results showed that asymmetric lifting with trunk rotation decreased maximum acceptable weight lifted by almost 10 percent.

Several EMG studies looked at the effect asymmetric loading had on the body. Andersson et al., (1977) investigated asymmetric loading of the straight back and lateral flexion of the back at 20 degrees were measured (back straight 100N left hand, back straight 100N right hand, back 20 degree lateral flexion 100N left hand, back 20 degree lateral flexion 100N right hand). During asymmetrical loading pressure values and myoelectric activity increased. The increase in myoelectric activity was comparatively greater on the contralateral side in the lumbar region than the ipsilateral side. Kumar and Davis, (1983) observed significantly higher intra–abdominal pressure and EMG activity in the erector spinae and external oblique muscles when lifting a 10 kg (22 lbs) load in lateral and oblique planes than in the sagittal plane.

In conclusion asymmetric lifting activities are more hazardous than symmetric lifting activities. To minimize risk, it is recommended to lessen shear force, avoid twisting when carrying a load and balance the load evenly.

2.9 Magnetic Resonance Imaging as a Modeling Tool

Proton nuclear magnetic resonance (NMR) detects the presence of hydrogen (protons) by subjecting them to a large magnetic field. The frequency of this proton "signal" is proportional to the magnetic field to which they are subjected during this relaxation process. In the medical application known as Magnetic Resonance Imaging (MRI), an image of a cross-section of tissue can be made by producing a well-calibrated magnetic field gradient across the tissue so that a certain value of magnetic field can be associated with a given location in the tissue. The history of Magnetic Resonance Imagery (MRI) goes back to 1937 when Columbia University Professor Isidor I. Rabi observed the quantum phenomenon dubbed nuclear magnetic resonance (NMR). He recognized that the atomic nuclei show their presence by absorbing or emitting radio waves when exposed to a sufficiently strong magnetic field.

In the 1950's, fifteen years after Rabis discovery, Herman Carr produced a one-dimensional MRI image as part of his research work while earning his PhD, he described the first techniques for using gradients in magnetic fields that led to the first example of magnetic resonance imaging. In 1960, Vladislav Ivanov may have been the first to invent an MRI imaging device, but a delay over decade long between his application and subsequent approval of his novel idea by the USSR State Committee for Inventions and Discovery left him behind the patent awarded to Raymond Damadian in 1974.

In 1971, Damadian, (1971) proposed that tumors and normal tissues can be distinguished in vitro by nuclear magnetic resonance, which could create a visual method for the diagnosis of cancer. One year later Damadian proposed the concept of MRI in a patent application and in 1974 was granted the first patent in the field of MRI for the concept of nuclear magnetic resonance for detecting cancer. What is interesting is that the patent granted to Damadian was granted for a process on how to detect cancer rather than how MR images would be produced.

On July 3, 1977 the first MRI body scan of a human being was performed and reported in the literature [Damadian et al., 1976]. The process used by Damadian was long, the first whole body scan took nearly five hours and the images were not particularly clear. Over the next few years MRI technology we associate with current practices would be improved. In 1973 Paul Lauterbur expanded on Carr's technique and developed a way to generate the first MRI images, in 2D and 3D [Lauterbur, 1973] and the first cross-sectional image of a living mouse [Lauterbur, 1974]. Later in the 1970's, Peter Mansfield, developed a mathematical technique that would allow scans to take seconds rather than hours and produce clearer images than Lauterbur had created. Later in the 1970's a team led by Scottish professor John Mallard built the first full body MRI scanner at the University of Aberdeen, and on August 28, 1980 they used this machine to obtain the first clinically useful image of a patient's internal tissues using MRI. Mallard and his team are credited with technological advances that led to the widespread introduction of MRI and how we use it today. MRI in a research setting has been in use since the 1970's but its use was not widespread.

Key-wording the acronym MRI into the search function for the journal Spine, revealed that on average MRI was used or cited four times a year in the 1970's, nine times a year in the 1980's, twenty-one times in the 1990's, twenty-six times in the 2000's and twenty-seven times in the 2010's. This increase in the use of MRI as costs lowered and image quality improved demonstrates a willingness of researchers to use MRI as a viable tool to better understand the body. In the late 1980's the use of MRI as a tool in the development of a back model started to take root. Prior to this time computed tomography (CT) scans were the method of choice, for instance Reid et al., (1987) used CT scans to develop regression equations for the prediction of the cross-sectional area of the rectus abdominis, psoas, and erector spinae, and the moment arm of the erector spinae. A big advantage for researchers to use MRI over

CT is that CT uses ionizing radiation, which is hard to justify using on healthy individuals whereas MRI uses (at this point) harmless radio waves. Before the decade came to an end, Tracy et al., (1989) took MRI's of 26 males to measure the position and cross-sectional areas of the muscles of the lumbar region to develop a regression analysis. We see that by 1990 a safer way to generate information on the deep muscles of the body, and particularly the back, can be employed by researchers.

Since the work of Tracy et al., there have been many researches who have used MRI technology to better understand the deeper regions of the body and use this information to help develop either more accurate biomechanical models or better understand different populations so that more accurate models using these groups of people could be developed in the future. Wood et al., (1996) were one of the first to look at different populations previously lumped together as one group. They took traverse magnetic resonance images at the L4-L5 level of 26 males of varying body mass index to study multiple muscle groups in lean and obese people. From the MRI data, they were able to calculate cross-sectional area and moment arms for lean and obese groups of people and compare the two groups. Comparison of muscle parameters for lean and obese subjects revealed minimal differences. A few years after Wood, Hoek van Dijke et al., (1999) noted the usefulness of MRI. This technology allowed them to qualify 3-D coordinates of muscle attachments when data were restricted to qualitative descriptions or directions of muscle fibers when they developed their model of the lower back and upper legs.

Researchers at The Ohio State University began to explore the use of MRI in more depth. Marras et al., (2001), used MRI technology to calculate muscle cross sectional area from the T-8 to the S-1 vertebral levels. This information was tabulated for the right and left sides of the latissimus dorsi, erector spinae, rectus abdominis, external and internal obliques, psoas major and quadratus lumborum for both males and females. The authors noted gender differences of the cross sectional area. These gender differences can affect the prediction of muscle forces and internal moments in biomechanical models, and may need to be accounted for to improve the predictability of spinal loading. In the same year, Jorgensen et al., (2001), used MRI data to quantify male and female trunk muscle moment-arms relative to the spine from the T-8 to S-1 region of the back. The authors concluded males have, on average, 15.9 percent larger moment-arms than females. These gender differences indicate that female specific moment-arms may need to be used to improve the accuracy of biomechanical models investigating female spinal loading. Several years later, Jorgensen et al., (2003), in an effort to quantify the maximum anatomical cross-sectional area of the lumbar back muscles, took sagittal and transverse plane scans with the subjects lying on their left side at four different torso flexion postures. The researchers concluded that the maximum anatomical cross-sectional area was located between the L3/L4 and L4/L5 level in the neutral posture and that the anatomical cross-sectional areas at the L4/L5 and L5/S1 decreased during torso flexion. Ranson et al., (2006), investigated the use of magnetic resonance imaging and image processing software to determine the functional cross-sectional area of the lumbar paraspinal muscles. Through use of this technology the authors observed measurements that were repeated three times showing excellent reliability.

Through the use of MRI data, Guzik et al., (1996), demonstrated that biomechanical models of the low back should be based on task-specific and subject-specific muscle function and precise geometry rather than depend on the values listed in the biomechanical modeling literature. Mayer et al., (2013), used MRI's to assess changes in back muscles during lifts and the authors noted that changes in transverse relaxation time in the multifidus and erector spinae was greater for the stoop than squat. A recommendation from their research was to use MRI and other biomechanical techniques "to fully characterize lumbar muscle activity during lifts for various populations, settings, postures, and loads". Finally, Gungor et al., (2015), reported "improved biomechanical modeling of the lumbar spine may allow better evaluation of low back pain risk" and that more accurate biomechanical input data would better predict the forces acting on the spine. Through the use of MRI data, architectural design software and tracing software, the cross-sectional area of the erector spinae muscle can be easily and reliably measured. Figure 2.16 illustrates the end result of an MRI processed using architectural design and tracing software.

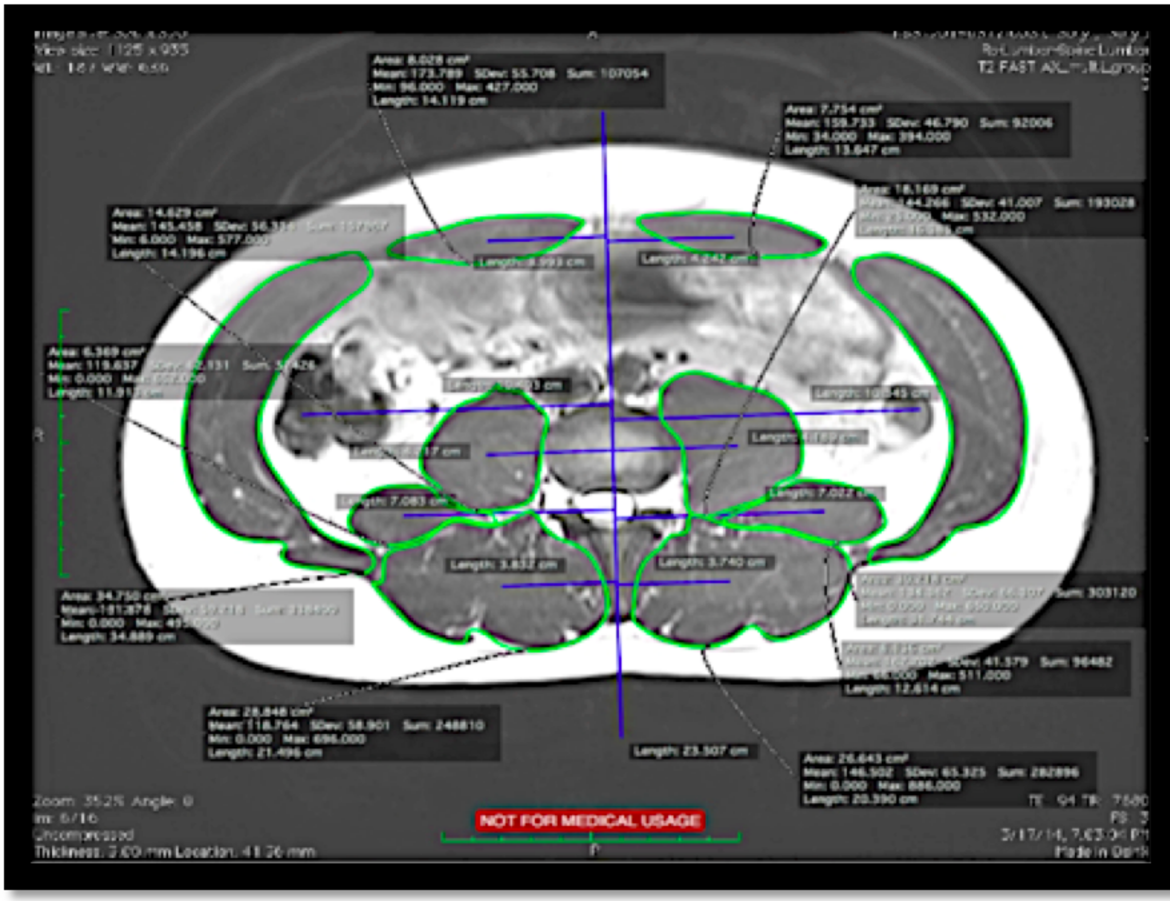

Figure 2.16: Example of an MRI scan processed using architectural design and tracing software

2.9.1 Summary of MRI Literature Search

The first MRI body scan took place in the 1970's and by the late 1980's, using MRI's was gaining favor by researchers over CT as a tool in the development of a back models as researchers realized they did not have to expose healthy individuals to ionizing radiation. Since then, MRI use as a research tool has rapidly increased as the costs have decreased and the image quality has improved. The literature shows many researchers who have used MRI technology to better understand the deeper regions of the body and used this information to help develop more accurate biomechanical models.

2.10 Co-Contraction

It has been established that the ligamentous spine is inherently unstable [Crisco et al., 1992], indicating that well coordinated muscle activity is required to maintain spinal stability. Co–contraction of the back muscles is required even in neutral upright postures because the passive structures of the spine are inadequate to maintain stability of the lumbar spine [Cholewicki and McGill, 1994]. Co–contraction, which is the simultaneous activation of the ipsilateral muscles, (antagonist) and the contralateral muscles, (agonist) around a joint can assist in maintaining spinal stability. Agonist–antagonist co–contraction serves to control the magnitude of an exertion or the speed of motion of limbs and increases the loading of joints. This activity provides joint stiffening, stability and controlled movement. The amount of muscle activation needed to ensure sufficient stability depends on the task, [McGill et al., 2013]. Generally for most day–to–day activities, an ordinary level of abdominal wall co–contraction is satisfactory. However, for tasks that require higher levels of muscle activity, co–contraction with the extensors and the abdominals will be necessary to ensure stability. Co–contraction can also substantially increase mechanical loads, such as increases in compressive and shear forces on lumbar spine. The ability of the muscles to partake in co–contraction is especially useful when performing asymmetrical tasks as these tasks are much more demanding than symmetric tasks, especially for the contralateral muscles. Contralateral muscles will exert extra forces in an asymmetric posture to compensate for the force exertion of antagonist muscles. In other words contralateral muscles are at a disadvantage during asymmetrical tasks and benefit from muscle co-contraction to maintain stability.

2.10.1 Lateral Flexion

Örtengren and Andersson, (1977) observed that for both a seated and standing subject, nonsymmetric hand loading resulted in EMG readings of the lumbar region being higher on the contralateral side of the erector spinae than the ipsilateral side. Yettram and Jackman, (1980) developed a linear programming model in which the total force of 171 muscle forces in the spinal column during lateral flexion where predicted. The activity level on the convex side was 141.4 N versus. 24.3 N on the concave side. Thelen et al., (1995) investigated the co–contraction of lumbar muscles in a variety of planes including lateral flexion. The authors noted that co–contraction was mostly dependent on the type of exertion and not on the subject preforming the exertion. Expected co–contraction muscles forces were 2-3 times greater during lateral bending activities. It was also observed that co–contraction is a major cause of spinal loading when performing lateral flexion. Lavender et al., (1995) investigated the effects lateral trunk bending had on eight trunk muscles. It was observed that the left and right external obliques as well as the left erector spinae had significant differences between a neutral and laterally bent posture. Faber et al., (2009) observed that low-back loading when lifting two loads beside the body compared to lifting one load in front of the body resulted in a decrease in abdominal co-contraction.

2.11 Modeling

2.11.1 University of Waterloo

McGill and Norman, (1987) observed that there has been an over-emphasis of the ability of intra abdominal pressure (IAP) to significantly reduce compressive loads on the spine. The low levels of abdominal activity observed, and which others have cited, leads the authors to conclude that there is not enough abdominal muscle activity to appreciably increase IAP levels high enough to significantly reduce compressive loads. Cholewicki and McGill, (1994) expanded on their previous work of an EMG Assisted Optimization (EMGAO) Model, which accounts for co-contraction patterns. They provided a simple 2-D example of individual muscle forces and the forces placed on the back in the L4/L5 region. A year later the authors compared their EMGAO approach with an optimization approach and an EMG approach to determine which model best predicts forces in the L4/L5 region. The authors conclude that there was little difference is the EMG and EMGAO methods but that the EMGAO had a smaller root mean square difference. Both EMG methods differed from the optimization method on average by 123 percent (RMS) for flexion and extension and by 218 percent for lateral bends [Cholewicki et al., 1995]. In an effort to predict low-back compression, McGill et al., (1996), suggested use of a polynomial equation that considered both muscle coupling and co-contraction. Compression can be estimated by inputting flexion-extension, lateral bending and axial twisting moments.

2.11.2 The Ohio State University

Granata and Marras, (1995b) observed that trunk extensor muscles generated lifting moments as much as 47 percent greater than the applied lifting moment to offset flexor antagonism. Further, the study showed that those biomechanical analyses that neglected muscle coactivity during dynamic lifting exertions might underestimate spine compressive force by as much as 45 percent and shear force by as much as 70 percent. In the same year the authors also observed that EMG-assisted modeling techniques may be employed to assess the biomechanical influence of trunk muscle coactivity that occurs during lifting as well as estimate the effects of motion induced muscle co–activity on spinal loading [Granata and Marras, 1995b]. Marras and Mirka, (1996) observed findings similar to McGill and Norman, (1987) suggesting that intra-abdominal pressure appears to be a by–product of trunk muscle co-activation. Marras and Granata (1997) evaluated spine loading during trunk lateral bending motions using an EMG-assisted model. Ten trunk muscle activities were used as input parameters. Muscle co–activation was observed in all lateral bends. Co–activation significantly increased during dynamic trials compared to the static trials.

Coactivity increased spinal loads by as much as 25 percent compared to values predicted by models that did not consider coactivity. Granata and Orishimo, (2001) observed through use of a 2–D model that muscle force in the abdominal and paraspinal muscles must increase with an increase in height of the external load. They noted that antagonistic co–contraction in the flexor muscles of the trunk increased in response to greater need for biomechanical stability.

2.11.3 Vrije Universiteit Amsterdam

deLooze et al., (1999) observed that abdominal muscles do not offer much of a contribution to peak spinal compression when lifting. The authors observed a relatively low abdominal contribution to compression when lifting with an increase in contribution towards the end of the lift. The abdominal effects mainly result from activation of the obliques. The activation of the external obliques was generally highest at the beginning of the lift and then declined, while the internal obliques was more active in the mid and end phase than in the beginning phase. The contributions could be retraced to the obliques rather than the rectus abdominis, while during the lift a shift in activation from the external to the internal obliques was observed. van Dieën et al., (2003) investigated if abdominal activity increases when handling unstable loads. The authors observed that abdominal co–activation increases when lifting an unstable load that weighed the same as a stable load and abdominal co–contraction during lifting helps provide spinal stability. van Dieën and Kingma, (2005) compared two methods of estimating spinal load. They observed that optimization based models which do not account for co–contraction of the muscles and EMG based models which take co–contraction into account, but usually assume equal activation of deep and superficial parts of a muscles yield fairly similar and closely correlated results.

2.11.4 Others

Researchers have observed that the inability of optimization approaches to predict antagonistic coactivity is recognized as one of the major shortcomings of this approach [Dreischarf et al., 2015]. This effect of neglecting antagonistic co–contraction on the L5–S1 spinal forces in a number of tasks was reported to be minor when comparing estimates of optimization and EMG based approaches [van Dieën and Kingma, 2005]. In contrast, others have reported much lower compression forces (23-43 percent) at the L4-L5 level when comparing optimization and EMG–based approaches [Cholewicki et al., 1995]. Takashima et al., (1979) observed that the cross-sectional area of the rectus abdominis, external obliques, internal obliques and transverse obliques all have an approximately equal area of 3.5 cm^2 and that the erector spinae muscles have a combined area of 48 cm^2. Also the maximum forces in resistance to lateral bending, rotation and twisting are 890 N and 130 N, respectively for each side of the erector spinae and rectus abdominis muscles and 420 N and 120 N respectively for the contralateral and ipsilateral oblique muscles. Hughes et al., (1995) used Karush–Kuhn–Tucker multipliers in an effort to estimate the effect of co–contraction of antagonist muscles on spinal compression forces. Co–contraction was modeled as an incremental increase in the lower bounds on the allowable muscle forces. The effect of co–contraction on spinal compression force was as high as 5.52 N additional spinal compression force for every additional N of muscle force. Kim and Chung, (1995) investigated the effect working posture, weight handled and frequency of lift had on trunk muscle (left and right erector spinae, left and right latissimus dorsi, left and right external obliques and left and right rectus abdomini) activity. They found significant differences in normalized EMG readings and body posture. Even though the relative muscle power of the ipsilateral muscles decreased during asymmetric tasks they still accounted for approximately 40 percent of the total muscle power. Further, the erector spinae and latissimus dorsi muscles were found to be most active in symmetrical lifting activities and the external obliques followed by the erector spinae and latissimus dorsi muscles were most active in asymmetric lifting tasks. The authors recommend that asymmetric body postures should be avoided and in cases where it cannot be avoided external loads should be placed on the opposite side of the lifters dominant hand. Lavender et al., (1993) investigated the effect moment application and twisting had on trunk muscle activation and co–contraction. The right erector spinae and left external oblique showed the greatest muscle activity in the study. Both of the muscles were more active than their contralateral counterparts. Also, four muscles, latissimus dorsi (left), erector spinae (left), external oblique (right) and rectus abdominis (right,) showed levels of activity similar in twisted and non–twisted postures. Their results coupled with other observations [(Pope et al., 1987) and (McGill, 1991) led the authors to conclude that co–contractions due to twisting are driven to stabilize the body rather than to generate torque and that biomechanical models that do not consider co–contraction underestimate mechanical loading of the spine.

2.12 Specific Aims

The broad aim of this research is to better understand the effect asymmetric lifting has on the low back and trunk muscles. Collecting anthropometric, muscle and lever arm information at the L-3 region of the back, muscle activity, and body position data it is anticipated that: (1) A biomechanically based model that can estimate the relative muscle contribution of each low back and trunk muscle during one-handed and asymmetric two-handed lifting activities can be developed; (2) A regression model that can estimate muscle size and mechanical lever arm lengths using easy to measure anthropometric measures such as height, weight, and Body Mass Index (BMI) can be developed; and (3) the "benefit" one could expect in reduction of back compressive forces when laterally lifting with two hands vs. one hand can be estimated. Ideally, this data can act as a basis for revising the one–hand lifting limits currently employed by the U.S. Army.

Chapter 3

Determination of the Best Predictive Model for One-Handed Lifts

3.1 Introduction

Work related musculoskeletal disorders account for a major portion of work-related injuries. Data from the Bureau of Labor Statistics reports that in the United States over 150,000 back injuries that involve days away from work occur each year. This accounts for over 17 percent of all cases involving days away from work in private industry [Bureau of Labor Statistics, 2016].

There is an abundance of research literature that focuses on two–hand manual material handling (MMH), especially involving; lifting, maintaining a neutral back posture, using two-hands and keeping the load in front of the body [Emanuel et al., 1956], [Snook, 1978], [Snook and Ciriello, 1991], [Waters et al., 1993], [Maiti and Ray, 2004], [Mayer et al., 2013] [Mohammadi et al., 2015].

However, a subsection of lifting tasks that has not been studied in depth involves one-hand lifting. Few studies have addressed the issue of one-handed lifting. For instance, Ayoub and Mital in their textbook noted that they were only able to identify eight studies which had addressed the problems of one–hand materials handling tasks [Ayoub, 1989]. A recent research article on one–handed lifting noted, "with a few exceptions, one-hand lifting has received no attention in the literature" [Kingma and van Dieën, 2004].

The limited amount of resources devoted to one-hand lifting does not seem to be justified as Garg (1983) indicated that he has observed and also received anecdotal reports from others that one–handed lifts in industry are a common occurrence. Fifteen years later Marras and Davis (1998) agreed with Garg's assertion by noting that one–hand lifts commonly occur in industry. For example, Kingma and van Dieën (2004) observed that workers are often forced to lift an object with one hand because the object in question only has one handle.

3.1.1 Measuring the Back's Response During One-Hand Lifting

Quantifying the effects one-hand lifting have on the body began over 50 years ago with the work of McConville and Hertzberg (1966) using a psychophysical experiment to determine a safe one-hand lift limit for Air Force personnel. Other researchers, [(Garg, 1983), (Mital and Asfour, 1983a), (Legg, 1985) and (Kilbom et al., 1992)], have used psychophysical and physiological methods to estimate one-hand lifter capacity but not the forces acting on the back.

There are few examples in the literature where back compressive force (BCF) was measured during one-hand lift activities. Often, other means were used to compare how performing one-hand or two-hand lifts influenced the forces acting on the back. Cook and Neumann (1987) investigated subjects walking while carrying loads at four different carrying positions, with one-hand lifting being one of the positions under consideration. Lumbar paraspinal electromyography (EMG) activity was measured and used to compare back muscle activity. Cook et al., (1991) conducted a dynamic comparison of two-hand stoop lifts and one-hand lifts where the free hand pushed down on the edge of a container. Differences in EMG activity of the lumbar paraspinal muscles were used to compare the different lift techniques.

Wilke et al., (1999) was able to measure intradiscal pressure by inserting a transducer directly into a healthy disc between the L–4/L–5 vertebrae in order to compare a one-hand carry of 19.8 kg and a two hand carry of 19.8 kg in each hand. The ability to measure intradiscal pressure directly did not necessitate the need to estimate BCF via a model or other estimating measures.

Ferguson et al., (2002) investigated spinal loading when conducting one–hand or two–hand lifts from a storage bin. The investigators estimated forces on the back using "a validated EMG-assisted biomechanical model". This appears to be the first mention in the literature of back forces estimated using EMG activity. Song and Chung (2004) used the same EMG-assisted model as Ferguson et al. (2002) to estimate trunk muscle co-activation during isometric exertion tasks. Jones et al., (2013) investigated the effect of bracing had on one-hand isometric force exertion during multiple MMH activities including lifting. The authors opted to only measure and compare hand forces during the performed tasks, no direct or indirect measures to estimate back forces during the lifting trials were made. McGill et al., (2013) investigated low back loads while walking and carrying: comparing the load carried in one hand or in both hands using EMG. The EMG signals were input to an anatomically detailed model of the spine to assess spine loading.

Biomechanical modeling of indeterminant systems varies significantly and there is no prescribed method for determining the relative pull of various muscles. There is no predominate method encouraged. Therefore, cross sectional area (CSA), moment lever arm length (MLAL), and combinations of each were investigated. Biomechanical experts encouraged trying a variety of measures to minimize investigator bias [Merryweather, 2016]. This resulted in consideration of CSA, MLAL, MLAL $\times$ CSA, and MLAL $\times$ CSA$^{1.5}$ weighted models.

EMG was used to compare back muscle activity for one-hand and two-hand lifts as well as an input for a model that estimates BCF. The work presented in this chapter uses EMG activity to determine how well four asymetric back models for BCF predict muscle tension in the erector spinae muscle group. Prediction of this muscle force is indicitive of overall model behavior. Each of the four developed models uses subject specific muscle geometry information such as CSA, MLAL, or a combination of CSA and MLAL [(Guzik et al., 1996) and (Gungor et al., 2015] to estimate how muscles will pull. The models also consider back muscle co-contraction [Granata and Marras, 1995a] to improve model realism and accuracy.

The aim of this research is to determine which of the four models under consideration bests predicts individual back muscle contribution and subsequent BCF during one-hand lifts to provide better estimations of BCF during asymmetric lifts.

3.2 Methods

3.2.1 Objective and Hypotheses

The objective of this experiment was to evaluate the most accurate approach to estimate back compressive forces by comparing the actual EMG values of each lifting trial with the model predicted EMG values for the erector spinae muscle group. Measures under investigation for approximating individual muscle contributions are:

1. Cross sectional area (CSA)
2. Mechanical lever arm length (MLAL)
3. MLAL $\times$ CSA
4. MLAL $\times$ CSA$^{1.5}$

It was assumed that models with the smallest absolute percentage difference between modeled and measured EMG forces were the best predictors.

The hypothesis of the experiment was that model performance would vary as a function of muscle contribution assumptions:

Null Hypothesis: No difference exists among predicted EMG values estimated using the various relative muscle contribution (RMC) assumptions.

$$H_0\text{: RMC EMG}_{CSA} = \text{RMC EMG}_{MLAL} = \text{RMC EMG}_{MLALxCSA} = \text{RMC EMG}_{MLALx(CSA)^{1.5}}$$

$$H_1\text{: RMC EMG}_{CSA} \neq \text{RMC EMG}_{MLAL} \neq \text{RMC EMG}_{MLALxCSA} \neq \text{RMC EMG}_{MLALx(CSA)^{1.5}}$$

3.2.2 Experimental Design

A within-subjects design was used to compare the four models. There were 358 total trials (10 subjects x 36 trial per subject less 2 trials where all EMG data was not completely processed by the software. This resulted in gaps where no muscle activity was recorded.) available for comparison. For example, the estimated EMG activity using the CSA weighted model for Subject 1, Trial 1 was compared to:

- the estimated EMG activity using the MLAL weighted model for Subject 1, Trial 1
- the estimated EMG activity using the MLALxCSA weighted model for Subject 1, Trial 1
- the estimated EMG activity using the MLALxCSA$^{1.5}$ weighted model for Subject 1, Trial 1

Each trial was rank ordered on a 1-4 scale with 1 assigned to the best performing model. Each subject performed thirty-six lifting trials (six symmetric and thirty asymmetric). Inferential statistics were used and can be found in Section 3.3.2.

Independent variables for this experiment were:

- Weight lifted by each hand
- Muscle effective mechanical lever arm length
- Assumptions regarding relative muscle contribution (e.g., CSA $\neq$ MLAL $\neq$ MLALxCSA $\neq$ MLALxCSA$^{1.5}$ weighting)

The dependent variable were:

- EMG activity at the left and right erector spinae muscle group

Controlled variables for this experiment were:

- Two adjustable dumbbells with a handle length of 10 cm
- The load was carried at the side of the body, with the center of mass at the handle
- A lifting trial was deemed acceptable if all of the following were met: shoulders were not raised, load was kept to the side of the body, and the torso remained in a neutral posture
- Lift duration met the 5 second minimum threshold.

The Auburn University Internal Review Board (IRB) approved the study protocol on October 31, 2015 [Auburn University, 2015b]. Approval notification documents can be found in Appendix B and Apprendix C. Once IRB approval was secured, recruitment for the study commenced. A sample flyer used to solicited interest in the study is included in Appendix D. Ten volunteers from the Auburn University student population that met the experiment inclusion criteria, including the ability to safely undergo an MRI procedure, were selected to participate in the study. The screening form used to determine if a participant met eligibility requirements is included in Appendix E. Each subject was consented using the approved IRB consent form, which can be found in Appendix F. Subjects also consented to be photographed during the lifting trials. Approved Samuel Ginn College of Engineering Photo Release forms for participants whose photograph was used can be found in Appendix G. Although "AU policy allows for the use of student photgraphs without consent if they are perfoming tasks associated with school activities" [Killian, 2016], fellow graduate students whose photographs were used during data collection also filled out photo release forms. These can also be found in Appendix G.

3.2.3 MRI Procedure

Participants underwent an MRI procedure that captured all low back and trunk muscle groups at the L–3 region of the back. Figure 3.1 shows two AUMRIRC Level–3 certified personnel overseeing an MRI procedure. Subjects were placed in a neutral lying position (supine posture) on the scanner bed and instructed to keep their body straight. A view of a subject in the MRI tube can be seen in Figure 3.2.

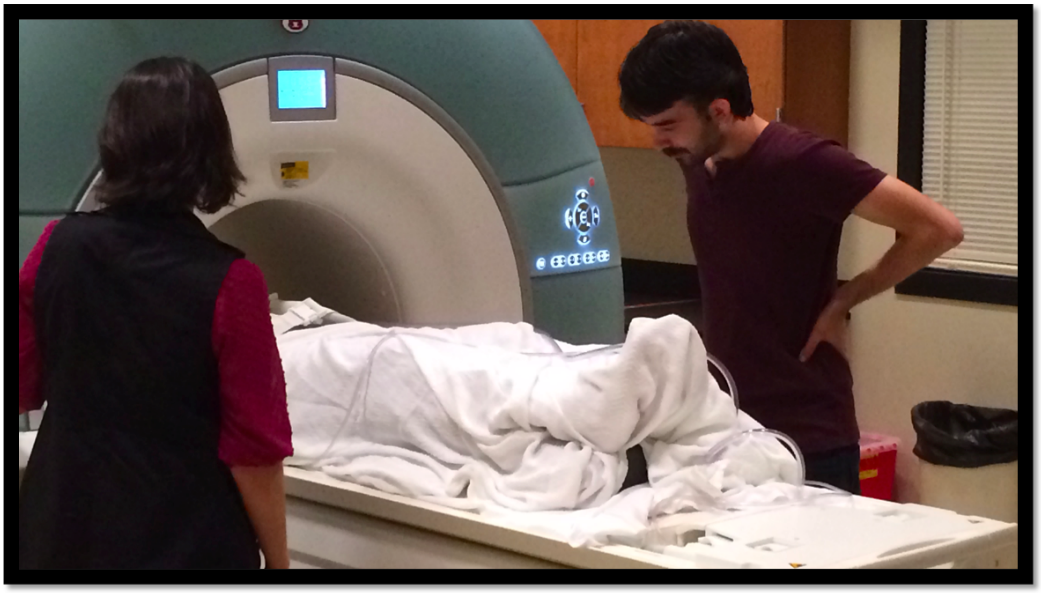

Figure 3.1: Participant Entering MRI Scanner

Figure 3.2: Participant in the MRI Scanner

Although the literature provides some guidance pertaining to subject positioning in the MRI scanner, additional guidance relating to subject positioning was given by an AUMRIC magnetic resonance physicist.

> “There is no clear right and wrong way to position the subjects. In most cases I would place “subject comfort” as a priority to avoid them from moving during the scan because they are distressed. In MRI there is a general safety rule to not have the hands touching each other since it may create an undesired “loop” pathway for the radio and magnetic fields through the body. This loop may result in radio frequency energy to resonate and possibly cause localized heating in the body. It turns out every person is different for what is comfortable for them, so you may need to be flexible to some extent. We always use the foam knee cushion to lift the knees for subjects that lie on their back. Pillows may be added or substituted if needed. We have many shapes of foam widgets that you can use. Based on your experiments objectives you may need to try different options to see what works best for good data and good comfort” [Beyers, 2016].

Based on this information, participants were informed of the undesired effects touching their hands could have and were instructed to keep arms at their side. A padded wedge was placed under participants knees, and pillows, if requested were added if participants felt it would increase their comfort and minimize movement during the MRI procedure. The data collector had the option to reposition a subject if they felt the current position would not yield accurate scans of the back. A localizer scan (preview scan) was performed to verify the image being scanned was suitable, if so an axial contiguous scan from the L–1/L–2 to the L–5/S–1 region of the back was performed. An example of a localizer scan is provided in Figure 3.3. An example of an operator performing an MRI scan is included in Figure 3.4.

A single image from the axial contiguous scan located at the center of the L–3 disc was used for further analysis. MRI procedure order was based on subject and AU MRI Research Center (AUMRIRC) availability. MRI procedure order is shown in Table 3.1. At a minimum two graduate assistants participated in the MRI data collection at the AUMRIRC to comply with AUMRIRC protocol of at least two Level–3 certified personnel operating the MRI scanner.

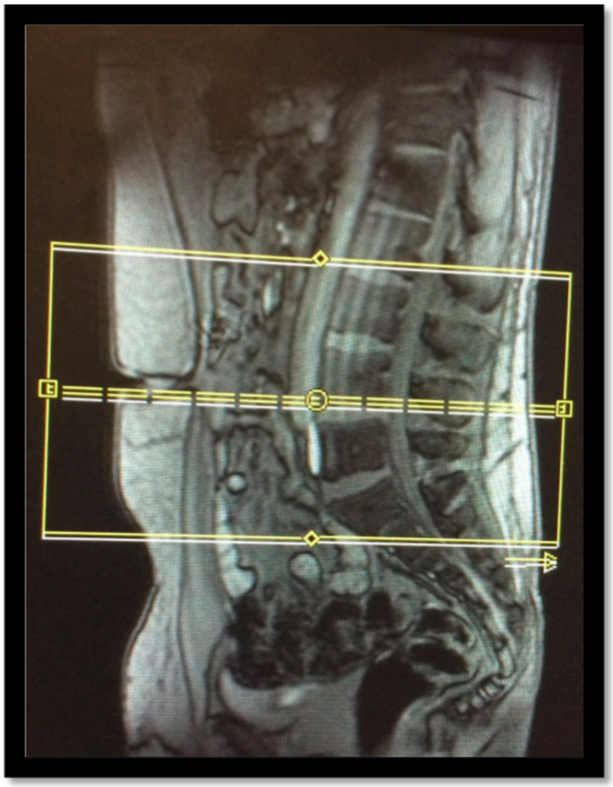

Figure 3.3: Example of a Localizer Scan

Figure 3.4: Operator Performing an MRI Scan

Table 3.1: MRI Procedure Order

Scan Order	Subject Number
Scan 1	M001
Scan 2	M004
Scan 3	M002
Scan 4	M007
Scan 5	M005
Scan 6	M006
Scan 7	M009
Scan 8	M010
Scan 9	M003
Scan 10	M008

3.2.4 EMG Procedure

Four 3M Red Dot electrodes, two for each investigated muscle were placed on the muscle belly of the left and right erector spinae, parallel to the direction of the muscle fiber. The higher electrode was placed at a two finger width lateral from the spinous process of the L-1 with a center-to-center spacing of 2.0 cm [Stegeman and Hermens, 2007]. Furthermore, electrodes were placed according to the manufacturers application instructions. First, application sites were cleaned with isopropyl alcohol, dry, and free of any body lotions. In instances where excessive hair was present it was removed. The skin was then lightly abraded using 3M 240 grit sandpaper. After skin preparation the electrode was attached to the subject according to manufacturers instructions. Specifically, no pressing on the electrode stud occurred during electrode placement. After the electrodes were secured on the subject, two Noraxon sensors, one for each investigated muscle were placed to the side of each electrode. Double sided tape and a drop of super glue were used to secure the sensors. An example of sensor and electrode placement can be found in Figure 3.5. To ensure the sensors or electrodes did not move during the lifting trials a band of self-adhering tape was wrapped around the participants low back. Figure 3.6 shows an example of this. This procedure was recommended by the AU Kinesiology Department [Jagodinsky, 2015] and resulted in EMG signals being recorded during all lifting trials without having to reattach the sensors or electrodes.

Left and right erector spinae MVC measurements were taken for each subject before the lifting trials. The MVC test was conducted with the subject in the prone laying position on a bench. One research assistant applied a downward force to the subjects left and right scapula. A second research assistant applied a downward force to the subjects waist. Lastly, a research assistant student applied a downward force to the subjects left and right ankle. The subject was then instructed to exert as much force as possible to raise the trunk upward off the bench (back extension) and flex the knee upward. The subject's MVC test followed the guidance provided in the booklet the ABC's of EMG [Konrad, 2005] and later verified by the AU Kinesiology Department as being acceptable [Jagodinsky, 2015].

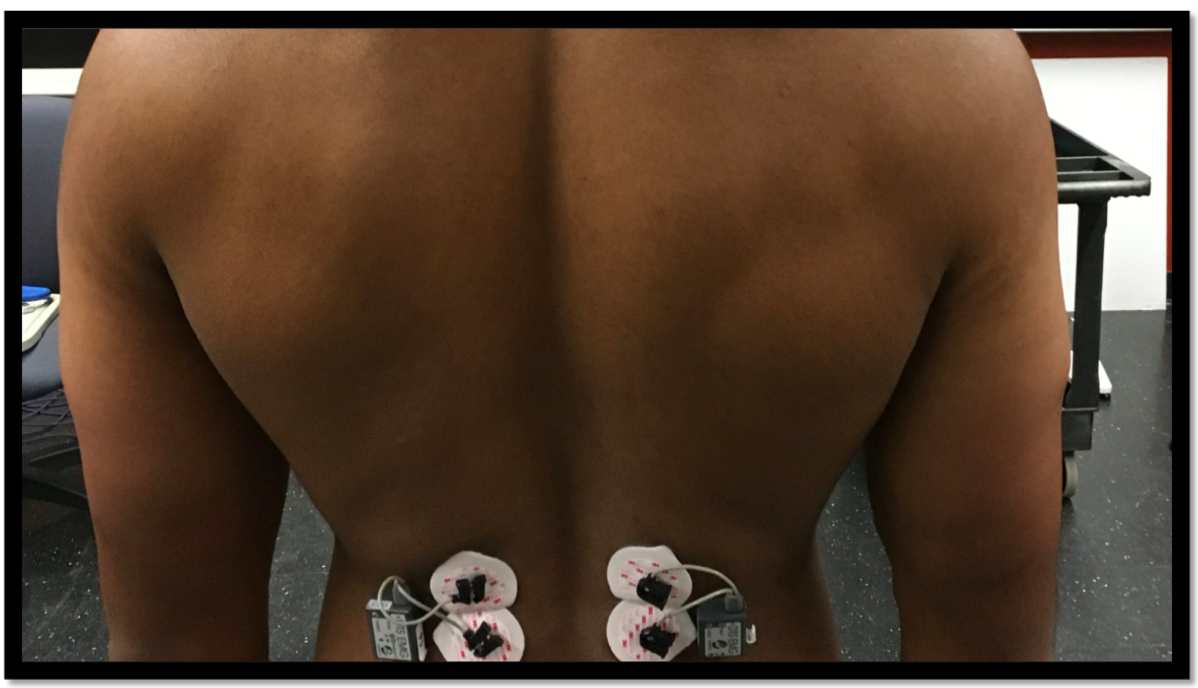

Figure 3.5: Example of Sensors and Electrodes Placed Near the Erector Spinae Muscles

Figure 3.6: Example of Self Adhering Tape Placed Over Sensors and Electrodes

All EMG signal processing and analyses were performed using custom LabVIEW software (version 2013, National Instruments, Inc., Austin, TX, USA). Specifically, the mean voltage value of the unprocessed EMG files was first subtracted to remove DC offset and the power spectral density of each EMG recording was examined to identify possible sources of interference (e.g., 60 Hz AC interference artifact or electrocardiogram). Transient artifacts were then attenuated using standard filtering methods [(Drake and Callaghan 2006) and (Redfern et al., 1993)]. Each raw EMG recording was then converted to an instantaneous root-mean-square (RMS) amplitude using a 50-sample moving window with a 30-sample overlap.

Figure 3.7 demonstrates the subjects position during the erector spinae MVC trial as well as the downward forces applied by the research assistants (white block arrows) and upward forces applied by the subject (black line arrows).

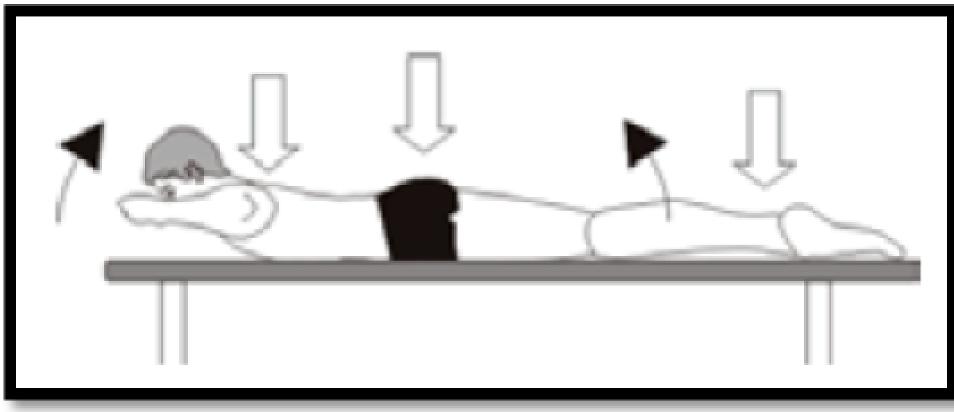

Figure 3.7: Erector Spinae MVC Posture

During the lifting trials, subjects were required to lift the weights for 5 seconds. A two second portion of the static hold time was chosen for data analysis since multiple systems were being used with no way of coordinating a 'true' start and end time for each system. Data used for analysis in this experiment were collected during a 2-4 second window of exertion within each 5-second lifting trial. The time period 0-2 seconds was considered as a loading phase, and 4-5 seconds as trial cessation (it was possible that nearing the end of each trial subjects could have anticipated unloading since they could hear the time being counted down). The 2-4 second window was viewed as the static maintenance phase [(Lehman and McGill, 2001) and (Marshall and Burnett, 2004)] and therefore used as a representation of muscular effort for the trial.

3.2.5 Xsens Procedure

Xsens is a data collection system that uses inertial measurement units and anthropometric data to create a biomechanical model of select body parts of interest [Xsens Technologies B.V., 2016]. Seventeen Xsens sensors were placed on the subject using straps and a harness so that a biomechanical model of select body parts of interest could be created, Figure 3.8 demonstrates a research participant being fitted with Xsens sensors. An image of a participants model created by Xsens is shown in Figure 3.9.

Figure 3.8: Participant Wearing Xsens Sensors

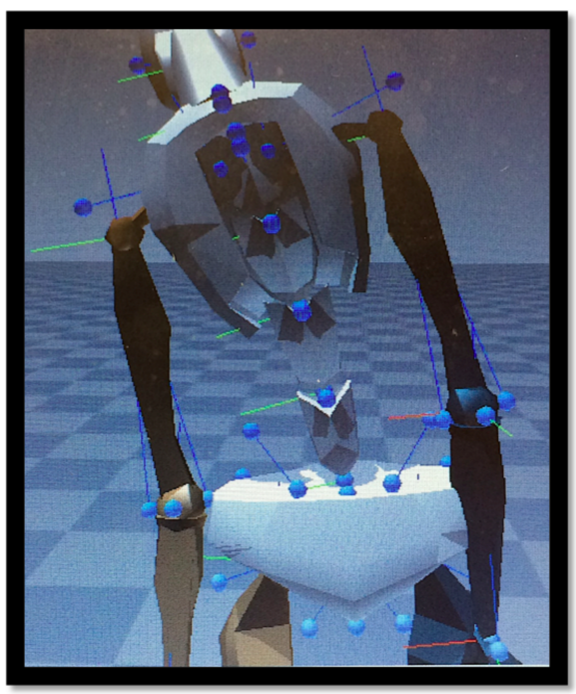

Figure 3.9: Xsens Model Created Using Participant Data

A listing of Xsens body part locations is provided in Table 3.2. The Xsens model provided an estimate of hand and back posture so that lever arms during weight lifting activities could be calculated and input into the muscle contribution model. Table 3.3 contains lever arms generated during Subject M010 erector spinae muscle calibration lifting trials.

Table 3.2: Xsens Sensor Body Part Location

Pelvis	R. Shoulder	L. Shoulder	R. Upper Leg	L. Upper Leg
Sternum	R. Upper Arm	L. Upper Arm	R. Lower Leg	L. Lower Leg
Head	R. Forearm	L. Forearm	R. Foot	L. Foot
	R. Hand	L. Hand		

Table 3.3: Lever Arms Generated by Xsens, Subject M010 Calibration Trials (cm)

Subject	**Weight**	**L Front**	**R Front**	**L Side**	**R Side**	**Flexion**	**Lateral**
M010	10 lbs.	18.34	25.53	8.37	13.47	9.94	-3.31
M010	20 lbs.	17.72	25.26	4.67	18.16	9.76	-4.16
M010	30 lbs.	16.30	24.15	3.86	14.33	15.48	-6.62
M010	40 lbs.	13.85	21.98	4.14	15.23	12.77	-4.66
M010	50 lbs.	17.99	24.48	3.15	15.64	12.28	-6.54

3.2.6 Lifting Procedure

Once a participant was equipped and confirmation of both the EMG and Xsens systems being operable, the lifting data collection portion of the experiment began. To ensure all subjects received the same instructions detailing how they were to lift during the experiment trials, each subject was read a script detailing how each lifting trial was to be performed. Once the subject indicated they understood all instructions they were asked to perform a test lifting trial with 20 pounds in each hand. The lifting trials would begin once the test trial was performed to the satisfaction of the lead investigator.

During the lifting data collection portion of the experiment all participants performed five calibration trials where they lifted 10, 20, 30, 40 and 50 pounds in each hand. In all instances, the order of the five calibration lifts was performed in order of lightest to heaviest weight. During the calibration trials all participants were instructed to keep the upper arms by their side and forearms bent at 90 degrees. The calibration trials were conducted so that a linear regression relationship could be established between EMG muscle activity and estimated muscle force. After the calibration trial, each subject was asked to conduct the same 36 lifting trials (6 symmetric and 30 asymmetric) with the order of trials randomized for each subject. Weights lifted in the trails ranged from 0–50 lbs. in increments of 10 lbs. The order of the thirty-six trials was randomly determined via a random number generator for each participant. At the completion of data collection, each subject had performed the same 36 lifting trials.

An example lifting trial is presented in Figure 3.10. A list of non-randomized lifting trials is provided in Table 3.4. A visual representation of all lifting trials in which the percent of MVC normalized EMG activity (left erector spinae muscle activity divided by left and right erector spinae muscle activity) is plotted against the difference in weight handled (weight in left hand – weight in right hand). As can be seen in Figure 3.11 the percentage of muscle activity of the left erector spinae muscle decreases as the difference in weight handled by the left hand increases.

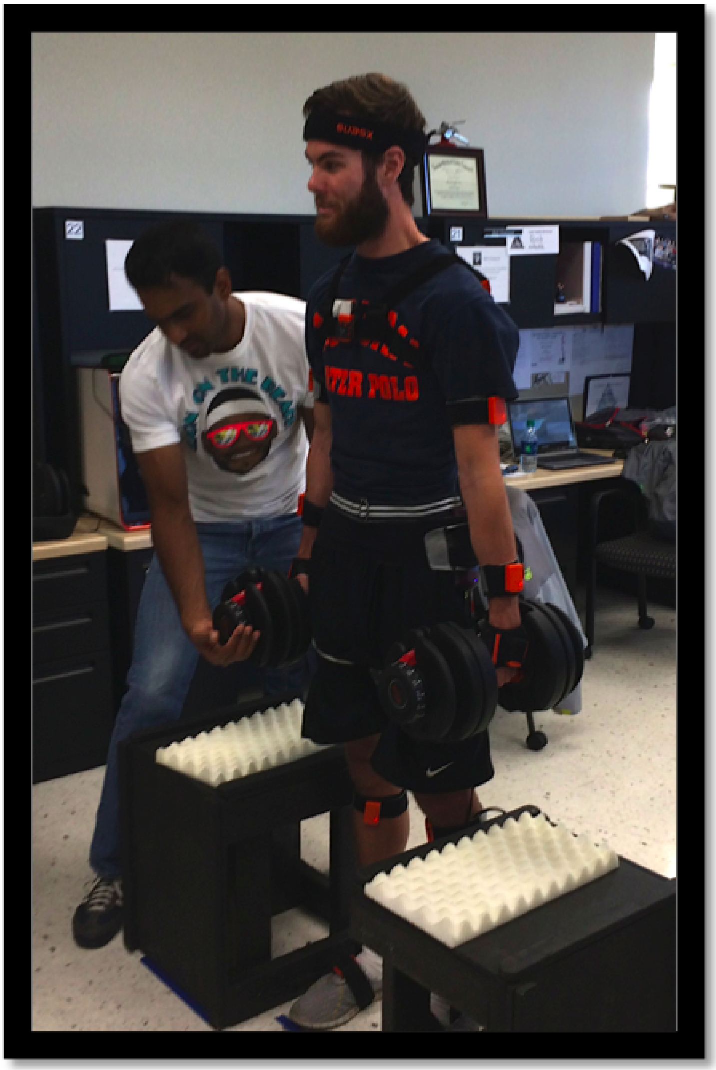

Figure 3.10: Lifting Trial Example

Table 3.4: Lifting Trials, Non-Randomized

		Left Hand					
		0 lbs.	10 lbs.	20 lbs.	30 lbs.	40 lbs.	50 lbs.
	0 lbs.	Trial 01	Trial 02	Trial 03	Trial 04	Trial 05	Trial 06
	10 lbs.	Trial 07	Trial 08	Trial 09	Trial 10	Trial 11	Trial 12
Right Hand	20 lbs.	Trial 13	Trial 14	Trial 15	Trial 16	Trial 17	Trial 18
	30 lbs.	Trial 19	Trial 20	Trial 21	Trial 22	Trial 23	Trial 24
	40 lbs.	Trial 25	Trial 26	Trial 27	Trial 28	Trial 29	Trial 30
	50 lbs.	Trial 31	Trial 32	Trial 33	Trial 34	Trial 35	Trial 36

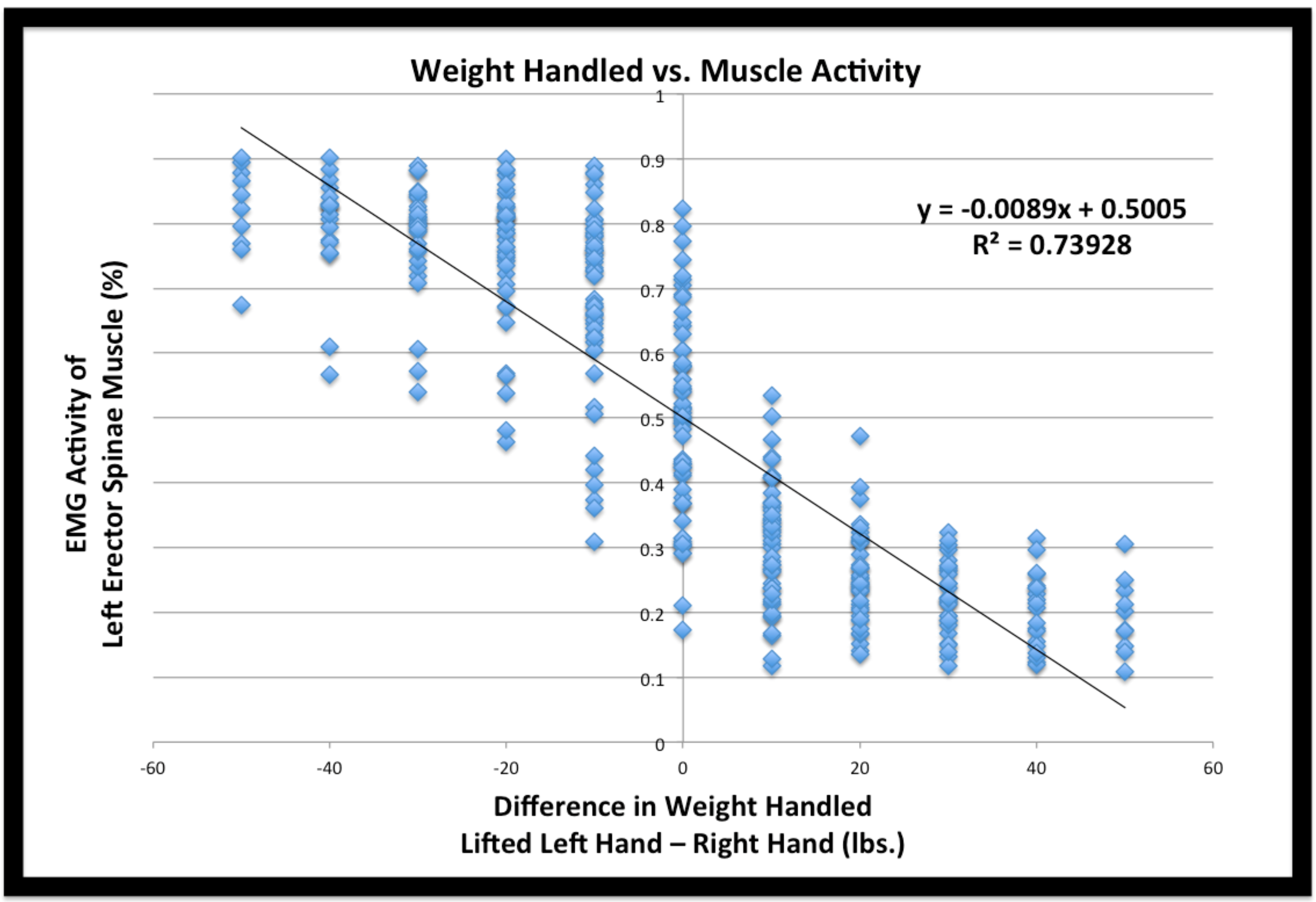

Figure 3.11: Muscle Activity vs. Difference in Weight Handled

3.2.7 Equipment

The following equipment was used for data collection:

1. Siemens Verio Open-Bore 3T MRI Scanner with lumbar coil
2. Noraxon EMG sensors
3. 3M electrodes
4. Double sided tape
5. Super glue
6. Self-adhering athletic tape
7. Anthropometry measuring kit
8. Skin calipers
9. Scale

The lumbar coil was used to improve spatial resolution around the spine. Additionally, two open source computer programs, OsiriX v4.0 and Open Source Computer Vision (OpenCV) were used to analyze MRI scans.

3.2.8 OsiriX

OsiriX is an image processing software package for medical research image processing applications. It has been specifically designed for navigation and visualization of multimodality and multidimensional images. OsiriX allows reference markers to be placed and measurements to be made on MRI images. It is dedicated to Digital Imaging and Communications in Medicine Images, i.e., .DCM extension, produced by MRI equipment [Rosset et al., 2004].

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3.2.9 OpenCV

OpenCV is a library of programming functions mainly aimed at real–time computer vision.

> "Computer vision is a field that includes methods for acquiring, processing, analyzing, and understanding images and, in general, high-dimensional data from the real world in order to produce numerical or symbolic information. This image understanding can be seen as the disentangling of symbolic information from image data using models constructed with the aid of geometry, physics, statistics, and learning theory" [Forsyth and Ponce, 2003].

OpenCV was used to biomechanically calculate structural dimensions from images marked using OsiriX. Muscle and disc centroids as well as MLALs were computed using OpenCV.

3.2.10 One-Hand Lift Model

A biomechanically based model to predict muscle forces of each muscle at the L–3 region of the back during symmetrical and asymmetrical lifting activities was developed. The model uses subject information collected from anthropometric measurements (height and weight), MRI scans (CSA and disc centroid to muscle centroid MLAL), EMG (left and right erector spinae muscle activity) and Xsens data (lever arm length from the L–3 region of the back to the left and right hand) during lifting trials. Specifically, the model predicted BCF from the resulting estimated muscle forces as well as body weight and dimensions. The developed model was created using the following assumptions:

- Muscle capability was set at 40N/cm^2
- Muscle pull cannot exceed its capability based on its cross sectional area
- Percent body weight over the L–3 is 48 percent of the entire body weight
- Co–contraction in the sagittal and lateral planes occurs to stabilize the core (estimated as percent of total muscle activation force)
- Lateral co–contraction due to unbalanced loads in the hands occurs (estimated from net moment of external loads)

Ideally, the predicted EMG values will align themselves with the recorded EMG values. The closer these values are the more accurate the models predictive ability is assumed to be. Predicting muscle force accurately still does not guarantee BCF calculations. Ideally, the predicted EMG values will align themselves with the recorded EMG values. The closer these values are, the more accurate the models predictive ability is assumed to be. Predicting muscle force accurately still does not guarantee BCF calculations, but it is the first step in developing an accurate model of asymmetric loading.

3.2.11 Statistical Analyses

A Chi–squared test was run to determine if the observed outcomes were significantly different than the expected outcomes for all rank order levels of the four models. A Chi–squared test was also run on each model to check for normality. A Wilcoxon signed-rank test was used to assess whether the models population mean ranks were statistically different from one another. Ryan–Joiner tests of normality were performed to determine if the muscle forces for all subjects and each individual subject were normally distributed ($\alpha = 0.05$).

3.3 Results

3.3.1 Descriptive Statistics of Subject Population

Ten students volunteered to participate in this study. Inclusion criteria included: being male, 25 years of age or younger, no prior history of back injury, and a Body Mass Index (BMI) of 30 kg/m^2 or less. The participants had a mean age of 22.8 years (SD=1.48), mean weight of 70.71 kg (SD=6.89), mean height of 178 cm (SD=7.21), and a mean BMI of 22.9 kg/m^2 (SD=2.77). Table 3.5 contains select anthropometric data for each study participant. Other anthropometric data collected includes: hip height, hip breadth, arm span, knee height, ankle height, shoulder breadth (bi-acromial), shoulder breadth (bi-deltoid), chest circumference, chest depth, neck circumference, waist circumference, abdominal depth, pectoral skinfold, abdominal skinfold, and thigh skinfold. In all, there are 15 anthropometric measures available for analysis. Tables 3.6 and 3.7 contain muscle CSA information for the muscle groups on the left and right side of the body respectively. These data were taken from MRI scans traced using OsiriX, Figure 3.12 shows a subjects processed MRI scan. Tables 3.8 and 3.9 contain mechanical lever arm lengths measured from the disc centroid to muscle centroid for muscle groups on the left and right side of the body, respectively. These data were calculated using MRI scans processed using OpenCV, Figure 3.13 shows a subject's processed MRI scan.

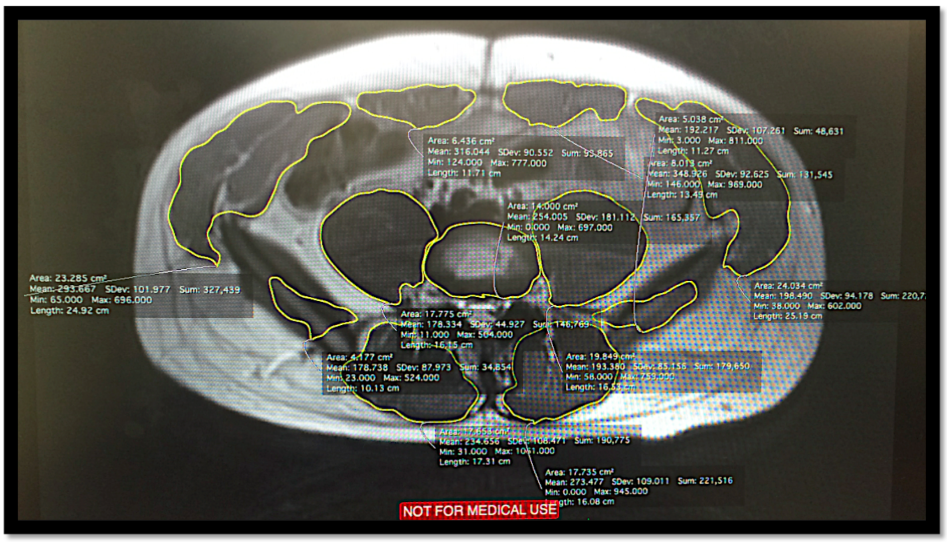

Figure 3.12: MRI with traced muscle groups and calculated CSA

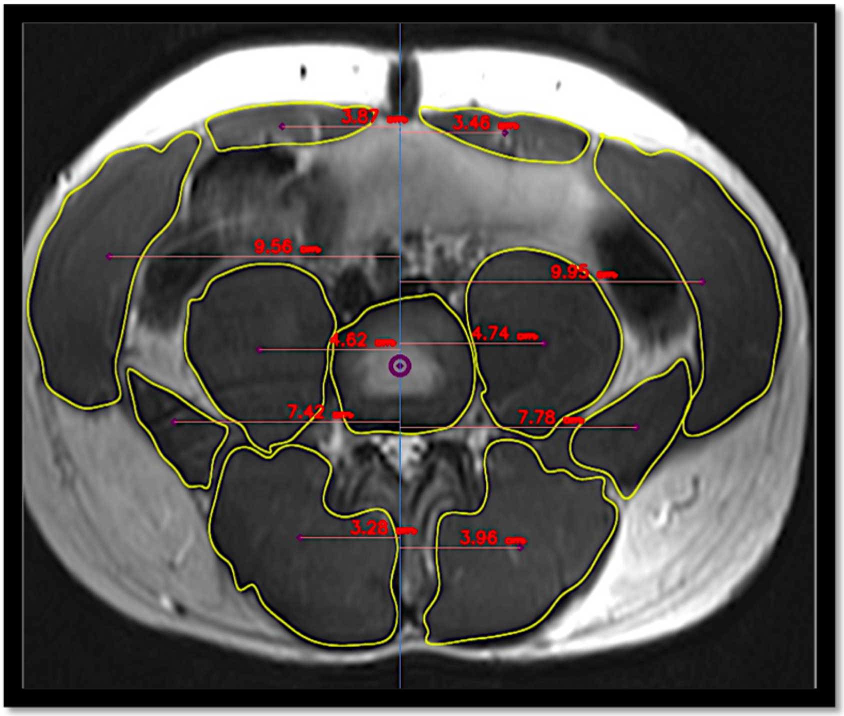

Figure 3.13: MRI with traced muscle groups and calculated mechanical lever arm lengths

Table 3.5: Selected Subject Anthropometric Data

Subject	**Age (yrs)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
M001	23	173	70.3	23.9
M002	25	177	74.8	23.9
M003	23	184	70.8	21.2
M004	25	175	65.3	21.8
M005	22	168	62.1	22.9
M006	23	170	69.9	24.9
M007	23	186	72.3	21.4
M008	20	187	73.3	21.8
M009	22	175	85.7	29.0
M010	22	185	62.6	18.7
Mean (SD)	22.8 (1.5)	178.0 (7.0)	70.7 (6.8)	22.9 (2.8)

Table 3.6: CSA, Left Muscle Groups (cm^2)

Subject	**L. Er. Spinae**	**L. Oblique**†	**L. Psoas**	**L. Rect. Abd.**	**L. Quad Lumb.**
M001	22.62	22.90	16.07	6.23	6.71
M002	23.67	22.47	19.96	7.66	2.35
M003	10.52	14.31	13.06	5.37	6.19
M004	19.16	26.94	13.23	5.93	5.22
M005	18.57	22.05	22.58	5.23	5.21
M006	17.65	23.29	17.78	6.44	4.17
M007	17.82	22.85	12.06	4.00	5.77
M008	27.03	24.99	15.46	6.52	5.19
M009	22.54	27.63	18.43	7.48	5.81
M010	27.67	22.34	12.77	4.81	7.11
Mean (SD)	20.73 (5.08)	22.98 (3.62)	16.14 (3.50)	5.97 (1.15)	5.38 (1.35)

† L. Oblique consists of the left internal oblique, external oblique and latissimus dorsi.

Table 3.7: CSA, Right Muscle Groups (cm^2)

Subject	**R. Er. Spinae**	**R. Oblique**†	**R. Psoas**	**R. Rect. Abd.**	**R. Quad Lumb.**
M001	26.14	20.77	19.81	6.72	6.18
M002	25.47	24.94	17.22	8.56	3.43
M003	9.95	13.75	14.58	6.24	5.47
M004	19.72	32.21	13.79	6.22	6.91
M005	19.73	22.23	22.02	5.38	7.75
M006	17.74	24.03	19.85	8.01	5.04
M007	18.12	25.15	13.22	4.51	5.97
M008	26.20	29.03	16.33	6.49	7.42
M009	23.75	28.57	16.46	7.95	6.60
M010	28.19	22.44	14.71	4.82	7.78
Mean (SD)	21.50 (5.52)	24.31 (5.12)	16.80 (2.93)	6.49 (1.37)	6.25 (1.36)

† R. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 3.8: Mechanical Lever Arm Length, Left Muscle Groups (cm)

Subject	L. Er. Spinae	L. Oblique†	L. Psoas	L. Rect. Abd.	L. Quad Lumb.
M001	4.09	11.44	4.56	4.53	8.27
M002	4.59	15.10	5.95	5.91	11.40
M003	3.47	14.39	7.39	4.38	10.26
M004	3.39	11.16	4.87	3.87	7.67
M005	3.28	9.56	4.62	3.87	7.72
M006	3.48	10.54	4.82	3.18	8.43
M007	3.45	10.38	4.54	3.26	7.46
M008	3.93	11.05	4.91	4.00	8.87
M009	3.68	11.13	4.72	2.69	7.03
M010	3.65	9.16	4.32	3.10	6.82
Mean (SD)	3.70 (0.40)	11.39 (1.92)	5.07 (0.93)	3.88 (0.93)	8.39 (1.45)

† L. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 3.9: Mechanical Lever Arm Length, Right Muscle Groups (cm)

Subject	R. Er. Spinae	R. Oblique†	R. Psoas	R. Rect. Abd.	R. Quad Lumb.
M001	3.81	10.55	4.36	3.40	8.82
M002	4.06	13.25	5.29	3.57	10.75
M003	2.06	12.73	6.14	3.72	9.00
M004	2.94	10.72	4.61	3.27	7.37
M005	3.96	9.95	4.74	3.46	7.78
M006	3.41	10.40	4.53	3.41	7.52
M007	3.26	10.01	3.75	2.74	8.02
M008	3.93	11.18	4.91	3.20	8.74
M009	3.64	12.53	5.25	4.18	6.91
M010	3.83	9.55	4.38	3.71	7.52
Mean (SD)	3.49 (0.61)	11.09 (1.30)	4.80 (0.65)	3.47 (0.38)	8.24 (1.12)

† R. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 3.10: Mechanical Lever Arm Lengths Recorded by Xsens, (cm)

Subject	**R. Er. Spinae**	**R. Oblique**[†]	**R. Psoas**	**R. Rect. Abd.**	**R. Quad Lumb.**
M001	3.81	10.55	4.36	3.40	8.82
M002	4.06	13.25	5.29	3.57	10.75
M003	2.06	12.73	6.14	3.72	9.00
M004	2.94	10.72	4.61	3.27	7.37
M005	3.96	9.95	4.74	3.46	7.78
M006	3.41	10.40	4.53	3.41	7.52
M007	3.26	10.01	3.75	2.74	8.02
M008	3.93	11.18	4.91	3.20	8.74
M009	3.64	12.53	5.25	4.18	6.91
M010	3.83	9.55	4.38	3.71	7.52
Mean (SD)	3.49 (0.61)	11.09 (1.30)	4.80 (0.65)	3.47 (0.38)	8.24 (1.12)

[†] R. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 3.11: Example Calibration Trials, Mechanical Lever Arm Lengths Recorded by Xsens, (cm) (Subject M009)

ID	**Trial Type**	**Trial No.**	**Weight 2 hands**	**Left Hand Hand to Back (in)-Mean**	**Left Hand Hand to Back (in)-Mean**
M009	Calibration	1	10 lbs.	9.784	9.533
M009	Calibration	2	20 lbs.	8.709	9.448
M009	Calibration	3	30 lbs.	9.967	10.037
M009	Calibration	4	40 lbs.	9.469	10.599
M009	Calibration	5	50 lbs.	9.330	10.738

3.3.2 Inferential Statistics

The literature suggests that even low levels of compressive load on the lumbar spine is enough for the back to recruit para–spinal muscle activation to maintain spinal stability

[Crisco et al., 1992]. The literature also notes that co–contraction of the back muscles occurs when lateral flexion takes place [(Thelen et al., 1995), (Lavender et al., 1995) and (Granata and Marras 1995)]. The amount of co–contraction that takes place during a lateral lift has been estimated to be approximately 28-32 percent [Marras and Granata, 1997] and as high as 32–57 percent [Thelen et al., 1995]. Due to these considerations, the one-hand lift model was run assuming a co-contraction value of 0.30 and a lateral "co"–contraction value of 0.10.

Assessing the accuracy of the four models when accounting for contraction was performed by considering only lateral "co"–contraction, only co–contraction, and both lateral "co"–contraction and co–contraction vs. absolute error. Considering only lateral "co"–contraction in each of the models from levels of 0.0 to 0.30, CSA weighted muscle contribution models were the best predicting models at all levels. A graph of all models at this contraction level can be found in Figure 3.14.

Considering only co–contraction in the models from levels of 0.0 to 0.30, there were three models that were the best. CSA weighted models were the best predicting models from 0.00 to 0.16, then MLALxCSA weighted models were the best predicting models from 0.16 – 0.21, and MLAL weighted models were the best predicting models from 0.21 to 0.30. Furthermore, after the 0.12 level, CSA weighted models progressively did a worse job in its predicting muscle forces, by the 0.30 co–contraction level, CSA weighted models were 66% worse than the best predictor, MLAL weighted models. A graph of all models at this contraction level can be found in Figure 3.15.

When considering both lateral "co"–contraction and co–contraction at multiple levels the MLAL weighted models are the best predicting models. They consistently have an absolute error of 10% and 19% less than the $LAxCSA^{1.5}$ and MLALxCSA weighted models, respectively. A graph of all models at this contraction level can be found in Figure 3.16. Due to the poor predictive abilities of the CSA weighted models at higher co–contraction levels, inclusion of the CSA in a model will negatively impact that models predictive ability.

It is unlikely any model using the CSA term will be the best predicting model.

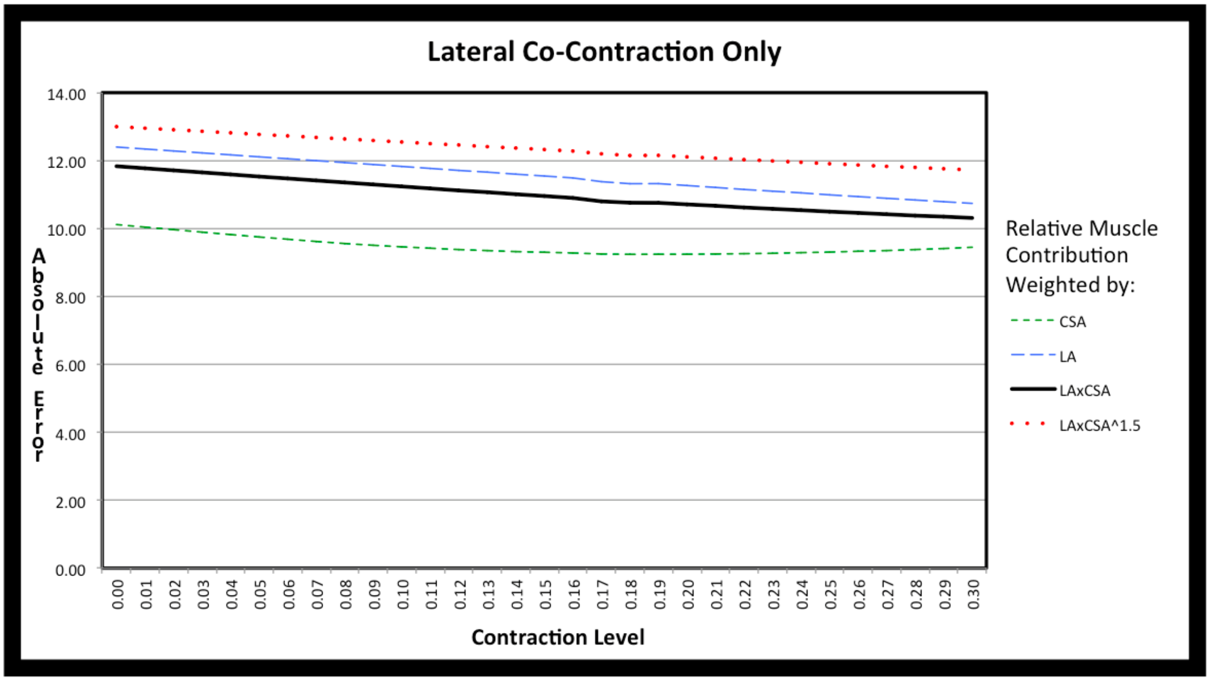

Figure 3.14: Absolute Error vs. Lateral Co-Contraction for All Models

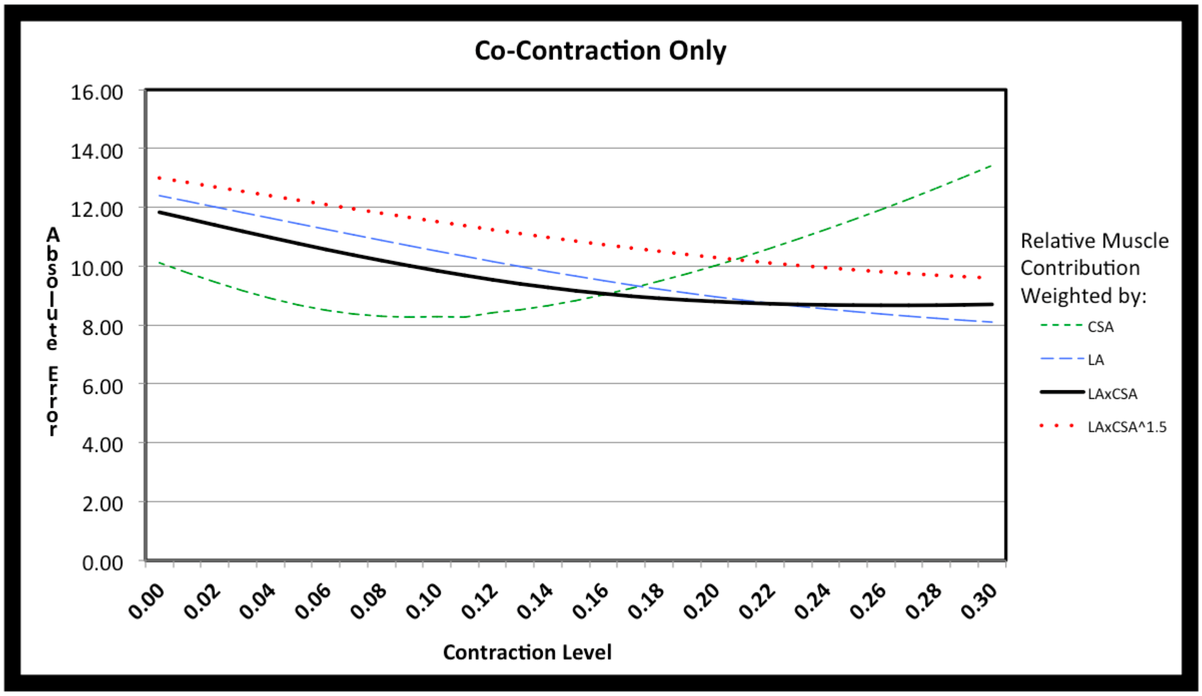

Figure 3.15: Absolute Error vs. Co-Contraction for All Models

Figure 3.16 demonstrates the effect co-contraction and lateral "co"–contraction levels have on each models performance when using absolute error as a basis for evaluation. The absolute average error of all models run at all trials at the specified contraction levels for Subject 1 can be seen in Figure 3.17. The absolute average error of all models run at all trials at the specified contraction levels for Subjects 1–10 can be found in Appendix H.

To evaluate the null hypothesis "No difference exists among predicted EMG values estimated using the various RMC assumptions", the output from the four one–hand lift models was assessed via multiple means.

First, each of the 358 trials (10 subjects x 36 trials/subject less two trials where EMG data was not viable) was ranked using a 1–4 scale in which 1 was assigned to the best performing model, 2 for the next best model, 3 for the third and 4 to the worse. In instances where two models performance was equal the rank order for the two models would be ranked with the same value. For instance if two models equally had the best prediction for a trial then their score for that trial would both be 1. The rank order for each model was tallied to see if one model consistently performed better than the others. The CSA model performed the best in 34 percent (122/358) of the trials yet it also performed the poorest in 60 percent (216/358) of the trials. Upon further investigation, two subjects accounted for 58 percent (71/122) of the instances where the CSA model was the best predictor. Rank order counts of running the model at the above specified values for all subjects during all trials can be found in Table 3.12.

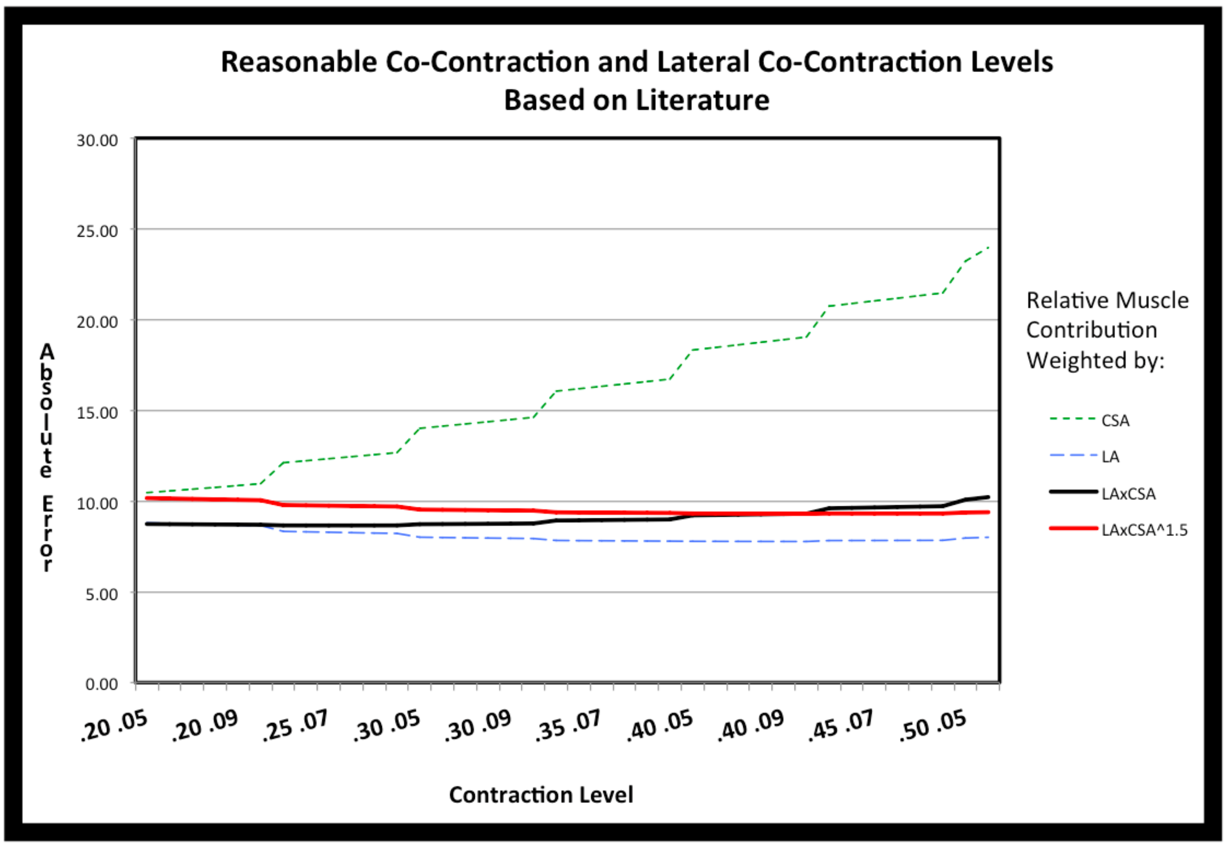

Figure 3.16: Absolute Error vs. Contraction Level at Different Contraction Levels

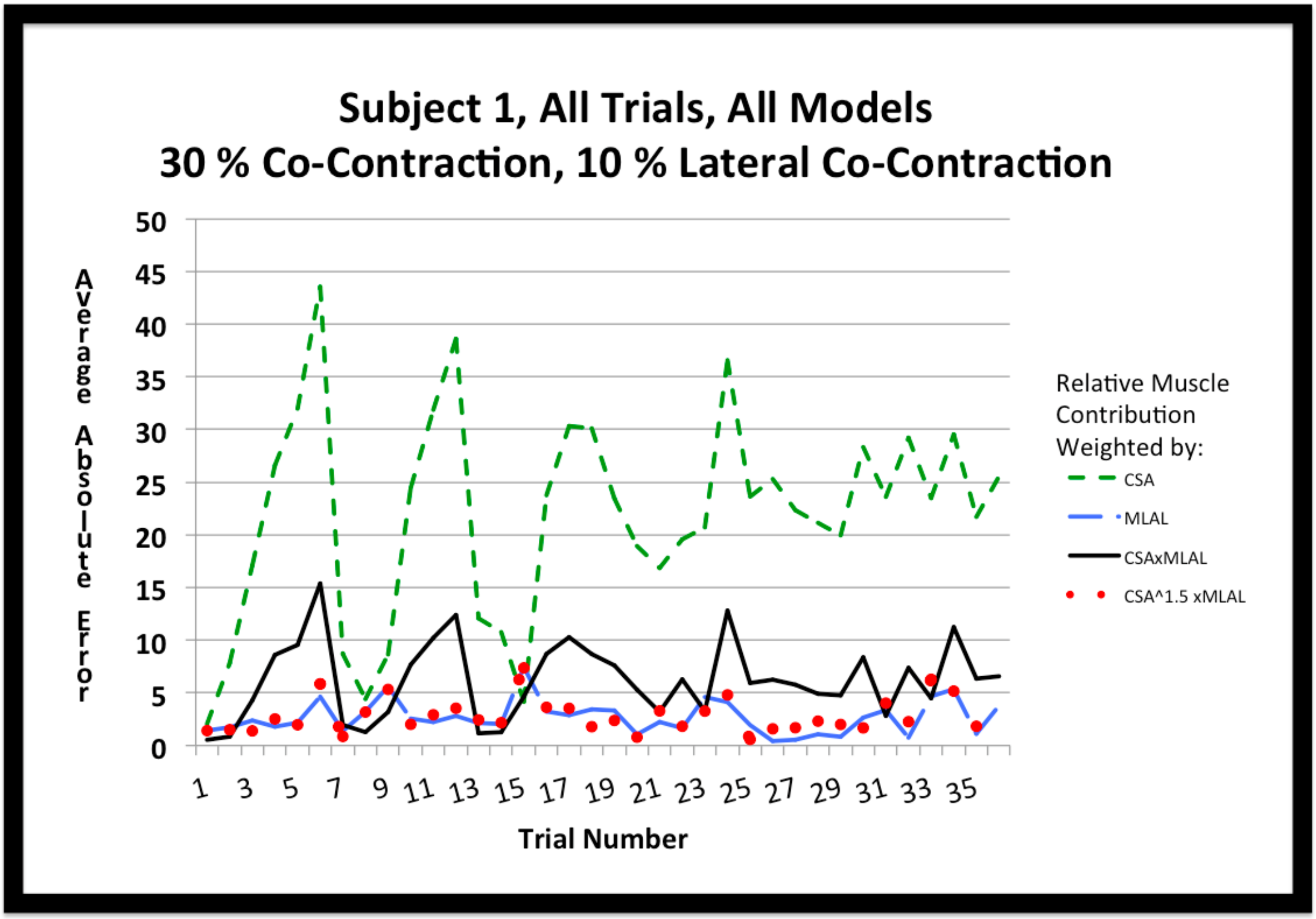

Figure 3.17: Subject 1, Average Absolute Error for All Trials, All Models

The average rank order was calculated by summing the trial ranks in each model and dividing by the total number of trials (358). Values closer to 1 will indicate the model in question is a good predictor of actual muscle force and therefore, a better input for comparing subsequent BCF. Values that approach 4 indicate the model did a poor job of predicting muscle forces. Two of the models, MLAL and MLALxCSA, appear to rank higher in their predictive abilities as their average rank order was 2.00 and 2.18 respectively, averages for CSA and MLALxCSA$^{1.5}$ were both 2.91. The average trail rank for each model can be found in Table 3.13.

Table 3.12: Trial Rank Order, Co-Contraction 0.30 and Lateral Contraction 0.10

Rank Order	**CSA**	**MLAL**	**MLALxCSA**	**MLALxCSA$^{1.5}$**
1	122	90	89	61
2	5	178	120	68
3	15	89	145	105
4	216	1	4	124

Table 3.13: Average Rank Order for Each Model, Co-Contraction 0.30 and Lateral Contraction 0.10

CSA	**MLAL**	**MLALxCSA**	**MLALxCSA$^{1.5}$**
2.91	2.00	2.18	2.91

A Chi–squared test was run to determine if the observed outcomes were significantly different that the expected outcomes for all rank order levels of the four models. Based on the Chi–squared test, it is not possible to determine if any one model weighting type out performs the others. Although the CSA model had the greatest number of number 1 rankings it did not exceed its expected count to the extent that it was a major contributor on the overall Chi–square statistic. However, the CSA model more than doubled its expected outcome for number 4 rankings. This lead to the highest contribution to the Chi-squared statistic. Based on the Chi-squared statistic it appears that CSA model is not the best predictor of BCF using RMC assumptions. Results on the Chi-squared test can be found in Table 3.14.

Table 3.14: Chi Squared Test on Model Rank Orders

Rank	**CSA**†	**MLAL**	**MLALxCSA**	**MLALxCSA$^{1.5}$**	**Total**
1	122	90	89	61	362
	90.5	90.5	90.5	90.5	
	10.964	0.003	0.025	9.616	
2	5	178	120	68	371
	92.75	92.75	92.75	92.75	
	83.02*	**78.356**	8.006	6.604	
3	15	89	145	105	354
	88.5	88.5	88.5	88.5	
	61.042	0.003	36.071	3.076	
4	216	1	4	124	345
	86.25	86.25	86.25	86.25	
	195.189	**84.262**	**78.436**	16.522	
Total	358	358	358	358	1432

† Table cell consists of actual count, expected count and contribution to chi-square statistic.
*Bolded items each comprise a greater than five percent contribution to the chi-square statistic.

The rank order data for each model was tested for normality. First histograms were created for all models to discern whether the shape approximates a normal distribution. The rank order histograms for CSA, MLAL and MLALxCSA do not appear to be randomly distributed. The normality of the MLALxCSA$^{1.5}$ could not be discerned visually. Rank order distribution graphs for each model can be found in Figures 3.18 through 3.21.

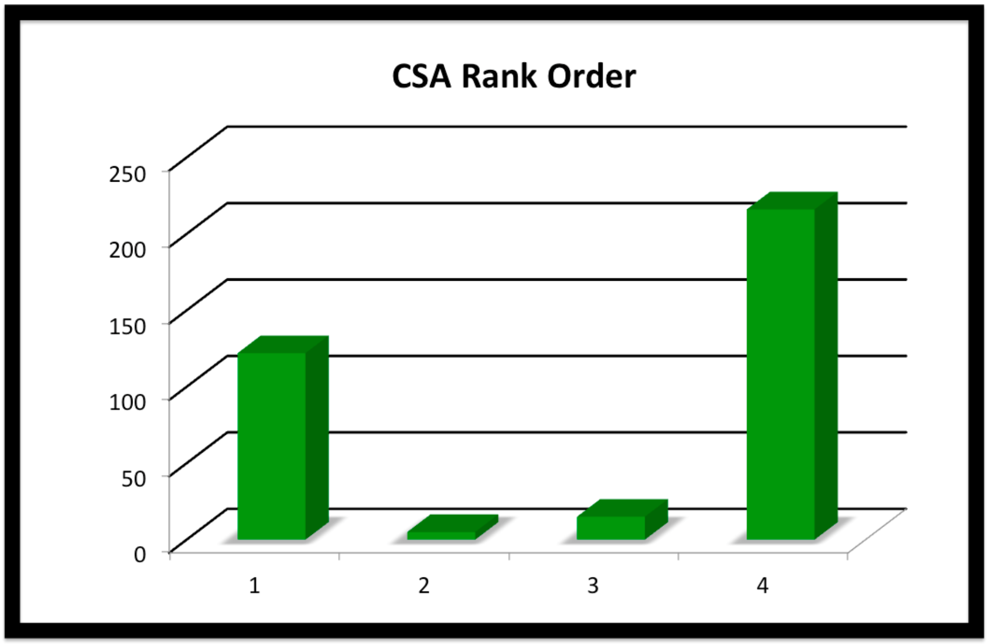

Figure 3.18: CSA Rank Order for All Trials (N=358)

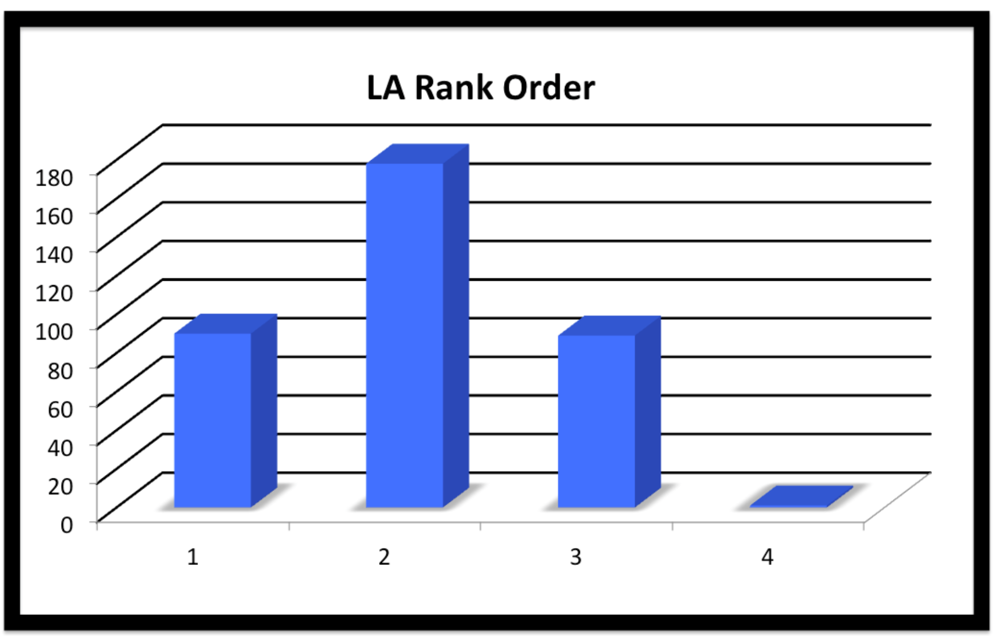

Figure 3.19: MLAL Rank Order for All Trials (N=358)

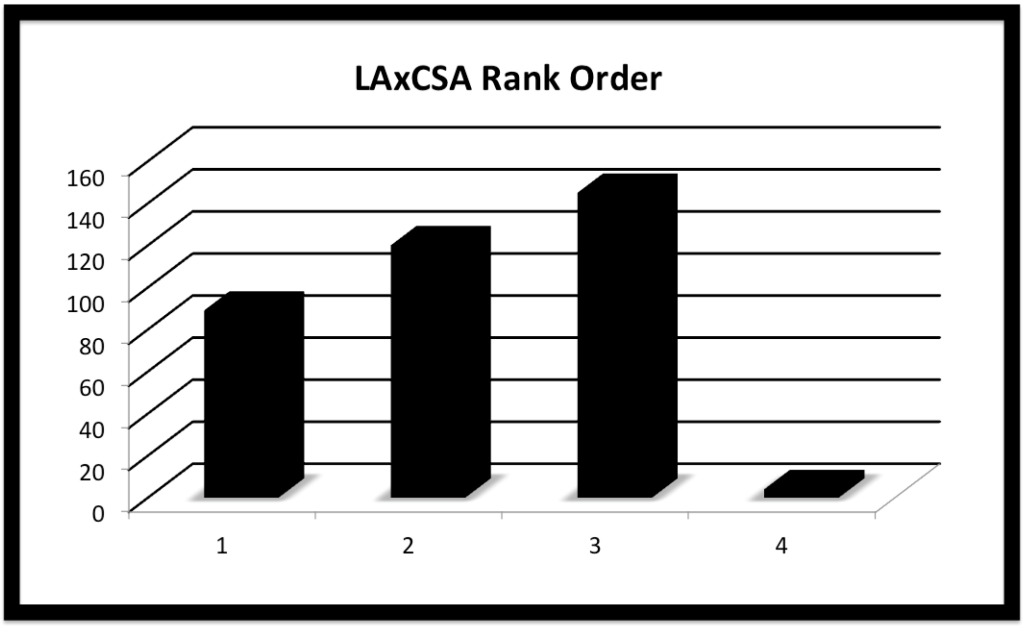

Figure 3.20: MLALxCSA Rank Order for All Trials (N=358)

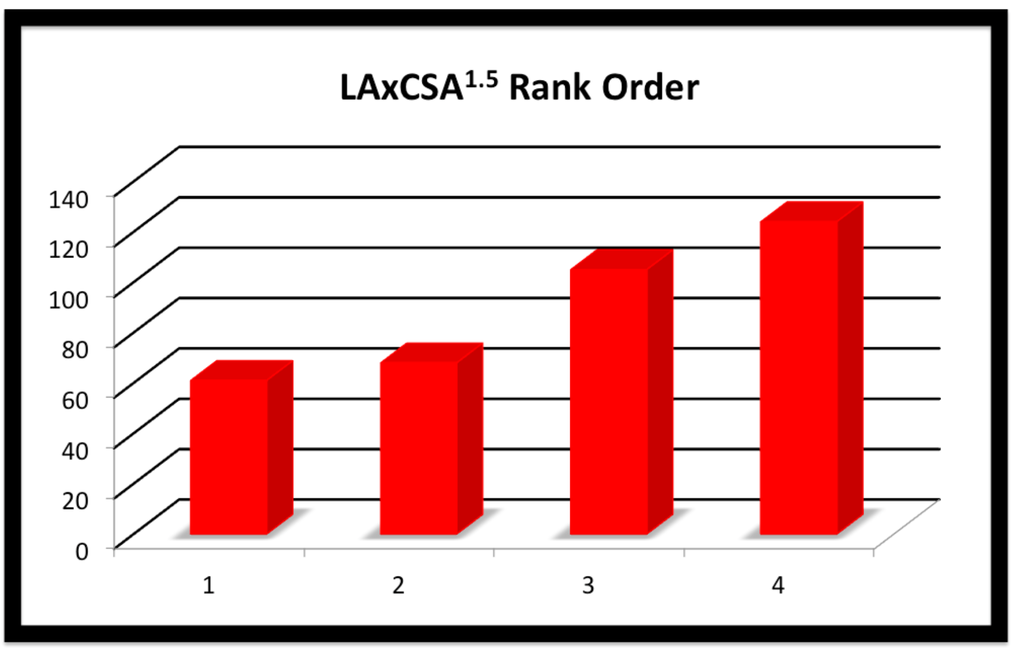

Figure 3.21: MLALxCSA$^{1.5}$ Rank Order for All Trials (N=358)

A Chi–square test was then performed on each model to check for normality. The results of the test indicate none of the considered models were normally distributed. Table 3.15 contains the p-values generated by running the Chi-square test on the models.

Table 3.15: Model Normality Test

Model	**p-value**	**Outcome**
CSA	$9.69\text{x}10^{-72}$	Reject null hypothesis
MLAL	$1.05\text{x}10^{-37}$	Reject null hypothesis
MLALxCSA	$3.08\text{x}10^{-27}$	Reject null hypothesis
MLALxCSA$^{1.5}$	$1.24\text{x}10^{-06}$	Reject null hypothesis

Due to the non–normality of the data and the use of ranking each models' performance the Wilcoxon signed–rank test was used to compare two models at a time via repeated measurements on a single sample to assess whether their population mean ranks were different. Since the MLAL weighted model has the lowest mean rank score it was compared to the other models. The results of the MLAL vs. CSA, MLALxCSA, and MLALxCSA$^{1.5}$ tests all resulted with the null hypothesis being rejected. In other words the average difference between the MLAL model rank order and the CSA, MLALxCSA and MLALxCSA$^{1.5}$ model rank orders was not zero. An indication that the MLAL model was different than the others is how the net positive sum approached the maximum positive value for the test (Max W). This resulted in z values that were greater than the critical z value and resulted in rejection of the null hypothesis that the average difference between the two averages under consideration was zero. MLAL rank order performance was significantly different than the other models performance. Since the MLAL weighted models had the lowest average rank scores and were significantly different than the other model rank averages it is inferred that it performed the best. Table 3.16 provides a summary of the calculated data using the Wilcoxon signed–rank test. Appendix I contains the calculations used to compare the

MLAL model with the other models.

Table 3.16: Wilcoxon Signed-Rank Test

N†	Comparison	Net Positive Sum	Max W	z	Critical Value of z at .0005 Level
357	CSA vs. MLAL	26,818	63,903	6.873	3.291
348	MLALxCSA1.5 vs. MLAL	41,316	60,726	11.000	3.291
346	MLALxCSA vs. MLAL	39,849	60,031	10.700	3.291

† Note: Trials used in each test may vary, if the difference between the models predictive ability is zero during a trial the trial is not considered in the analysis.

3.4 Discussion

The purpose of this experiment was to evaluate the most accurate approach to estimate back compressive forces by comparing the actual EMG values of each lifting trial with the model predicted EMG values. Accurately predicting muscle forces is a necessary step towards accurately computing resulting back compressive forces. The lower the relative percent error between the actual and predicted EMG values, the more accurate a given models' predictive ability should be. Lifting activities under consideration were symmetrical two–hand and asymmetrical one–hand and two–hand lifts. Predictions were made by comparing actual EMG levels of the erector spinae muscles during lifting trials with EMG values estimated by several models. The results of the experiment led to the rejection of the null hypothesis and to accept the alternative hypothesis that a difference exists among the accuracy of various relative muscle contribution assumptions. The amount of co-contraction present will influence which model is the best predictor of muscle forces and subsequent BCF. For instance plotting absolute error vs. lateral "co"–contraction it becomes evident that the best predicting models are weighted by CSA and rarely exceed percent errors of 10 percent and their performance was approximately 20 percent or better than all other models at lateral “co”–contraction levels up to 15 percent. Once lateral “co”–contraction levels exceed 15 percent, the CSA weighted models predictive ability begins to diminish. Similarly, absolute error vs. co-contraction level shows that the CSA weighted model has the lowest absolute error until co-contraction levels reached approximately 15 percent, from that point forward it ceases to be the best predictor and by co-contraction levels of approximately 21 percent it becomes the worse predicting model. This is important since other researchers have proposed co–contraction levels at higher levels (>30% e.g.). In contrast MLAL, for the most part, has a steady decrease in absolute error as co-contraction levels increase. Additionally, since the other two models under consideration, MLALxCSA and MLALxCSA$^{1.5}$ weighted models were built with the CSA term being a major contributor to the models output it is unlikely they will become the best predictor of BCF beyond the .21 co-contraction level. The observation of the MLAL weighted model being the best BCF predictor and CSA weighted model being the worst based on absolute error was also seen at other “reasonable” contraction levels reported by the literature. At every level co–contraction and lateral “co”–contraction levels (co-contraction levels between .20 – .50 and lateral “co”–contraction levels between .05 –.10) the MLAL model out performed the other models.The implications of the results demonstrate the need for including co–contraction in lifting models and that the MLAL is an important variable to consider in order to predict BCF during lifting activities.

3.5 Limitations

Several limitations were associated with the study. During development of the lifting model not all muscle groups were considered, as there was concern that the MRI scans would not be able to differentiate the internal and external oblique or if the latissimus dorsi would be distinguishable from the obliques. Therefore, both oblique muscles and the latissimus dorsi were considered as one muscle group. This created a larger muscle group, thereby potentially overestimating the obliques relative muscle contribution, especially on measures that considered the CSA of a muscle. Using the erector spinae muscles as the basis for predicting back compressive muscle force based on EMG muscle activity seems to have influenced the predictive abilities of the model. The calibration trials had r^2 values that ranged from 0.694 to 0.985 (18 of 20 regression lines had r^2 values ranging .816 - .985), the calibration trials were performed with the forearm at approximately a 90° angle from the upper arm. This posture resulted in higher muscle activity than what was observed in the experiment lifting trials in which the arm was in a resting by the side in a neutral posture resulting in an angle of 180°. This posture yielded much lower erector spinae muscle activity resulting in the model being unable to accurately predict muscle forces in which EMG activity was less than 10 microvolts. Finally, the study was limited to 10 participants. The participants selected for the study had to meet multiple inclusion criteria which resulted in a homogeneous test population. More participants, would have been desirable but funding only allowed for 10 subjects to be scanned at the AUMRIRC. To improve the predictive ability of the back model during lateral lifting activities consider collecting EMG measurements during the calibration and lifting trials at an additional muscle group site, such as the obliques as it is likely they would register greatly muscle activity. While likely not a major factor, erector spinae muscle calibration trials were not randomized and no co-contraction was assumed. Future experiments should randomize trial order, and include a "zero" load weight" and consider co–contraction. Also, subjects with poor calibration curves (e.g. $r^2 \leq 0.85$ should be eliminated from analysis) since model accuracy is assessed by predicting EMG value which cannot be reliably done without a predictor equation for EMG for each subject. Further, updates to the model should consider the internal obliques, external obliques, and latissimus dorsi individually as it may improve its accuracy. Lastly, increase the subject sample size and minimize inclusion criteria to minimize the effects of variability and increase the power of the experimental data.

3.6 Conclusion

Based on the different models performance based on expected literature cited co–contraction and lateral "co"–contraction levels, all models that included the CSA weighted term were not reliable. The CSA weighted model was the worst performing model at co-contraction levels past 21 percent. All weighted models that contained this term were not as accurate as the only model that did not have this term. Furthermore, the MLAL weighted model had the lowest average rank order. It is concluded that a difference exists among the BCF estimated using the various RMC assumptions. The MLAL weighted model is considered to be the best performing weighted model when trying to predict muscle forces and subsequent BCF during symmetric and asymmetric lifting tasks.

Future work should consider enhancements to the model to improve its predictive ability. Specifically the model should:

- Consider muscle fiber orientations. Muscle angles were assumed to pull directly in line with the spine.
- Consider the same co–contraction as the final model during muscle calibration trials.
- Increase sample size to include a more heterogeneous population that includes females, subjects of various sizes, and subjects with diverse body composition.

3.7 Acknowledgments

I would like to thank the following people for all of their assistance:

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Chapter 4

Comparison of the BCF when Laterally Lifting with Two Hands vs. One Hand

4.1 Introduction

Data from the Bureau of Labor Statistics, (2014) reveals that more than one million workers suffer back injuries each year and they account for one of every five workplace injuries or illnesses. Furthermore, one-fourth of all compensation indemnity claims involve back injuries, costing industry billions of dollars on top of the pain and suffering borne by employees. According to Liberty Mutual, the most disabling workplace injuries and illnesses in 2014 amounted to more than $59 billion in direct workers compensation costs, averaging more than $1 billion dollars per week. They also identified overexertion as the largest contributor to the overall burden, accounting for $15.1 billion, or 25.3%, of the total cost [Liberty Mutual Research Institute for Safety, 2014]. Bernard and Fine, (1997) declare the true cost of work-related overexertion injuries and disorders in the United States is not known. They do however provide conservative estimates of annual expenditures, based on workers compensation payments and other direct costs, ranging between $13 to 20 billion which is equivalent to $19.4 to 29.8 billion [Saving.Org, 2016]. The total cost to society is believed to be substantially higher due to various indirect costs that are not included in the conservative estimates. In conclusion, back injuries occur frequently and are costly, and no approach has been found for completely eliminating back injuries caused by lifting, though it is believed that a substantial portion can be prevented by an effective control program and ergonomic design of work tasks.

4.1.1 One–Hand Lifting

While there is an abundance of literature that has focused on two–handed MMH tasks [(Poulsen and Jørgensen, 1971), (Snook, 1978), (Karwowski, 1991), (Waters et al., 1993), (Maiti and Ray, 2004) and (Mayer et al., 2013)], few studies have addressed the issue of one–hand lifting. Kingma and van Dieën, (2004) observed that “one–hand lifting has received no attention in the literature”. Quantifying the amount of one–hand lifting activity that occurs in an industrial setting is difficult to gauge as the BLS or OSHA do not classify one–hand lifts differently from two–hand lifts.

A study in which seven modes of carrying an identical load was conducted. Carrying by hands was observed to be the worst method [Datta and Ramanathan, 1971]. Anecdotally both Garg, (1983) and Marras and Davis, (1998) indicated that they have observed and also received confirmation from others that one–hand lifts in industry is a common occurrence.

It has been reported that one-hand lifting resulted in features observed to be associated with low back disorders. Unsupported one–hand lifting tasks appear to load the spine more than two-handed lifts which can increase one’s risk of suffering a low back disorder [Allread et al., 1996]. It has also been observed that increased asymmetry corresponds to increased spinal loads when both hands are involved in the lift or if the lift was performed with one hand on the opposite side of the load reaching across the body [Marras and Davis, 1998]. Kingma and van Dieën, (2004) observed that workers are often forced to lift an object with one hand because the object in question only has one handle. Finally, multiple researchers have identified one-hand lifting taking place when removing items out of deep storage bins [(Cook et al., 1991), (Ferguson et al., 2002) and (Jones et al., 2013)]. Therefore, considering the potential injury risks to workers, direct and indirect injury costs to industry and increased costs of goods to consumers, it is apparent that one-hand lifting tasks are important to study.

4.1.2 One–Hand Carrying

McGill, (2013) conducted a one–hand carrying study with a subject population of six. It was observed that one–hand carrying resulted in more low back compression than splitting the load equally and holding with two hands. It was also observed that carrying an equal load (30 kg) in each hand produced lower spine compression than carrying one 30 kg load. The results of the study were similar to Wilke et al., (2001), in which a pressure transducer was inserted in the L4–5 disc of a single volunteer. The authors observed the pressure in the back during multiple activities, including one–hand carrying of a case weighting 19.8 kg and a symmetric two–hand carry of two 19.8kg cases. The intradiscal pressure of the one–hand asymmetric lift was 1.0 MPa while the two–hand carry yielded an intradiscal pressure of only 0.9 MPa.

Looking into the different one-hand lifting standards in more detail confirms that no standard looks at the compressive back force acting on the back during one–hand lift activities. There is a gap in the literature as no one–hand lift guidance is based on biomechanical data. This is important to consider as recent biomechanical studies by Wilke, (2001) and McGill, (2013) illustrate the effects one–hand lifts have on the lifters BCF. The studies illustrate the potential risks associated with asymmetric lifting and carrying. Both Wilke and McGill identified carrying loads in one hand resulted in more load on the low back than when the load was split between two hands.

4.1.3 Summary

The literature suggests that when lifting to the side of the body, a one–hand lift is preferable. However, when lifting in front of the body a two hand lift is suggested. In cases where only one-hand can be used to lift in front of the body then using the second hand to support the body will provide benefit to the lifter [Graveling et al., 2003]. Standards in place that consider one-hand lifting [(ACGIH, 2016), (European Committee for Standardization, 2005), and (Guild et al., 2010)] do not consider the biomechanical costs to the back, namely

BCF, when performing one–hand lifts. Biomechanical forces need to be considered as they can be used to quantify the risks the back faces when performing this type of asymmetrical lift.

It is proposed that using MRI technology which can obtain a clear transverse image of the back muscles at the L–3 region and use of EMG data to validate the muscle forces being generated during one-hand and two-hand lifts, a model of the low back and trunk muscles can be developed to predict BCF's during one–hand and two–hand asymmetric lifting activities. The purpose of this experimental study is twofold.

The first aim of this study is to compare the BCF when laterally lifting an array of weights (10, 20, 30, 40, 50 lbs.) symmetrically (weight lifted is divided equally between both hands) and asymmetrically (weight lifted is lifted by one hand). If a difference exists then a one–hand lifting discount or "scaling" factor, such as a multiplier can be applied to existing lifting standards. The use of a multiplier as a discounting factor in determining "safe lifting guidance" has been used in the original NLE [NIOSH, 1981] and revised NLE [Waters et al., 1993], MIL STD 1472 versions C [Department of Defense, 1999] through G [Department of Defense, 2012] and the Safety Guidelines for Ergonomics Engineering of Semiconductor Manufacturing Equipment [Guild et al., 2010].

The second aim of this study is to compare the BCF when laterally lifting twice as much weight (20, 40, 60, 80, 100 lbs.) symmetrically (weight lifted is divided equally between two hands) and half that weight (10, 20, 30, 40, 50 lbs.) asymmetrically (weight lifted by one hand). This can lead to justification that under certain circumstances, namely avoidance of asymmetric one–hand lifts there is a "lift two benefit". In other words, doubling the amount of weight handled so that each hand is carrying the same amount of weight may actually reduce BCF.

4.2 Methods

4.2.1 Objective and Hypotheses

The objectives of this experiment were to compare the BCF when laterally lifting equal amounts of weight with two hands (weight split equally between both hands) vs. one hand holding all the weight. For example, lifting "X" lbs. with two hands vs. lifting $\frac{1}{2}$"X" lbs. with one hand and to explore one-handed lifting discount or "scaling" factors that can be applied to existing models such as the:

- ACGIH Tables for Lifting
- RNLE
- MIL STD 1472G

The hypotheses of the experiment were:

Hypothesis 1: Differences between one and two hand lifts are not simply directly proportional to the total weight lifted. Asymmetry will alter BCF.

H_0: $\mathrm{BCF}_{\Sigma\ \textit{Symmetrically held weight} = x} = \mathrm{BCF}_{\Sigma\ \textit{Asymmetrically held weight} = x}$

H_1: $\mathrm{BCF}_{\Sigma\ \textit{Symmetrically held weight} = x} < \mathrm{BCF}_{\Sigma\ \textit{Asymmetrically held weight} = x}$

Hypothesis 2: BCF will increase as the amount of weight lifted increases, more if asymmetrically lifted. BCF is a function of asymmetry.

H_0: $\mathrm{BCF}_{\Sigma\ \textit{Symmetrically held weight} = 2x} = \mathrm{BCF}_{\Sigma\ \textit{Asymmetrically held weight} = x}$

H_1: $\mathrm{BCF}_{\Sigma\ \textit{Symmetrically held weight} = 2x} < \mathrm{BCF}_{\Sigma\ \textit{Asymmetrically held weight} = x}$

4.2.2 Experimental Design

Independent variables for this experiment were:

- Weight lifted by each hand
- Muscle effective mechanical lever arm length

- Assumptions regarding relative muscle contribution

The dependent variable was:

- EMG activity at the left and right erector spinae muscle group

The Auburn University Internal Review Board (IRB) approved the study protocol on October 31, 2015 [Auburn University, 2015b]. Approval notification documents can be found in Appendix B and Apprendix C. Once IRB approval was secured, recruitment for the study commenced. A sample flyer used to solicited interest in the study is included in Appendix D. Ten volunteers from the Auburn University student population that met the experiment inclusion criteria, including the ability to safely undergo an MRI procedure, were selected to participant in the study. The screening form used to help determine if a participant met eligibility requirements is included in Appendix E. Each subject was consented using the approved IRB consent form, which can be found in Appendix F. Subjects also consented to be photographed during the lifting trials. Approved Samuel Ginn College of Engineering Photo Release forms for participants whose photograph was used can be found in Appendix G. Although "AU policy allows for the use of student photgraphs without consent if they are perfoming tasks associated with school activities" [Killian, 2016], fellow graduate students whose photograph was used during data collection also filled out photo release forms, and can be found in Appendix G as well.

4.2.3 Procedure

The procedure used in this experiment is the same that was performed in Chapter 3. Sections 3.2.3, 3.2.4 and 3.2.5 discuss the MRI, EMG and Xsens systems respectively. These systems were used to build the lifting model

4.2.4 Equipment

The following equipment were used for data collection:

1. Siemens Verio Open-Bore 3T MRI Scanner with lumbar coil
2. Noraxon EMG sensor
3. 3M electrode
4. Double sided tape
5. Super glue
6. Self-adhering athletic tape
7. Anthropometry measuring kit
8. Skin caliper
9. Scale

The lumbar coil was used to improve spatial resolution around the spine. Additionally, two open source computer programs, OsiriX v4.0 and Open Source Computer Vision (OpenCV) were used to analyze MRI scans. Sections 3.2.8 and 3.2.9 contain more information on OsiriX and OpenCV respectively.

4.2.5 Model Selection

The model used for data analysis was based on the mechanical lever arm length (MLAL), which was demonstrated to be the best fit of the four models under consideration in Chapter 3. The co–contraction and lateral contraction levels inputted into the model were 0.30 and 0.10, respectively. The contraction values were selected as they represent reasonable estimates reported from the literature [(Crisco et al., 1992) and (Marras and Granata, 1997)].

4.2.6 Statistical Analyses

Ryan–Joiner tests of normality were performed to determine if the BCF for all subjects and each individual subject were normally distributed ($\alpha = 0.05$). A Two Sample Paired T-Test was used to determine if mean of BCF for symmetrical lifting (total weight lifted = x) was the same as the mean BCF for asymmetrical lifting (total weight lifted = x) ($\alpha = 0.05$).

4.3 Results

4.3.1 Descriptive Statistics

Ten students volunteered to participate in this study. Inclusion criteria included being; male, 25 years or age or younger, no prior history of back injury, no current back pain and a Body Mass Index (BMI) of 30 kg/m^2 or less. The participants had a mean age of 22.8 years (SD=1.48), mean weight of 70.71 kg (SD=6.89), mean height of 178 cm (SD=7.21), and a mean BMI of 22.9 kg/m^2 (SD=2.77). Table 4.1 contains select anthropometric data for each study participant.

Other descriptive information that was collected to build the BCF model, including muscle CSA, MLAL, and lever arm distances between the hands and back can be found in section 3.3.1, Descriptive Statistics of Subject Population.

4.3.2 Inferential Statistics Results, Hypothesis 1

A Ryan-Joiner normality test was conducted for each subject to determine if the collected data demonstrated a normal distribution, Figure 4.1 graphically represents the results for Subject 1. Other subject data was similar to what was observed for Subject 1. The results of the Ryan–Joiner normality tests illustrated in Figure 4.1 suggest that the BCF for each subject and for all subjects exhibited a normal distribution. Figure 4.2 demonstrate graphical representations of Ryan-Joiner Normality Tests for Subjects 1-10. Appendix J contains graphical representations of normality for all subjects. Appendix K contains the BCF for all subjects during all trials.

Table 4.1: Selected Subject Anthropometric Data

Subject	**Age (yrs)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
M001	23	173	70.3	23.9
M002	25	177	74.8	23.9
M003	23	184	70.8	21.2
M004	25	175	65.3	21.8
M005	22	168	62.1	22.9
M006	23	170	69.9	24.9
M007	23	186	72.3	21.4
M008	20	187	73.3	21.8
M009	22	175	85.7	29.0
M010	22	185	62.6	18.7
Mean (SD)	22.8 (1.5)	178.0 (7.0)	70.7 (6.8)	22.9 (2.8)

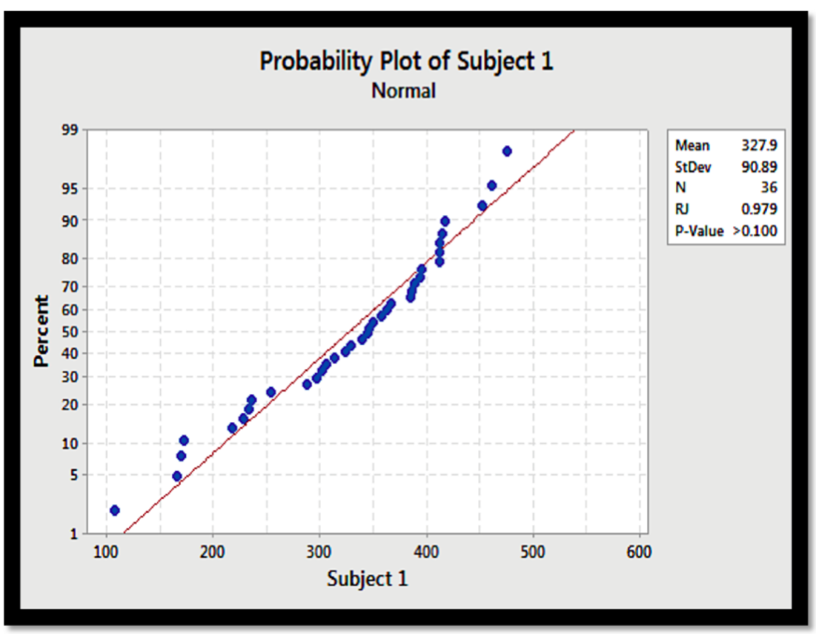

Figure 4.1: Ryan–Joiner Normality Test for Subject 1

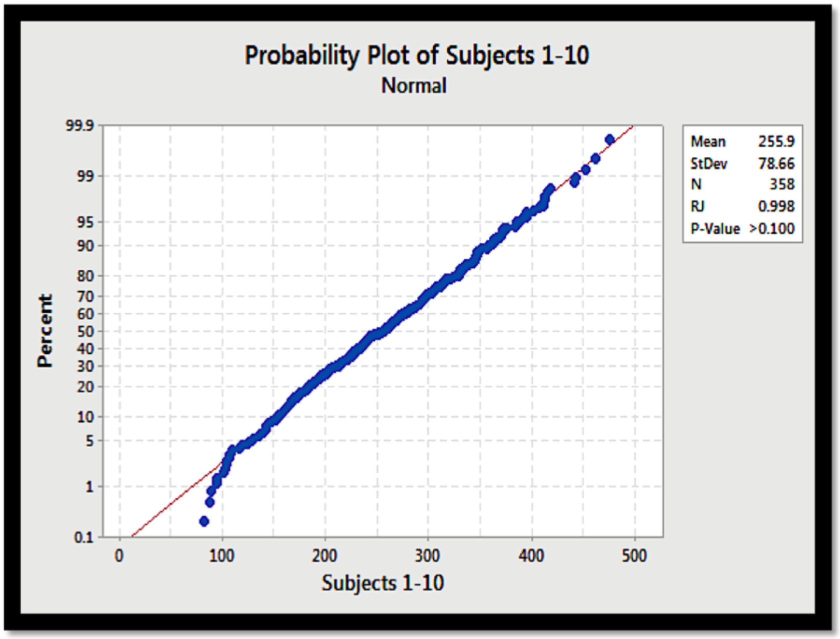

Figure 4.2: Ryan–Joiner Normality Test for Subjects 1-10

Table 4.2: Ryan-Joiner Normality Test Results

Subject	**N**	**RJ Value**	**P-Value**
1	36	0.979	>0.100
2	36	0.990	>0.100
3	35	0.987	>0.100
4	36	0.984	>0.100
5	36	0.990	>0.100
6	36	0.989	>0.100
7	36	0.991	>0.100
8	36	0.997	>0.100
9	35	0.993	>0.100
10	36	0.997	>0.100
1–10	358	0.998	>0.100

Paired Two–Tailed T–Tests were run comparing the estimated BCF generated by all subjects when lifting $\frac{1}{2}$ X lbs. in each hand with lifting X lbs. in their left hand. Similar comparisons were made when lifting $\frac{1}{2}$ X lbs. in each hand and with lifting X lbs. in their right hand.

It should be noted that weights lifted during the lifting trials were in multiples of 10. However, subsequent analyses required consideration of weights that were a multiple of 5. In situations where a weight that was a multiple of 5 was needed, it was estimated by averaging the symmetric lifting trials of the next lower and next higher multiple of 10. For instance, the estimated BCF of a 15-pound lift was estimated by averaging the BCF of 10-pound and 20 pound lifts.

Results of the T-tests indicated rejection of the null hypothesis, that there is a difference in estimated BCF when the same amount of weight is lifted symmetrically with two hands and asymmetrically with one-hand.

The estimated BCF for all subjects performing asymmetric and symmetric lifts at each weight were considered independently for the left and right hand, this resulted in the evaluation of 10 lifts.

A few (3) data points were observed to be considerably different than expected. Upon further examination, the hand to back lever arm distance generated by Xsens for these trials were much smaller than expected, suggesting erroneous data or outliers. The presence of outliers may be explained from the following excerpt taken from the Xsens MVN User Manual.

> "The MVN system does not have an absolute positioning system. Therefore, the characters will show some drift over time in terms of absolute position in space with respect to the origin (defined at calibration), [Xsens Technologies B.V., 2016]."

Two conditions were used to accept if a data point was an outlier. If the data point failed both conditions it was considered an outlier. The first condition was the data point could be considered an outlier if it met the criteria using the interquartile range outlier test. In this test low value outliers are defined as observations that fall below the first quartile (Q1) less 1.5 times the interquartile range (IQR), which is mathematically represented as (Q1-1.5IQR). The second condition was the Xsens calculated hand to hand breadth was less than 50 percent of the 5th percentile male shoulder breadth. Note: The 5th percentile male shoulder breadth is 47.74 cm, 50 percent of this value concerted to inches is 9.40 inches, [Konz and Johnson, 2000]. Using this two-part criteria, three data points were considered outliers as the Xsens estimate was less than the anthropometric estimate and the observed data point did not pass the interquartile range outlier test. The data points are:

- Subject 2, Trial 19, 0 lbs. Left Hand, 30 lbs. Right Hand
- Subject 2, Trial 25, 0 lbs. Left Hand, 40 lbs. Right Hand
- Subject 5, Trial 19, 0 lbs. Left Hand, 30 lbs. Right Hand

Therefore, after removing outlier values, trials that required 30 lbs. to be lifted only had data from 8 subjects and trials that required 40 lbs. to be lifted only had data from 9 subjects. Paired T–Tests were still used for these trials. Also, note that in place of a value the term outlier will take its place in the appropriate tables. A summary of the outlier tests is provided in Table 4.3

Table 4.3: Outlier Test Results

Subject/Trial	Xsens Breadth (inches)	Shoulder Breadth 5th Percentile (inches)†	Q1-1.5xIQR	Q1
M002/19	3.58	9.40	1.91	5.00
M002/25	1.82	9.40	1.27	5.00
M005/25	1.30	9.40	0.97	7.10

† Threshold value used is 50% of a 5th percentile males shoulder breadth. All subjects were close to 50th percentile.

Percent differences in estimated BCF were made by summing and averaging the asymmetric estimated BCF of all subjects and comparing that average with the summed average of the subjects symmetric estimated BCF. For example consider the values in Table 4.12 . The average estimated BCF for the asymmetric lift (50 lbs. Left Hand, 0 lbs. Right Hand) was 346.3 lbs.. This was compared to the average estimated BCF for the symmetric lift (25 lbs. Left Hand, 25 lbs. Right Hand) which was 197.5 lbs.. The percent difference of the two averages was calculated. In this case, the percent difference in estimated BCF when asymmetrically lifting the same amount of weight compared to symmetrically lifting that weight with two hands resulted in a 75.3% increase in BCF. The ten lifting trials under consideration all resulted in higher estimated BCF when lifting equal amounts of weight asymmetrically with one hand versus symmetrically with two hands. The percent increase in BCF when lifting asymmetrically rather than symmetrically ranged from approximately 25-75 percent depending on the magnitude of the load.

The results of the ten lifting scenarios under consideration all demonstrate that one–hand lifting is more stressful to the back than two-hand lifting of the same amount of weight. This was not unexpected as Cook et al., (1987) reported that paraspinal EMG activity was significantly increased when performing a one–hand carry vs. carrying the same amount of weight in a backpack. Allread et al., (1996) concluded that unsupported one–hand lifting, loads the spine more than two–hand lifting. Although the study did not quantify how much more spine loading occurred, it did state that "back motion characteristics previously found to be associated with low back disorders were all significantly higher for one handed lifts". Additionally, Wilke et al., (2001) demonstrated with one subject that a load (single crate) carried in one hand resulted in substantially more compressive load on the low back than doubling the load (two crates) and carrying one in each hand symmetrically.

The estimated BCF generated from every weight under consideration (10, 20, 30, 40 and 50 lbs.) for the left and right hands showed a significant difference in estimated BCF when compared to the symmetric lifting trial. Tables 4.4 to 4.13 illustrate estimated BCF for symmetric and asymmetric lifts at each investigated weight level as well as T–Test results. Furthermore, as the level of asymmetry increased, so did the difference in estimated BCF. For instance when lifting 5 lbs. symmetrically in each hand (10 lbs.) and lifting 10 lbs. asymmetrically (left hand lifting 10 pounds) there was a 32.7 lb. (27.1%) difference in estimated BCF. When lifting 25 lbs. symmetrically in each hand (50 lbs.) and lifting 50 lbs. asymmetrically (left hand lifting 50 pounds) there was a 148.8 lb. (75.3%) difference in estimated BCF.

Table 4.4: BCF (lbs.) of Symmetric and Asymmetric 10-Pound Lifting Trials

Subject	**10 lbs. Left Hand, 0 lbs. Right Hand**	**5 lbs. Left Hand,† 5 lbs. Right Hand**	**0 lbs. Left Hand, 10 lbs. Right Hand**
1	148.7	120.6	151.8
2	143.8	115.8	138.8
3	157.7	121.7	156.4
4	146.8	112.2	145.1
5	138.7	111.9	152.4
6	160.1	122.3	163.1
7	158.8	126.9	174.4
8	155.7	129.1	169.3
9	181.7	142.7	179.6
10	141.5	104.0	140.5
Mean (SD)	153.4 (12.5)	120.7 (10.8)	157.1 (14.1)

† BCF values for 5 lbs. Left Hand, 5 lbs. Right Hand are estimates.

There is approximately a 28% increase average of estimated BCF over all subjects for 10 lb. asymmetric vs. symmetric lifts.

Table 4.5: T–Test Results for Asymmetric vs. Symmetric 10-Pound Lifting Trials

N	**Lifting Scenario Comparison**	**P-Value**
10	10 lbs. L, 0 lbs. R vs. 5 lbs. L, 5 lbs. R	0.000
10	0 lbs. L, 10 lbs. R vs. 5 lbs. L, 5 lbs. R	0.000

Table 4.6: BCF (lbs.) of Symmetric and Asymmetric 20-Pound Lifting Trials

Subject	**20 lbs. Left Hand, 0 lbs. Right Hand**	**10 lbs. Left Hand, 10 lbs. Right Hand**	**0 lbs. Left Hand, 20 lbs. Right Hand**
1	209.0	137.6	202.2
2	161.3	128.4	166.2
3	203.4	142.5	184.1
4	190.4	129.8	181.7
5	192.8	135.0	192.2
6	201.4	141.4	219.6
7	206.2	145.0	203.6
8	207.3	151.2	230.3
9	239.5	161.8	234.2
10	173.8	125.6	196.2
Mean (SD)	198.5 (21.2)	139.8 (16.1)	201.0 (21.8)

There is approximately a 43% increase average of estimated BCF over all subjects for 20 lb. asymmetric vs. symmetric lifts.

Table 4.7: T–Test Results for Asymmetric vs. Symmetric 20-Pound Lifting Trials

N	**Lifting Scenario Comparison**	**P-Value**
10	20 lbs. L, 0 lbs. R vs. 10 lbs. L, 10 lbs. R	0.000
10	0 lbs. L, 20 lbs. R vs. 10 lbs. L, 10 lbs. R	0.000

Table 4.8: BCF (lbs.) of Symmetric and Asymmetric 30-Pound Lifting Trials

Subject	**30 lbs. Left Hand, 0 lbs. Right Hand**	**15 lbs. Left Hand,[†] 15 lbs. Right Hand**	**0 lbs. Left Hand, 30 lbs. Right Hand**
1	262.7	152.1	258.4
2	216.0	140.1	Outlier
3	268.4	152.9	265.9
4	237.3	146.9	239.1
5	237.5	149.1	Outlier
6	292.0	158.0	288.0
7	280.1	179.5	290.8
8	266.2	167.1	305.0
9	265.2	186.6	294.9
10	230.0	150.8	229.7
Mean (SD)	255.5 (24.1)	158.8 (1648)	271.5 (27.6)

[†] BCF values for 15 lbs. Left Hand, 15 lbs. Right Hand are estimates.

There is approximately a 64% increase average of estimated BCF over all subjects for 30 lb. asymmetric vs. symmetric lifts.

Table 4.9: T–Test Results for Asymmetric vs. Symmetric 30-Pound Lifting Trials

N	**Lifting Scenario Comparison**	**P-Value**
10	30 lbs. L, 0 lbs. R vs. 15 lbs. L, 15 lbs. R	0.000
10	0 lbs. L, 30 lbs. R vs. 15 lbs. L, 15 lbs. R	0.000

Table 4.10: BCF (lbs.) of Symmetric and Asymmetric 40-Pound Lifting Trials

Subject	**40 lbs. Left Hand, 0 lbs. Right Hand**	**20 lbs. Left Hand, 20 lbs. Right Hand**	**0 lbs. Left Hand, 40 lbs. Right Hand**
1	308.4	166.5	281.1
2	204.8	165.9	Outlier
3	313.6	173.3	315.9
4	229.0	163.9	268.9
5	274.9	163.2	293.7
6	331.9	174.6	346.6
7	334.4	214.0	335.1
8	313.0	183.0	371.2
9	329.2	211.4	343.1
10	270.3	175.9	314.0
Mean (SD)	291.0 (45.1)	177.8 (20.3)	318.8 (33.4)

There is approximately a 71% increase average of estimated BCF over all subjects for 40 lb. asymmetric vs. symmetric lifts.

Table 4.11: T–Test Results for Asymmetric vs. Symmetric 40-Pound Lifting Trials

N	**Lifting Scenario Comparison**	**P-Value**
10	40 lbs. L, 0 lbs. R vs. 20 lbs. L, 20 lbs. R	0.000
10	0 lbs. L, 40 lbs. R vs. 20 lbs. L, 20 lbs. R	0.000

Table 4.12: BCF (lbs.) of Symmetric and Asymmetric 50-Pound Lifting Trials

Subject	**50 lbs. Left Hand, 0 lbs. Right Hand**	**25 lbs. Left Hand,† 25 lbs. Right Hand**	**0 lbs. Left Hand, 50 lbs. Right Hand**
1	367.8	193.2	319.0
2	293.6	173.7	182.0
3	358.8	193.3	346.1
4	265.1	190.7	216.6
5	330.4	183.0	362.4
6	363.1	202.4	383.8
7	442.0	220.6	347.3
8	372.2	205.5	440.2
9	362.3	227.8	406.3
10	307.9	185.3	369.7
Mean (SD)	346.3 (49.5)	197.5 (16.8)	337.3 (80.5)

† BCF values for 25 lbs. Left Hand, 25 lbs. Right Hand are estimates.

There is approximately a 73% increase average of estimated BCF over all subjects for 50 lb. asymmetric vs. symmetric lifts.

Table 4.13: T–Test Results for Asymmetric vs. Symmetric 50-Pound Lifting Trials

N	**Lifting Scenario Comparison**	**P-Value**
10	50 lbs. L, 0 lbs. R vs. 25 lbs. L, 50 lbs. R	0.000
10	0 lbs. L, 50 lbs. R vs. 25 lbs. L, 50 lbs. R	0.000

The biomechanical approach, with respect to lifting, emphasizes the forces and torques acting on the body. The low back, especially the L–4/L–5 disc and L–5/S–1 disc are considered the weak link in this system because this is the location of theoretical maximum stress. Also, a disproportionate numberof injuries occur in these areas. There are three broad categories that can be considered to improve lifting outcomes: (1) increase the strength of the worker; (2) decrease the stress associated with the lifting technique and task; or (3) a combination of (1) and (2); increase worker strength and decrease worker stress [Konz and Johnson, 2000]. Increasing the strength of the worker through use of job selection is discouraged due to potential legal troubles from excluding people or a segment of the population from jobs. Furthermore, selecting stronger workers does not address the root cause of the problem. Decreasing the stress associated with the lifting task so that more people can perform the task is a well established means of improving a task [Snook and Ciriello, 1991]. A means of decreasing stress on the back during lifting activities is to employ a neutral lifting posture. For instance, the RNLE considers symmetry in their formula and will not even consider a lift or lower for evaluation if it is performed with only one hand. Figures 4.3 to 4.6 demonstrate the effect lifting symmetry has on estimated BCF.

The results on the study could form the basis for a manufacturer implementing a two-hand lift policy. The percent increase in estimated BCF comparing asymmetric and symmetric lifts of equal amount of weight ranged from approximately 25% to 76% depending on the magnitude of the load.

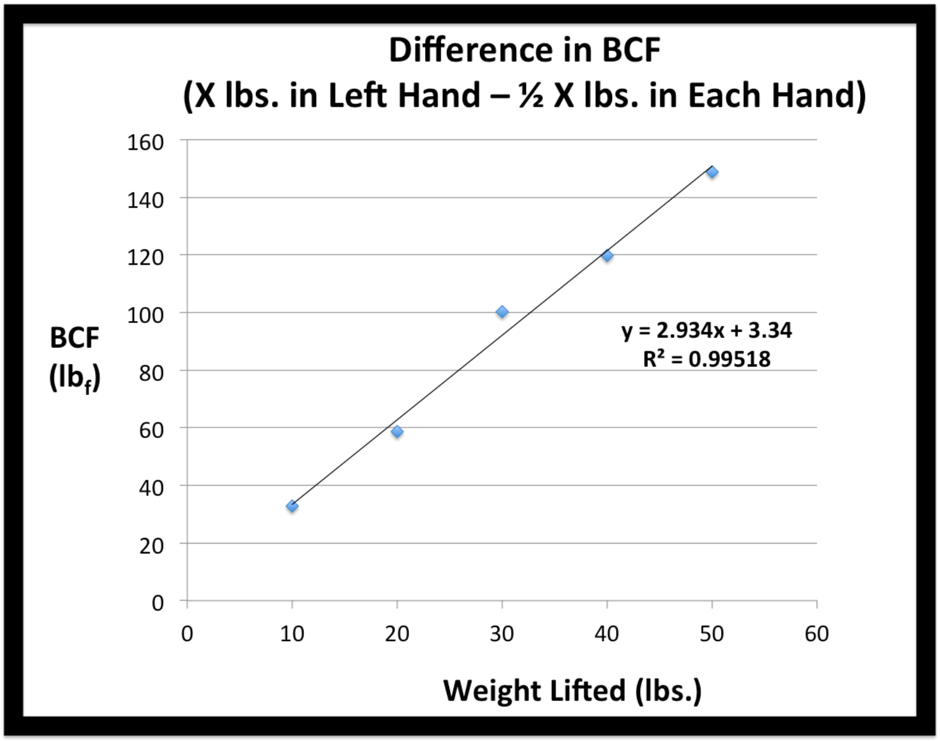

Figure 4.3: Difference in BCF, Asymmetric Lifting, Left Hand

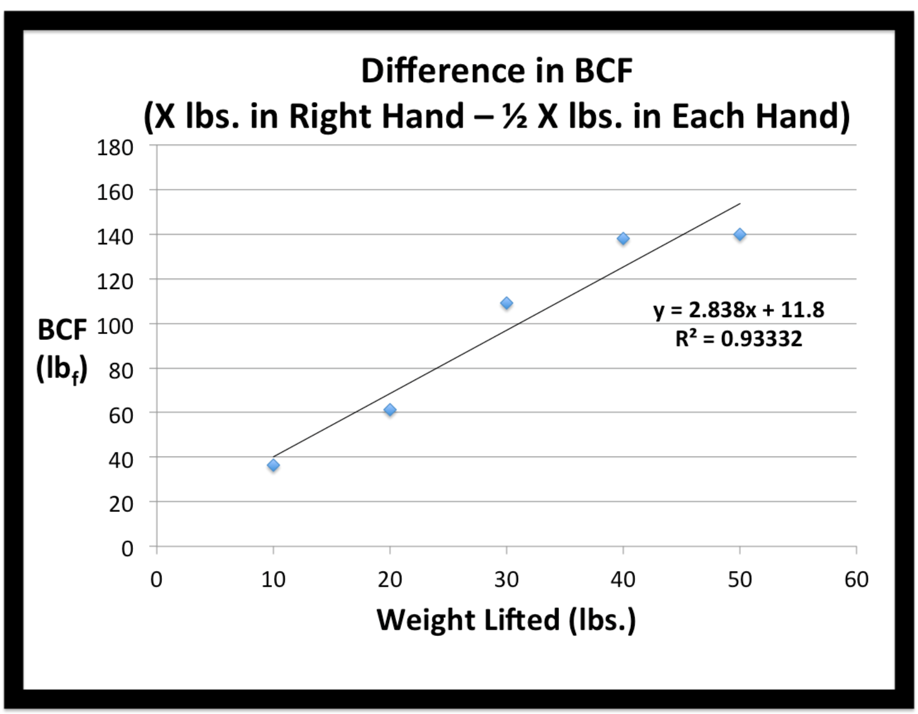

Figure 4.4: Difference in BCF, Asymmetric Lifting, Right Hand

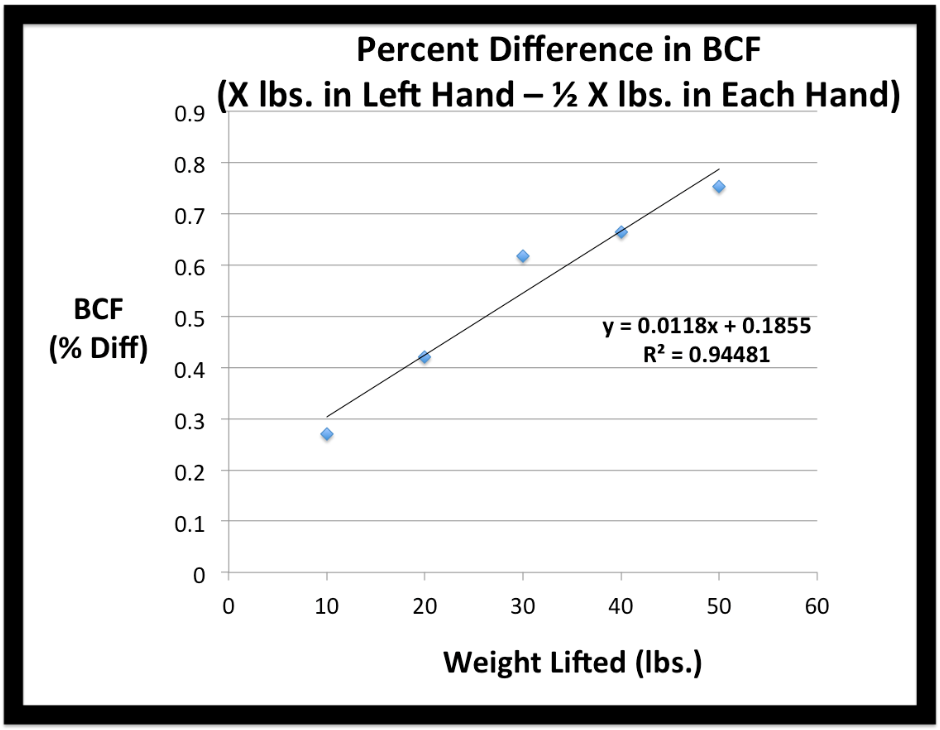

Figure 4.5: Percent Difference in BCF, Asymmetric Lifting, Left Hand

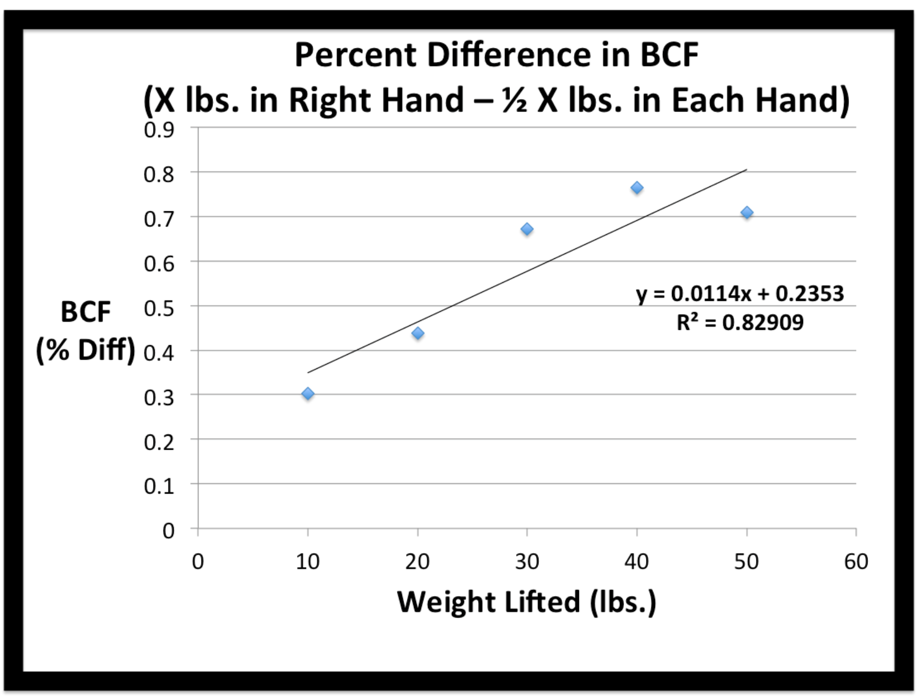

Figure 4.6: Percent Difference in BCF, Asymmetric Lifting, Right Hand

4.3.3 Inferential Statistics Results, Hypothesis 2

Results of the two-sample paired t-tests indicate rejection of the null hypothesis is warranted. The alternative hypothesis, asymmetry will alter BCF was supported. At all levels of asymmetry, increases in estimated BCF were present. The estimated BCF for all subjects performing asymmetric and symmetric lifts at each weight were considered independently for the left and right hand, this resulted in the evaluation of 10 lifts. Percent differences in estimated BCF were made by summing and averaging the asymmetric estimated BCF of all subjects and comparing that average with the summed average of the subjects symmetric estimated BCF. For example consider the values in Table 4.22. The average estimated BCF for the asymmetric lift (50 lbs. Left Hand, 0 lbs. Right Hand) was 346.3 lbs.. This was compared to the average estimated BCF for the symmetric lift (50 lbs. Left Hand, 50 lbs. Right Hand) which was 279.0 lbs.. The percent difference of the two averages was calculated. In this case the percent difference in estimated BCF when asymmetrically lifting half as much weight compared to symmetrically lifting twice as much weight resulted in 24.1% higher BCF. The ten lifting trials under consideration all resulted in higher estimated BCF when lifting half as much weight asymmetrically than lifting twice as much weight symmetrically. Higher BCF values ranging from 9-26 percent were observed when lifting asymmetrically rather than symmetrically. Estimated BCF values and P–Values for analyzed lifting trials can be found in Tables 4.14 to 4.23.

The experiment results were not unexpected as the literature reports that asymmetric lifting, via, load distribution is detrimental to the health of the lifter. Allread et al., (1996) investigated one-hand and two-hand lift activities in three different asymmetric positions. For one-hand lifts the lifter had back motion characteristics known to put a lifter at greater risk for a back injury. Mital and Fard, (1986) investigated the effects of lifting symmetrical and asymmetrical objects symmetrically and asymmetrically. Reported results demonstrated that subjects lifted 8.5 percent less weight when assuming asymmetrical postures and none reported asymmetrical lifting was easier than symmetrical lifting. Garg and Banaag, (1988) investigated asymmetric lifting and reported that maximum acceptable weight was significantly lower and heart rate and RPE were significantly higher in the asymmetric plane when compared to lifting in the symmetric plane.

EMG studies that investigated the effect asymmetric loading had on the body demonstrated an increase in myoelectric activity on the contralateral side in the lumbar region as asymmetrical loading increased. The increase in myoelectric activity was comparatively greater on the contralateral side in the lumbar region than the ipsilateral side [(Andersson et al., 1977) and (Kumar and Davis, 1983)].

The BCF differences when lifting twice as much weight symmetrically vs. half as much weight asymmetrically were statistically significant at both lighter and heavier weights under consideration. This seems to be inconsistent with what McGill et al., (2013) reported. In their study, not only was there no significant difference found in spine load in the 10 kg condition (i.e. carrying 10 kg in one hand vs. carrying to kg in each hand). It was also reported at low loads the torso mass dominates any differences between hand conditions but at higher loads the load dominates. However, at the higher weights under investigation, the results of the experiment are consistent with McGill's finding that adding more load would result in larger discrepancies in spine compression.

In the textbook Manual Materials Handling, the authors assert that asymmetric MMH tasks are the norm in industry and not the exception. They also report that lifting asymmetrical objects is more stressful than lifting symmetrical objects, [Ayoub, 1989]. Asymmetric lifting has been reported to increase low back and trunk muscle activity, [Anderson et al., 1985]. The estimated BCF generated from asymmetrically lifting half as much weight than lifting twice as much weight symmetrically was 9 – 26 % higher, which is comparable to what is reported in the literature [(Wilke et al., 2001) and (McGill et al., 2013)].

Symmetrical lifting of twice as much weight places less stress on the back than asymmetrical lifting of half as much weight. This finding may be of value to occupational safety and health professionals since recommending doubling the amount of weight lifted is rarely considered an ergonomic intervention. An example of this application would be situations where splitting the load equally between both hands is not an option. When possible, however, splitting loads into two equal and symmetrically held loads would be much preferred.

In conclusion asymmetric lifting activities are more hazardous than symmetric lifting activities. When lifting, to minimize risk, it is recommended to lift balanced loads.

Table 4.14: Comparison of Back Compressive Force When Lifting Twice as Much Weight Symmetrically (20 lbs.) vs. Lifting Half as Much Weight Asymmetrically (10 lbs.)

Subject	**10 lbs. Left Hand, 0 lbs. Right Hand**	**10 lbs. Left Hand, 10 lbs. Right Hand**	**0 lbs. Left Hand, 10 lbs. Right Hand**
1	148.7	137.6	151.5
2	143.8	128.4	138.8
3	157.7	142.5	156.4
4	146.8	129.8	145.1
5	138.7	135.0	152.4
6	160.1	141.4	163.1
7	158.8	145.0	174.4
8	155.7	151.2	169.3
9	181.7	161.8	179.6
10	141.5	125.6	140.5
Mean (SD)	153.4 (12.5)	139.8 (11.1)	157.1 (14.1)

There is approximately a 11% increase average of estimated BCF over all subjects for 10 lb. asymmetric vs. 20 lb. symmetric lifts.

Table 4.15: T–Test Results Comparing Back Compressive Force When Lifting Twice as Much Weight Symmetrically (20 lbs.) vs. Half the Weight Asymmetrically (10 lbs.)

N	**Lifting Scenario Comparison**	**P-Value**
10	10 lbs. L, 0 lbs. R vs. 10 lbs. L, 10 lbs. R	0.000
10	0 lbs. L, 10 lbs. R vs. 10 lbs. L, 10 lbs. R	0.000

Table 4.16: Comparison of Back Compressive Force When Lifting Twice as Much Weight Symmetrically (20 lbs.) vs. Lifting Half as Much Weight Asymmetrically (20 lbs.)

Subject	**20 lbs. Left Hand, 0 lbs. Right Hand**	**20 lbs. Left Hand, 20 lbs. Right Hand**	**0 lbs. Left Hand, 20 lbs. Right Hand**
1	209.0	166.5	202.2
2	161.3	151.8	166.2
3	203.4	173.3	184.1
4	190.4	163.9	181.7
5	192.8	163.2	192.2
6	201.4	174.6	219.6
7	206.2	214.0	203.6
8	207.3	183.0	230.3
9	239.5	211.4	234.2
10	173.8	175.9	196.2
Mean (SD)	198.5 (21.2)	177.8 (20.3)	201.0 (21.8)

There is approximately a 12% increase average of estimated BCF over all subjects for 20 lb. asymmetric vs. 40 lb. symmetric lifts.

Table 4.17: T–Test Results Comparing Back Compressive Force When Lifting Twice as Much Weight Symmetrically (40 lbs.) vs. Half the Weight Asymmetrically (20 lbs.)

N	**Lifting Scenario Comparison**	**P-Value**
10	20 lbs. L, 0 lbs. R vs. 20 lbs. L, 20 lbs. R	0.002
10	0 lbs. L, 20 lbs. R vs. 20 lbs. L, 20 lbs. R	0.002

Table 4.18: Comparison of Back Compressive Force When Lifting Twice as Much Weight Symmetrically (60 lbs.) vs. Lifting Half as Much Weight Asymmetrically (30 lbs.)

Subject	**30 lbs. Left Hand, 0 lbs. Right Hand**	**30 lbs. Left Hand, 30 lbs. Right Hand**	**0 lbs. Left Hand, 30 lbs. Right Hand**
1	262.7	219.9	258.4
2	216.0	195.6	Outlier
3	268.4	213.2	265.9
4	237.3	217.5	239.1
5	237.5	202.7	Outlier
6	292.0	230.2	288.0
7	280.1	227.2	290.8
8	266.2	222.8	305.0
9	265.2	244.2	294.9
10	230.0	194.7	229.7
Mean (SD)	255.5 (24.1)	217.3 (16.1)	271.5 (27.6)

There is approximately a 20% increase average of estimated BCF over all subjects for 30 lb. asymmetric vs. 60 lb. symmetric lifts.

Table 4.19: T–Test Results Comparing Back Compressive Force When Lifting Twice as Much Weight Symmetrically (60 lbs.) vs. Half the Weight Asymmetrically (30 lbs.)

N	**Lifting Scenario Comparison**	**P-Value**
10	30 lbs. L, 0 lbs. R vs. 30 lbs. L, 30 lbs. R	0.000
10	0 lbs. L, 30 lbs. R vs. 30 lbs. L, 30 lbs. R	0.000

Table 4.20: Comparison of Back Compressive Force When Lifting Twice as Much Weight Symmetrically (80 lbs.) vs. Lifting Half as Much Weight Asymmetrically (40 lbs.)

Subject	**40 lbs. Left Hand, 0 lbs. Right Hand**	**40 lbs. Left Hand, 40 lbs. Right Hand**	**0 lbs. Left Hand, 40 lbs. Right Hand**
1	308.4	241.9	281.1
2	204.8	222.0	Outlier
3	313.6	239.0	315.9
4	229.0	240.8	268.9
5	274.9	236.0	293.7
6	331.9	270.3	346.6
7	334.4	276.4	335.1
8	313.0	270.0	371.2
9	329.2	274.0	343.1
10	270.3	225.3	314.0
Mean (SD)	291.0 (45.1)	216.2 (44.3)	318.8 (33.4)

There is approximately a 22% increase average of estimated BCF over all subjects for 40 lb. asymmetric vs. 80 lb. symmetric lifts.

Table 4.21: T–Test Results Comparing Back Compressive Force When Lifting Twice as Much Weight Symmetrically (80 lbs.) vs. Half the Weight Asymmetrically (40 lbs.)

N	**Lifting Scenario Comparison**	**P-Value**
10	40 lbs. L, 0 lbs. R vs. 40 lbs. L, 40 lbs. R	0.000
10	0 lbs. L, 40 lbs. R vs. 40 lbs. L, 40 lbs. R	0.000

Table 4.22: Comparison of Back Compressive Force When Lifting Twice as Much Weight Symmetrically (100 lbs.) vs. Lifting Half as Much Weight Asymmetrically (50 lbs.)

Subject	**50 lbs. Left Hand, 0 lbs. Right Hand**	**50 lbs. Left Hand, 50 lbs. Right Hand**	**0 lbs. Left Hand, 50 lbs. Right Hand**
1	367.8	287.2	319.0
2	293.6	225.7	182.0
3	358.8	245.5	346.1
4	265.1	251.1	216.6
5	330.4	279.3	362.4
6	363.1	283.2	383.8
7	442.0	325.8	347.3
8	372.2	320.4	440.2
9	362.3	290.6	406.3
10	307.9	281.6	369.7
Mean (SD)	346.3 (49.5)	279.0 (31.4)	337.3 (80.5)

There is approximately a 22% increase average of estimated BCF over all subjects for 50 lb. asymmetric vs. 100 lb. symmetric lifts.

Table 4.23: T–Test Results Comparing Back Compressive Force When Lifting Twice as Much Weight Symmetrically (100 lbs.) vs. Half the Weight Asymmetrically (50 lbs.)

N	**Lifting Scenario Comparison**	**P-Value**
10	50 lbs. L, 0 lbs. R vs. 50 lbs. L, 50 lbs. R	0.000
10	0 lbs. L, 50 lbs. R vs. 50 lbs. L, 50 lbs. R	0.014

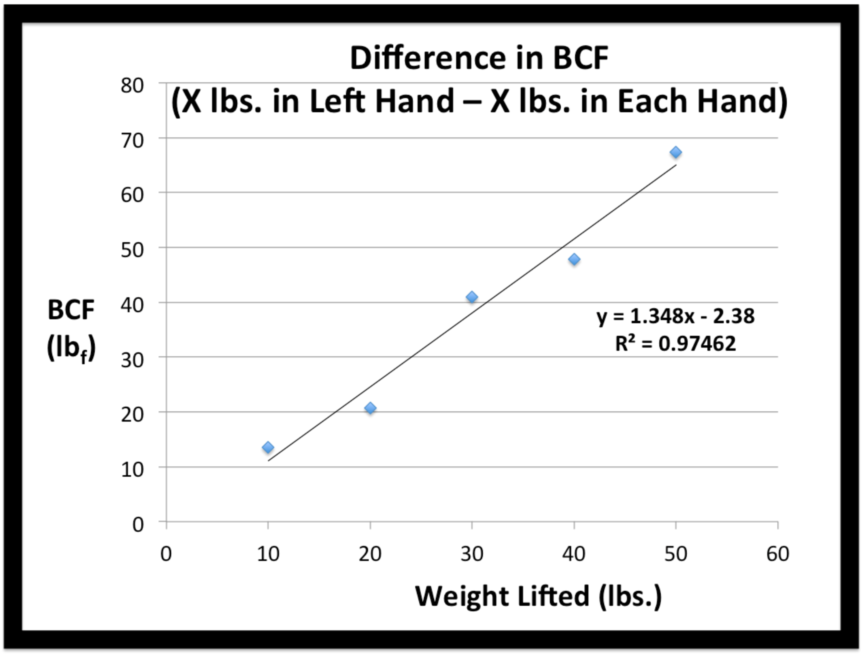

Figure 4.7: Difference in BCF, Two Hands vs. Left Hand

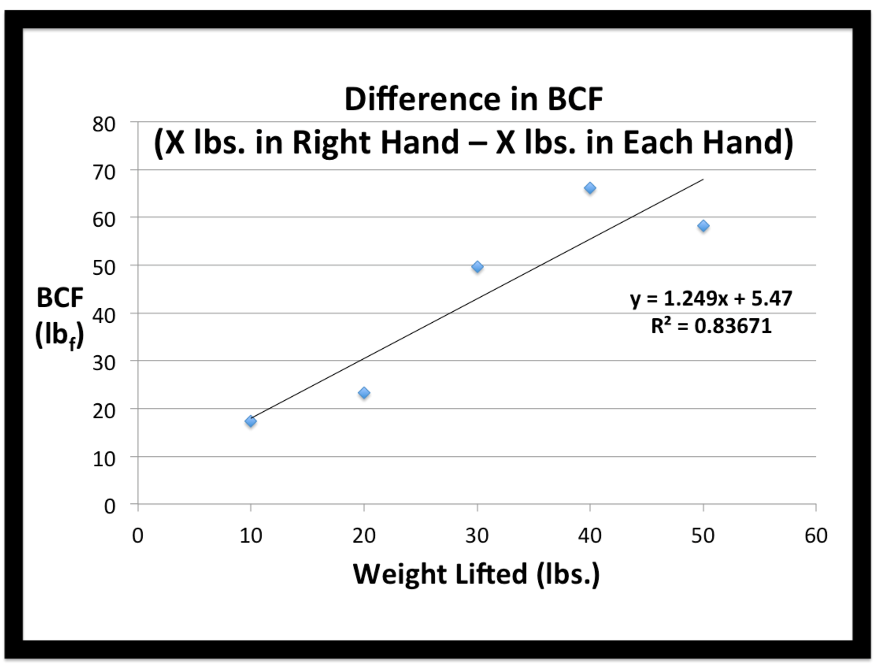

Figure 4.8: Difference in BCF, Two Hands vs. Right Hand

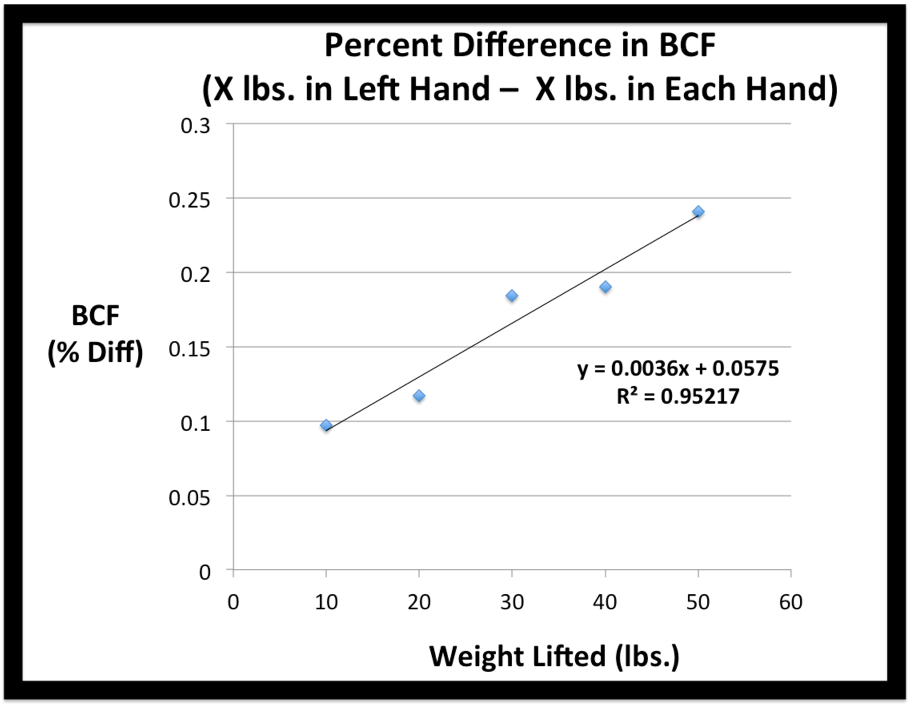

Figure 4.9: Percent Difference in BCF, Two Hands vs. Left Hand

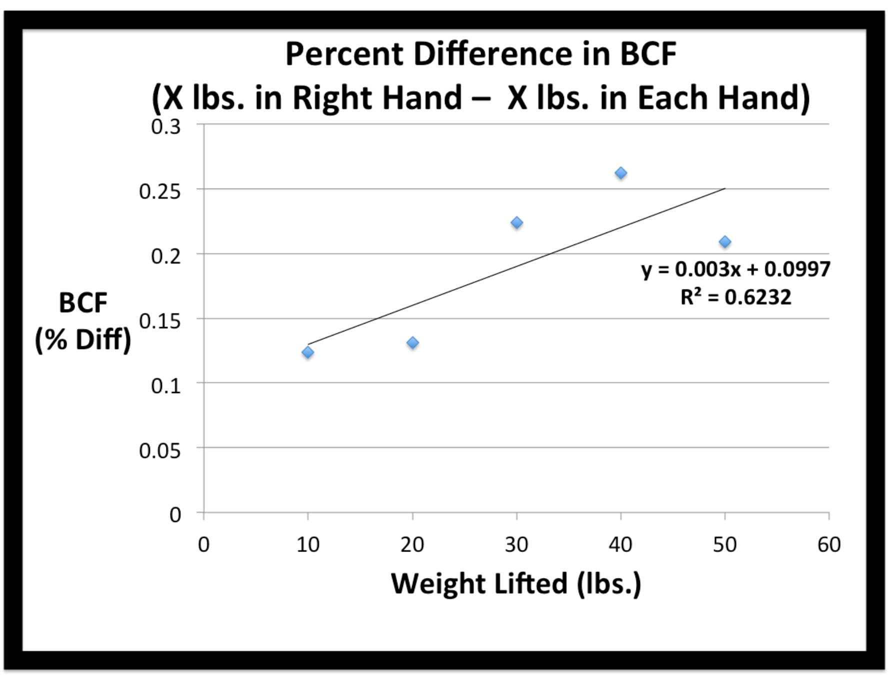

Figure 4.10: Percent Difference in BCF, Two Hands vs. Right Hand

4.4 Discussion

The purpose of the experiments was to determine the effects asymmetrical lifting had on BCF. In the first experiment, the subjects BCF was compared when equal amounts of weight were lifted symmetrically ($\frac{1}{2}$ X lbs. in each hand) vs. asymmetrically (X lbs. in one hand). In the second experiment, BCF was compared when twice as much weight was lifted symmetrically (X lbs. in each hand) vs. lifting half as much asymmetrically (X lbs. in one hand). In both experiments, the null hypotheses were rejected. The null hypothesis of Experiment 1 was Differences between one and two hand lifts will be directly proportional to the total weight lifted. Asymmetry will not alter BCF. The null hypothesis of Experiment 2 was BCF will increase as the amount of weight lifted increases regardless if lifted symmetrically or asymmetrically. BCF is directly proportional to weight lifted. In the first experiment, the average BCF between symmetrical and asymmetrical lifting trials was statistically significantly different for every left–hand and right–hand trial. In the second experiment, similar to the first experiment, the average BCF between symmetrical and asymmetrical lifting trials was statistically significantly different for every left–hand and right–hand trial.

In the first experiment, at the highest level of asymmetry, 50-pounds, there was over a 75% reduction in BCF when lifting equal amounts of weight symmetrically rather than asymmetrically in the left hand or right hand. The lifting scenarios presented in experiment 1 yielded a 27% to 76% increase in estimated BCF when lifting the same amount of weight asymmetrically vs. symmetrically. In the second experiment, the lifting scenarios yielded a 9% to 26% increase in estimated BCF when lifting the same amount of weight asymmetrically vs. symmetrically. Stated a different way, lifting twice as much weight symmetrically places less force on the back than lifting half as much asymmetrically. This effect increases as the weight lifted increases. Although counter intuitive, this result was not unexpected as Wilke et al., (2001) reported an 11 percent increase in BCF when a single subject carried one crate weighing 19.8 kg (43.6 lbs.) asymmetrically versus carrying two crates symmetrically.

In both experiments, symmetrical lifting is the preferred method of lifting. These results have many implications. In an industrial environment, there should be no reason to consider one–hand lifting for weights over 30 pounds. For instance, maintenance workers should be provided two smaller toolboxes rather than one larger toolbox as a preventive measure to minimize back injury risk. Second, although counter intuitive, lifting more weight symmetrically is easier than lifting less weight asymmetrically, likely due to minimizing muscle co–contraction that takes place during asymmetric lifting. Both experiments make a case for developing a biomechanically derived one–hand multiplier or other discounting factor that can be applied to an existing two hand lifting standard.

4.5 Limitations

There were three limitations associated with this study. First, only lateral lifts in which the weight held was a multiple of 10 were considered. This limited the number of symmetrical and asymmetrical comparisons that could be assessed without the need for interpolating BCF values. Second, the study was limited to 10 participants. The participants selected for the study had to meet multiple inclusion criteria which resulted in a homogeneous test population. More participants would have been desirable but funding only allowed for 10 subjects to be scanned at the AUMRIRC. Due to participant inclusion criteria, a fairly homogeneous study group was assessed. Lastly, using the erector spinae muscles as the basis for predicting back compressive muscle force based on EMG muscle activity seems to have influenced the predictive abilities of the model. The calibration trials had r^2 values that ranged from 0.694 to 0.985 (18 of 20 regression lines had r^2 values ranging .816 - .985), the calibration trials were performed with the forearm at approximately a 90° angle from the upper arm. This posture resulted in higher muscle activity than what was observed in the experiment lifting trials in which the arm was in a resting by the side in a neutral posture resulting in an angle of 180°. This posture yielded much lower erector spinae muscle activity resulting in the model being less able to accurately predict muscle forces in which EMG activity was relatively low (less than 10 microvolts).

4.6 Conclusions

The first objective of this study was to compare estimated BCF when lifting the same amount of weight symmetrically with two hands vs. asymmetrically with one hand. It was proposed that asymmetry will affect estimated BCF and the greater the level of asymmetry the greater the estimated BCF. All performed trials yielded significant results, the estimated BCF percent difference when lifting equal amount of weight asymmetrically was significantly greater than lifting symmetrically. Additionally, as the level of asymmetry increased, so did the difference in estimated BCF. The second objective of the study was to compare estimated BCF when lifting twice as much weight symmetrically with two hands vs. half of much weight asymmetrically with one hand. It was proposed that asymmetry will affect estimated BCF and the greater the level of asymmetry the greater the estimated BCF. Using the MLAL relative contribution model, estimated BCF was significantly different at all lifting levels for the left and right hand. Similar to the first experiment, as the level of asymmetry increased, so did the difference in estimated BCF.

Future work should consider enhancements to the model to improve its predictive ability. Specifically the model should:

- Consider muscle fiber orientations. Muscle angles were assumed to pull directly in line with the spine.
- Consider the same co–contraction as the final model during muscle calibration trials.
- Increase sample size to include a more heterogeneous population that includes females, subjects of various sizes, and subjects with diverse body composition.

4.7 Acknowledgments

I would like to thank Dr. Adam Jagodinsky from the Kinesiology Department at Auburn University for his advice as well as my fellow graduate students in the Industrial Engineering Department, Yousif Abulhassan, Fehmi Capanoglu, Bob Granzow, Rong Huangfu, Abhishek Rao, Menekse Salar and Akash Shettannavar who selflessly volunteered to collect data during all experimental trials.

Chapter 5

Predicting Muscle Size and Location by Gross Anthropometric Measurements

5.1 Introduction

The annual prevalence of low back pain in the United States has been estimated at more than one-quarter of the U.S. population [Deyo et al., 2006]. Low back pain is the leading cause of inactivity in people under 45 years old [Andersson, 1999]. It can affect over 50% of workers over a work career [Rowe, 1971] and the lifetime prevalence has been reported at 80 percent [Rubin, 2007]. The costs associated with work-related low back pain are high. It has been reported that, on average, low back pain costs over $8,000 per claim in direct costs, and accounts for one third of workers' compensation costs even though they make up only 16 percent of all claims [Webster and Snook, 1994]. In 1988, it was estimated that 22 million cases of back disorders occurred in the United States which resulted in almost 150 million lost work days [Guo et al., 1995]. Liberty Mutual Research Institute for Safety (2014) estimates that overexertion, which includes injuries related to lifting, pushing, pulling, holding, carrying, or throwing cost $13.6 billion dollars in direct costs to businesses. As long as manual material handling (MMH) activities take place in an industrial work environment, the risk of an overexertion injury, namely low back pain, is possible [Andersson, 1981], as it has been estimated that "30% of all occupational injuries in the United States are caused by overexertion of objects that weigh 50 lb or less [National Safety Council, 1996]."

Modeling of the low back musculature can be a useful tool in helping to understand the risks associated with MMH. Biomechanical models and laboratory studies are used to help determine how forces act on the body and how these exposures can result in physiological responses that may ultimately lead to a work-related musculoskeletal disorder (WMSD) injury [(Kromodihardjo and Mital, 1986) and (Mital and Kromodihardjo, 1986b)]. Typical biomechanical studies observe the magnitude and direction of forces exerted during manual handling tasks, exertion required to operate tools and equipment, the location where external forces act on the body, and the posture required while performing the task. Biomechanical modeling has been used to help explain the back compressive forces acting on the body and evaluate back injury potential. "By comparing a model's behavior with the actual behavior of a system, insight into how components of the system function are coordinated to achieve desired outcomes" [Chaffin et al., 1999].

Garg, (1983) anecdotally indicated that he has observed and also received confirmation from others that one–handed lifts in industry are a common occurrence. Fifteen years later, Marras and Davis, (1998) agreed with Garg's assertion by noting that one–hand lifts are a common occurrence in industry. Kingma and van Dieën, (2004) observed that workers are often forced to lift an object with one hand because the object in question only has one handle. Others [(Cook et al., 1991), (Ferguson et al., 2002), and (Jones et al., 2013)] have identified one–hand lifting taking place when removing items out of deep storage bins. Therefore, looking into the challenges faced by lifters only using one hand and better understanding the individual back muscle contribution and back compressive fores during these types of lifts could provide an impetus for a one–hand lift standard to be developed. Currently, there are no biomechanical models available for occupational safety and health professionals to use that estimate the relative contribution of each low back and trunk muscle during one-hand lifting activities.

This study was proposed to investigate if a meaningful relationship exists between easy to measure gross anthropometric characteristics and an individuals back muscle size and location. This relationship can improve the estimation of back compressive force (BCF) and be used as part of the assessment for estimating risks during asymmetrical lifting tasks. The objectives of this experiment were to: (i) measure low back and trunk muscles and effective muscle lever arm lengths of each subject; (ii) collect a variety of easy to access anthropometric measures and (iii) determine which anthropometric measures could best predict muscle cross sectional area (CSA) and effective muscle lever arm (EMLA) length.

5.1.1 Literature Review of Muscle Function and Size Estimation Via MRI

There are multiple means researchers can use to explore and describe the morphology of low back and trunk muscles. Gross dissection of a cadaver has been used to measure muscle architecture, [Delp et al., 2001] and determine muscle force capacity [Bogduk et al., 1998]. A noted drawback of using cadaver measurements in modeling is that the subjects used are typically elderly and, therefore, may have been inactive for long periods of time before their death [McGill et al., 1998] or otherwise not representative of workers currently preforming MMH tasks [Marras et al., 2001]. Ultrasound imaging has been used to obtain muscle CSA, shape and symmetry of the muscle on the left and right size of the spine [Hides et al., 1992]. Although ultrasound can provide real time data, it has the drawback of requiring physical contact with the body. Computed tomography (CT) scans have been used to collect low back and trunk muscle data as the procedure provides accurate information [(Reid et al., 1985) and (McGill et al., 1998)]. The drawback to CT scans are exposing healthy individuals to ionizing radiation and not producing images with a contrast quality as good as MRI scans. The literature shows many researchers who have used MRI technology to better understand the deeper regions of the body and used this information to help develop more accurate biomechanical models [(Tracy et al., 1989), (Jorgensen et al., 2001, (Marras et al., 2001) and (Gungor et al., 2015)].

In perhaps the first study that used MRI to study all the low back and trunk muscle groups, Tracy et al., (1989) measured the paraspinal muscles of 26 male subjects, of which 22 were thought to have disc degeneration, to collect data for use in biomechanical models. MRI scans were taken with the subjects laying supine with the hips extended. Regions of the spine assessed were from the L2–L3 to the L5–S1, with transverse sections taken through each intervertebral disc. The authors were able to describe the changes each muscle group underwent as it moved down the spine, as well as measure the CSA and position of each muscle position at each lumbar level. It appears there was no methodology to accurately determine muscle centroid as “the center of each muscle was assessed visually.” This may impact the “true” values of the muscle position. Two muscle group areas, the psoas and rectus abdominis were reported to have potential predictors that led to a significant regression equation.

In 2001, Jorgensen et al., (2001) collected male and female trunk moment arm information across multiple levels of the thoracic and lumbar spine to determine if a gender based difference existed between the different vertebral levels; and to determine if predictive moment arm equations could be developed using “external anthropometric measures.” MRI scans were taken on 30 subjects, 20 female and 10 male, who reported no history of “activity limiting chronic back or leg injuries.” Subjects were positioned in a supine posture with knees extended and hands lying across their abdomen. Muscle and disc centroids were determined using software that allowed a computer mouse to inscribe regions of interest. Muscle moment arms were then calculated taking the difference in distance between the muscle centroid and vertebral body centroid. Predictive moment arm equations were based on eight linear regression independent variables and a combination of these variables to create 13 new variables, for a total of 21 variables that were considered. Significant coronal plane regression equations developed had R^2 values that ranged from .198 – .677 for females and .398 – .897 for males. The authors observed that: the most consistent significant predictors for male coronal plane moment arms were the HeightxWeight and Height/Weight HTWT and HTDWT independent variables.

Marras et al., (2001) added to the work of Jorgensen et al., (2001) by using the same subject population and experimental methodology to quantify “trunk muscle cross-sectional areas of male and female spine loading muscles.” The authors observed that “anthropometric measures about the xyphoid process and combinations of height and weight resulted in better predictions of cross-sectional areas than when using traditional anthropometry”.

In an effort to enhance the understanding on psoas geometry which previously had been dependent on "cadaveric dissections" Reid et al., (1994) used MRI to study the geometry of the psoas muscle. Their methodology only reported that subjects were in a suppine position, with the hips extended, and to remain motionless. Santaguida and McGill, (1995) used MRI to to assess the line of action and mechanical function of the psoas major muscle. Their methodology included having subjects scanned in the supine position with a neutral lumbar curvature. Gungor et al., (2015) collected data from symptomatic subjects who had previously undergone an MRI procedure to confirm if they had any medical abnormalities in the lumbar spinal region. There were 163 subjects (82 males, 81 females) whose MRIs met inclusion criteria for consideration. Subjects were positioned in the MRI in a head-first-supine posture while their arms placed on their sides and knees were slightly flexed with a cushion under the legs. OsiriX software (v4.0), was used to capture regions of interest in the low back muscles for further analysis. These muscles were further analyzed using Rhinoceros software (v4.0) and its plug–in software Grasshopper (v0.8.0052) to calculate the erector spinae CSAs. The authors observed that "the results of the present study agree with some studies but are larger than most previous studies".

5.1.2 Literature Review Recap

Use of MRI is a viable way to measure muscle CSA and lever arm lengths. There is agreement on how the subject should be positioned in the MRI tube, (head first, in a supine posture with their arms placed either on their sides or lying on their abdomen and knees slightly flexed with a cushion under the legs). There is also agreement on how the torso musculature should be scanned, scan slices typically between 5–10 mm apart, perpendicular to the scanning bed, at transverse levels through the appropriate centers of the vertebral body [(Tracy et al., 1989), (Jorgensen et al., 2001) and (Gungor et al., 2015)].

The use of MRI technology has given researchers the ability to improve biomechanical models. Now actual human data can be collected safely, relatively easily, and inexpensively compared to the past. The benefits of using MRI include researchers being able to observe anthropometric differences exists among different populations.

5.2 Methods

Ten volunteers from the Auburn University student population that met the experiment inclusion criteria, including the ability to safely undergo an MRI procedure, were selected to participant in the study. Each subject underwent an MRI procedure that captured all low back and trunk muscle groups at the L–3 region of the back, Figure 5.1 shows two AUMRIRC Level–3 certified personnel overseeing an MRI procedure. MRI procedure order was based on subject and AU MRI Research Center (AUMRIRC) availability. MRI procedure order is shown in Table 5.1. The Auburn University Internal Review Board (IRB) approved the study protocol on October 31, 2015 [Auburn University, 2015b]. Subjects were consented, reminded of time requirements, risks associated with undergoing an MRI procedure, and filled out an AUMRIRC Pre-Entry Screning Form [AUMRIRC, 2015]. Auburn University protocol approval can be found in Appendix D. At a minimum two graduate assistants participated in the MRI data collection at the AUMRIRC to comply with AUMRIRC protocol of at least two Level–3 certified personnel operating the MRI scanner.

Table 5.1: MRI Procedure Order

Trail Number	**Subject Number**
Trial 1	M001
Trial 2	M004
Trial 3	M002
Trial 4	M007
Trial 5	M005
Trial 6	M006
Trial 7	M009
Trial 8	M010
Trial 9	M003
Trial 10	M008

5.2.1 Objective and Hypothesis

The objective of this study was to develop a regression model using easily measured gross anthropometric characteristics to predict an individual's back muscle size and location using MRI data.

The hypothesis of the experiment is:

Null Hypothesis: There is no meaningful relationship (significant correlation) between the measured anthropometric variables and an individual's back muscle size and location.

$$H_0 : a(x) \neq b(y) + c(z)$$
$$H_1 : a(x) = b(y) + c(z)$$

5.2.2 Experimental Design

Independent variables for this experiment were:

- Anthropometric variables

- Muscle cross sectional area
- Muscle location

The dependent variable was:

- Transverse MRI taken at the L–3 region of the back

The Auburn University Internal Review Board (IRB) approved the study protocol on October 31, 2015 [Auburn University, 2015b]. Approval notification documents can be found in Appendix B and Apprendix C. Once IRB approval was secured, recruitment for the study commenced. A sample flyer used to solicited interest in the study is included in Appendix D. Ten volunteers from the Auburn University student population that met the experiment inclusion criteria, including the ability to safely undergo an MRI procedure, were selected to participant in the study. The screening form used to help determine if a participant met eligibility requirements is included in Appendix E. Each subject was consented using the approved IRB consent form, Appendix F. Subjects also consented to be photographed during the lifting trials. Approved Samuel Ginn College of Engineering Photo Release forms for participants whose photograph was used can be found in Appendix G. Although "AU policy allows for the use of student photgraphs without consent if they are perfoming tasks associated with school activities" [Killian, 2016], fellow graduate students whose photograph was used during data collection also filled out photo release forms, and can be found in Appendix G as well.

5.2.3 Procedure

The MRI procedure used in this experiment is the same that was performed in Chapter 3 and can be found in Section 3.2.3.

5.2.4 Equipment

A Siemens Verio Open-Bore 3T MRI Scanner with lumbar coil was used for all the MRI procedures. The lumbar coil was used to improve spatial resolution around the spine. Scanner software required height and weight information which was collected using a tape measure and typical "bathroom" scale located within the AUMRIRC. Additional anthropometric measurements were collected using a standard anthropometry measuring kit and skin calipers. Additionally, two open source computer programs, OsiriX v4.0 and Open Source Computer Vision (OpenCV) were used to analyze MRI scans.

5.2.5 OsiriX

OsiriX, an image processing software package for medical research image processing application. It has been specifically designed for navigation and visualization of multimodality and multidimensional images. It is dedicated to Digital Imaging and Communications in Medicine Images, i.e., .DCM extension, produced by MRI equipment [Rosset et al., 2004].

5.2.6 OpenCV

OpenCV is a library of programming functions mainly aimed at real–time computer vision. "Computer vision is a field that includes methods for acquiring, processing, analyzing, and understanding images and, in general, high-dimensional data from the real world in order to produce numerical or symbolic information. This image understanding can be seen as the disentangling of symbolic information from image data using models constructed with the aid of geometry, physics, statistics, and learning theory" [Forsyth and Ponce, 2003].

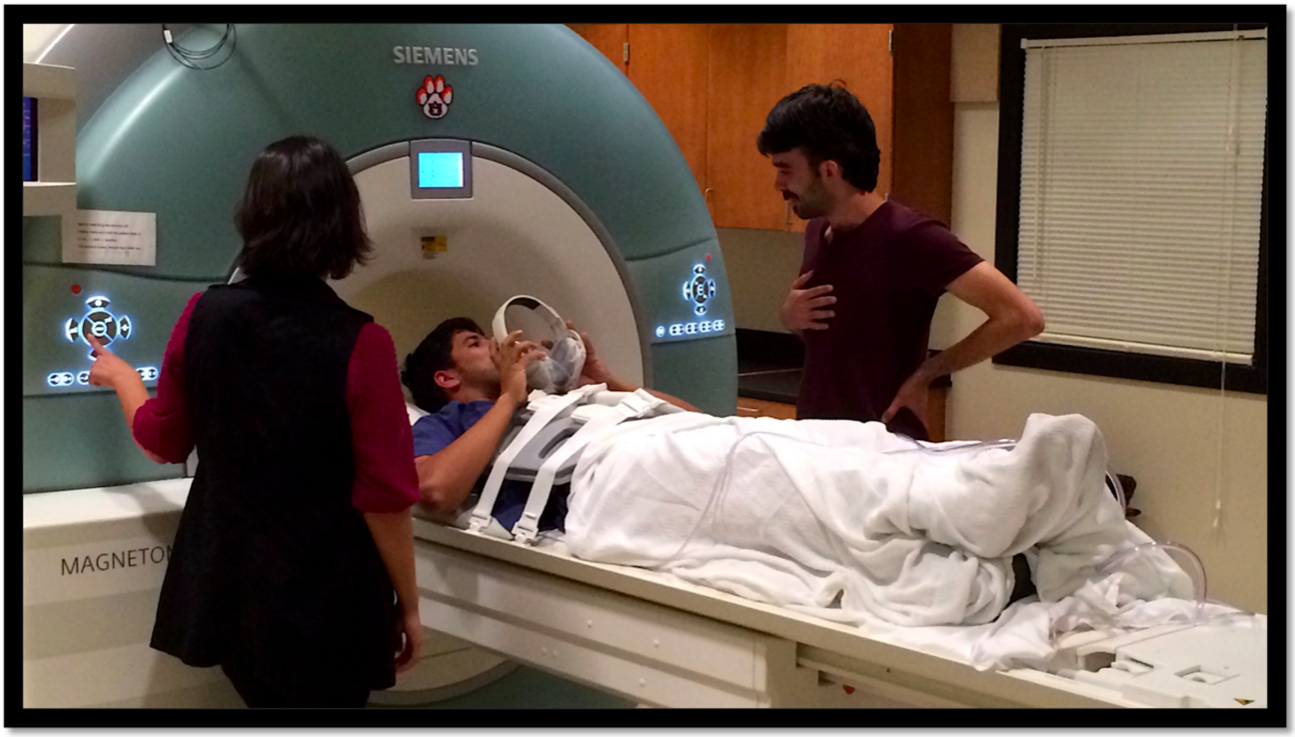

Figure 5.1: Siemens Verio Open–Bore 3T MRI Scanner

5.2.7 Statistical Analyses

The goal of this experiment was to determine a regression relationship between muscle size and anthropometric data. MRI data for 10 subjects was collected and yielded CSA and mechanical lever arm lengths for the; left and right erector spinae, left and right oblique group (combines internal oblique, external oblique, and latissimus dorsi), left and right psoas, left and right rectus abdominis, and left and right quadratus laborum. Fourteen (14) anthropometric measurements were collected to facilitate creation a regression equation. A list of the anthropometric measures can be found in Table 5.2.

Table 5.2: Collected Anthropometric Measures

Height	Neck Circumference
Weight	Waist Circumference
BMI	Chest Circumference
Pectoral Skinfold	Abdominal Skinfold
Hip Breadth	Thigh Skinfold
Chest Depth	Shoulder Breadth (bi-acromial)
Abdominal Depth	Shoulder Breadth (bi-deltoid)

Initially, a best subsets regression was run to create a regression equation for the left erector spinae. There was no anthropometric variable with a p value less than .05. This may be due to having a low population size of n=10. In order to increase the likelihood of creating a regression equation with variables with a calculated p value of less than .05 a paired t-test was run to determine if there was a difference between the left and right erector spinae values. The results indicated there was not. In order to "double" the subject population, left and right muscle groups were combined (in this case left and right erector spinae) which effectively yields a new population size of n=20 to facilitate the creation of a regression relationship that can predict muscle size based on anthropometric variables. Based on the success of combining the left and right erector spinae values, subsequent t-tests were performed on all remaining muscle groups and CSAs. All groups demonstrated no statistical difference between the left and right side. A stepwise regression model was employed to analyze the data to determine the best predictors for the regression equations.

5.3 Results

5.3.1 Descriptive Statistics

Ten students volunteered to participate in this study. Inclusion criteria included: being male; 25 years or age or younger; no prior history of back injury; and a Body Mass Index

(BMI) of 30 kg/m^2 or less. The mean age of participants was 22.8 years (SD=1.48), mean weight of 70.71 kg (SD=6.89), mean height of 178 cm (SD=7.21), and a mean BMI of 22.9 kg/m^2 (SD=2.77). Table 5.3 contains select anthropometric data for each study participant. Other anthropometric data collected includes:

- hip height
- hip breadth
- knee height
- shoulder breadth (bi-acromial)
- shoulder breadth (bi-deltoid)
- chest circumference
- chest depth
- neck circumference
- waist circumference
- abdominal depth
- pectoral skinfold
- abdominal skinfold
- thigh skinfold

In addition to the fourteen anthropometric measures available for analysis, twelve additional predictor variables developed using a combination of two anthropometric measures (for instance height divided by weight) were considered.

Tables 5.4 and 5.5 contain muscle CSA information for the muscle groups on the left and right side of the body respectively. These data were derived from an MRI scan traced using OsiriX, Figure 5.2 shows a subject's processed MRI scan. Tables 5.6 and 5.7 contain EMLA lengths measured from the disc centroid to muscle centroid for muscle groups on the left and right side of the body respectively. These data were taken from an MRI scan processed using Open CV, Figure 5.3 shows a subjects processed MRI scan.

Table 5.3: Selected Subject Anthropometric Data

Subject	**Age**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
M001	23	173	70.3	23.87
M002	25	177	74.8	23.90
M003	23	184	70.8	21.22
M004	25	175	65.3	21.78
M005	22	168	62.1	22.92
M006	23	170	69.9	24.92
M007	23	186	72.3	21.37
M008	20	187	73.3	21.82
M009	22	175	85.7	29.00
M010	22	185	62.6	18.65

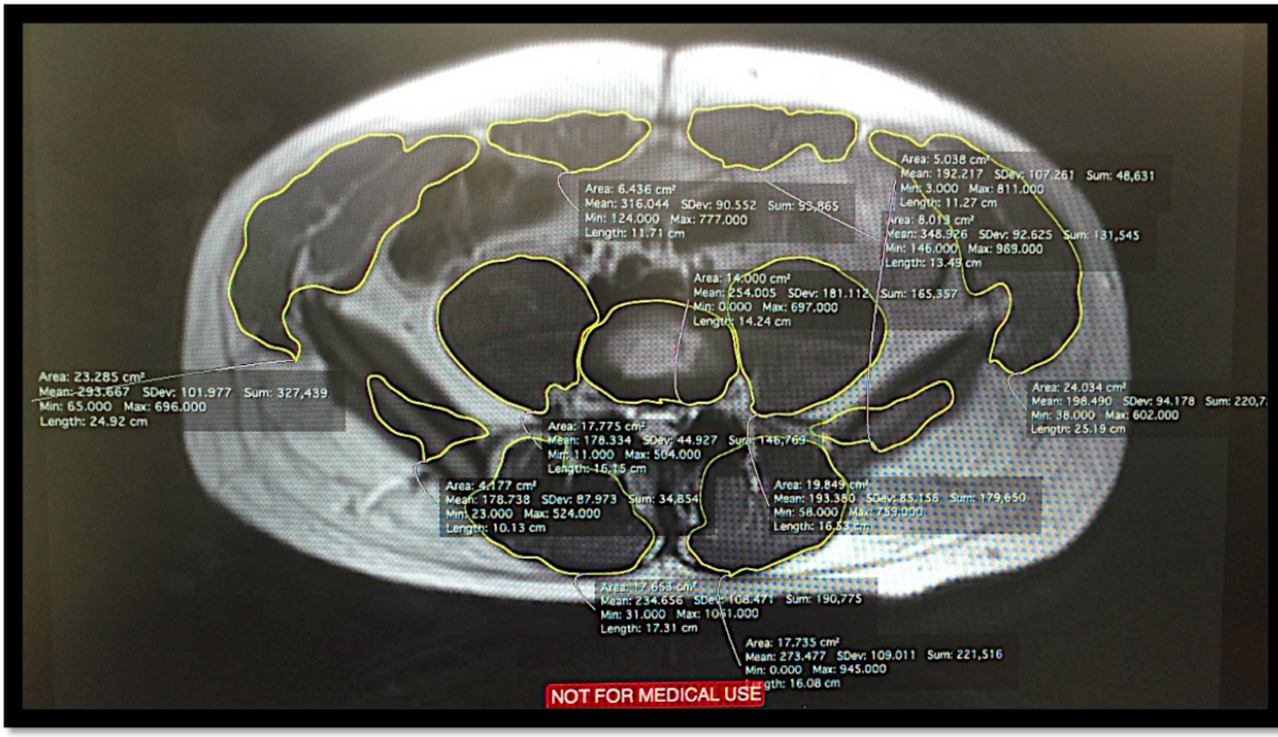

Figure 5.2: MRI with traced muscle groups and calculated CSA

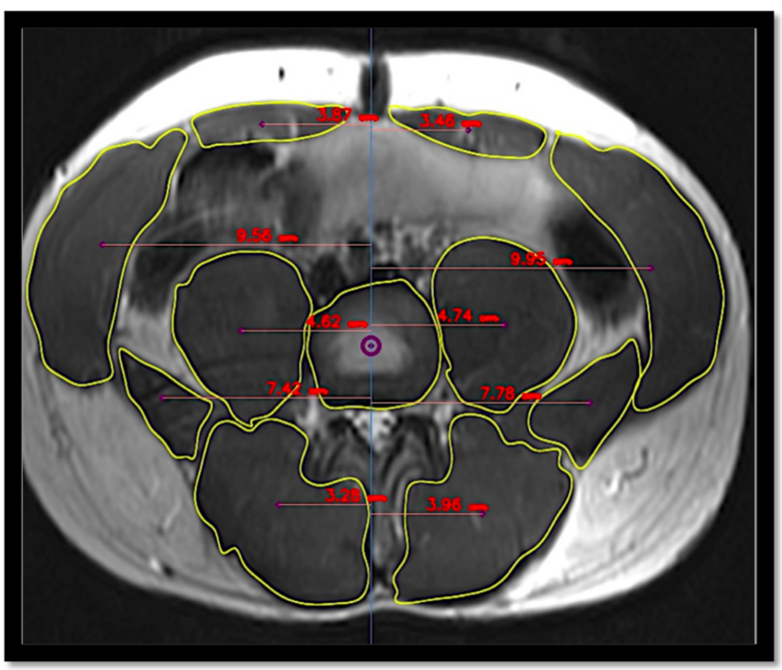

Figure 5.3: MRI with traced muscle groups and calculated mechanical lever arm lengths

Table 5.4: CSA, Left Muscle Groups (cm^2)

Subject	**L. Er. Spinae**	**L. Oblique**†	**L. Psoas**	**L. Rect. Abd.**	**L. Quad Lumb.**
M001	22.62	22.90	16.07	6.23	6.719
M002	23.67	22.47	19.96	7.66	2.355
M003	10.52	14.31	13.06	5.37	6.197
M004	19.16	26.94	13.23	5.93	5.221
M005	18.57	22.05	22.58	5.23	5.214
M006	17.65	23.29	17.78	6.44	4.177
M007	17.82	22.85	12.06	4.00	5.778
M008	27.03	24.99	15.46	6.52	5.19
M009	22.54	27.63	18.43	7.48	5.811
M010	27.67	22.34	12.77	4.81	7.111
Average (SD)	20.73 (5.08)	22.98 (3.62)	16.14 (3.50)	5.97 (1.15)	5.38 (1.35)

† L. Oblique consists of the left internal oblique, external oblique and latissimus dorsi.

Table 5.5: CSA, Right Muscle Groups (cm^2)

Subject	**R. Er. Spinae**	**R. Oblique**†	**R. Psoas**	**R. Rect. Abd.**	**R. Quad Lumb.**
M001	26.14	20.77	19.81	6.72	6.18
M002	25.47	24.94	17.22	8.56	3.43
M003	9.95	13.75	14.58	6.24	5.47
M004	19.72	32.21	13.79	6.22	6.91
M005	19.73	22.23	22.02	5.38	7.75
M006	17.74	24.03	19.85	8.01	5.04
M007	18.12	25.15	13.22	4.51	5.97
M008	26.20	29.03	16.33	6.49	7.42
M009	23.75	28.57	16.46	7.95	6.60
M010	28.19	22.44	14.71	4.82	7.78
Average (SD)	21.50 (5.52)	24.31 (5.12)	16.80 (2.93)	6.49 (1.37)	6.25 (1.36)

† R. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 5.6: Mechanical Lever Arm Length, Left Muscle Groups (cm)

Subject	L. Er. Spinae	L. Oblique[†]	L. Psoas	L. Rect. Abd.	L. Quad Lumb.
M001	4.09	11.44	4.56	4.53	8.27
M002	4.59	15.10	5.95	5.91	11.40
M003	3.47	14.39	7.39	4.38	10.26
M004	3.39	11.16	4.87	3.87	7.67
M005	3.28	9.56	4.62	3.87	7.72
M006	3.48	10.54	4.82	3.18	8.43
M007	3.45	10.38	4.54	3.26	7.46
M008	3.93	11.05	4.91	4.00	8.87
M009	3.68	11.13	4.72	2.69	7.03
M010	3.65	9.16	4.32	3.10	6.82
Average (SD)	3.70 (0.40)	11.39 (1.92)	5.07 (0.93)	3.88 (0.93)	8.39 (1.45)

[†] L. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

Table 5.7: Mechanical Lever Arm Length, Right Muscle Groups (cm)

Subject	R. Er. Spinae	R. Oblique[†]	R. Psoas	R. Rect. Abd.	R. Quad Lumb.
M001	3.81	10.55	4.36	3.40	8.82
M002	4.06	13.25	5.29	3.57	10.75
M003	2.06	12.73	6.14	3.72	9.00
M004	2.94	10.72	4.61	3.27	7.37
M005	3.96	9.95	4.74	3.46	7.78
M006	3.41	10.40	4.53	3.41	7.52
M007	3.26	10.01	3.75	2.74	8.02
M008	3.93	11.18	4.91	3.20	8.74
M009	3.64	12.53	5.25	4.18	6.91
M010	3.83	9.55	4.38	3.71	7.52
Average (SD)	3.49 (0.61)	11.09 (1.30)	4.80 (0.65)	3.47 (0.38)	8.24 (1.12)

[†] R. Oblique consists of the right internal oblique, external oblique and latissimus dorsi.

5.3.2 Inferential Statistics

Regression equations were created to determine if easy to measure anthropometric data could be used to predict muscle and disc CSA as well as EMLA distances. Fourteen predictor variables based on anthropometric measurements as well as twelve predictor variables developed using a combination of two anthropometric measures (e.g. height divided by weight) were analyzed. Predictors and their abbreviations can be found in Table 5.8. Regression equations pertaining to muscle CSA, EMLA length and disc CSA can be found in Tables 5.9, 5.10 and 5.11 respectively.

In building the regression model, the goal was to choose as small a number of variables as possible so that the constructed model would be simple and have good predictive ability.

Minitab (v17) statistical software package was used to build all regression models. A stepwise regression was used to identify the best-fitting regression model for each back muscle and mechanical lever arm. The reasons for this selection was that there were too many predictors available for a backward elimination regression to take place and using a best subsets would necessitate the need to fit the model with regression to look at p-values, variance inflation factors (VIF), and residuals.

Performing the stepwise regression the model started with no predictors. Predictors were entered and removed in a stepwise manner until there was no justifiable reason to enter or remove predictors. Minitab ceases to add or subtract from the model when all variables not included in the model have p-values that are greater than a specified Alpha-to-Enter value, which was set at 0.15 and when all variables that are in the model have p-values that are less than or equal to a specified Alpha-to-Remove value, which was also set at 0.15.

Table 5.8: Terms Used in Regression Equations

Term	**Definition**
Weight	WT
Height	HT
Body Mass Index	BMI
Hip Breadth	HIPBR
Shoulder Breadth Bi-Acromial	SBBA
Shoulder Breadth Deltoid	SBD
Chest Circumference	CC
Waist Circumference (Army)	WC
Neck Circumfrance (Army)	NC
Chest Depth	CD
Abdominal Depth	AD
Pectoral Pinch (3-point)	PP
Abdominal Pinch (3-point)	AP
Thigh Pinch (3-point)	TP
Height*Weight	HT*WT
Weight/Height	HT/WT
Chest Circumference/Weight	CC/WT
Chest Circumference/Height	CC/HT
Chest Depth/Weight	CD/WT
Chest Depth/Height	CC/HT
Abdominal Depth/Weight	AD/WT
Abdominal Depth/Height	AD/HT
Abdominal Pinch/Weight	AP/WT
Abdominal Pinch/HT	AP/HT
Waist Circumference/Weight	WC/WT
Waist Circumference/Height	WC/HT

The minimum threshold for an acceptable regression model was if the regression model yielded p-values no greater than .05 for all predictors, a Lack of Fit greater than .05, and a VIF less than 3.0 for all predictors. However, if the model did not meet any of the threshold criteria, then predictors were removed from the model in an effort to improve its predictive ability. The model would be refit by removing predictors with a p-value greater than .05, then, if necessary, the model would be refit again if there were predictors with a VIF greater than 3.0. A correlation matrix was created and used to determine the dependence between two predictors.

Table 5.9: Muscle Size Regression Equations (cm^2)

Muscle	**Regression Equation**	$\mathbf{R^2}$	**S.E.**	**P-value**
Er. Spinae	(92.7 - 1.231*HIPBR -137.1*AD/WT)	64.7	3.26	0.008
Oblique	(28.4 + 0.338*CC - 0.944*SBBA)	63.3	2.80	0.014
Psoas	(78.0 - 0.3456*HT)	55.1	2.18	0.001
Rect. Abd.	(-5.96 + 0.5097*CD + 6.77*AD/WT)	69.9	0.28	0.043
Quad. Lumb.	(16.15 - 3.280*PP - 26.80*CD/WT)	63.1	0.90	0.006

Table 5.10: Lever Arm Regression Equations (cm)

Muscle	**Regression Equation**	$\mathbf{R^2}$	**S.E.**	**P-value**
Er. Spinae	(9.50 - 0.1133*HIPBR - 10.22*AD/WT)	40.4	0.42	0.048
Oblique	(9.563 + 2.619*PP)	45.2	1.21	0.001
Psoas	(5.79 +0.2263*AD - 0.0589*CC)	50.2	0.59	0.028
Rect. Abd. †	(2.242 + 0.0475*PP)	7.4	0.30	0.247
Quad. Lumb.	(14.32 + 2.341*PP - 0.0816*CC)	45.7	0.98	0.050

† Not statistically significant.

Table 5.11: Disc Size Regression Equation (cm^2)

Regression Equation	$\mathbf{R^2}$	**S.E.**	**P-value**
(26.98 -0.4120*SBD + 20.73*AD/WT)	63.8	0.70	0.002

5.4 Discussion

The purpose of the experiment was to develop a regression model using easily measured gross anthropometric characteristics to predict an individual's back muscle size and location using MRI data. The null hypothesis, there is no meaningful relationship, i.e. significant correlation between measured anthropometric variables and an individual's back muscle size and location was rejected. Based on the results of the experiment, there is indeed a meaningful relationship between anthropometric variables and an individual's back muscle size and location. This was expected as the literature has demonstrated researchers who have used MRI technology to better understand the deeper regions of the body and used this information to help develop more accurate biomechanical models [(Jorgensen et al., 2001) and (Gungor et al., 2015)].

Developed muscle size and lever arm regression equations were significant for all muscle groups except for the rectus abdominis. Also, muscle size regression equations were more accurate than lever arm regression equations. Muscle size regression equations R^2 values ranged from 55.1 – 69.9 whereas lever arm regression equations ranged from 40.4 – 50.2. The disc had an R^2 value of 63.8. This illustrates that the procedures in place were capable of generating meaningful regression equations and fits into the expectations that were identified in previous research. Although no regresson relationships could be determined for the rectus abdominis this was not unexpected. Jorgensen et al., (2001) in their research were unable to generate a regression equation of the left rectus abdominis for female subjects.

Ten regression equations were created using only 10 of the 26 anthropometric terms available. These terms were all related to height, weight, shoulder breadth, chest circumference chest depth, abdominal depth, and pectoral pinch. Three variables, chest circumference, abdominal depth/weight, and pectoral pinch, were the most frequently occurring variables. Each was present in three of the equations and accounted for 50% of the terms used to create the muscle and disc regression equations. The muscle size, lever arm, and disc regression equations needed either 1 or 2 terms to create a regression equation, with an average of 1.75 terms per equation.

It was attempted to determine if common body measurement techniques could predict muscle size and location. The Army Body Fat Calculator which uses height, neck circumference, and waist circumference and the Jackson–Pollock 3–spot body fat test which uses pectoral, abdominal, and thigh skinfolds were assessed. Neither technique was able to predict a muscle size or location. However, pectoral pinch was present in three of the ten regression equations.

The main differences between observed and reported regression equations are:

- The predominant predictors for lever arm equations reported by Jorgensen et al., (2001) were height times weight and height divided by weight whereas in the experiment performed there were five predictors (hip breath, abdominal depth divided by weight, pectoral pinch, abdominal depth and chest circumference), none appearing more than twice that comprised the lever arm regression equations.

- The predominant predictors for muscle CSA reported by Marras et al., (2001) were anthropometric measures about the xyphoid process and combinations of height and weight whereas in the experiment performed there were eight different predictors with only abdominal depth divided by weight appearing more than once.

The results indicate that commonly used anthropometric data such as height, weight and trunk dimensions should still be considered as the “gold standard” for use in building regression equations of the low back and trunk muscles.

Finally, the data provide insight that using MRI scans can provide accurate muscle size and location information so that biomechanical models can be built to predict stress on the back during lifting activities.

5.5 Limitations

A few limitations were associated with this study. Although the subject population was fairly uniform in that only males, 25 years of age or younger, with a BMI under 30 lbs/in^2 were only considered, there was a wide variation in the groups' muscle sizes. Due to the small population size, (n=10), this variability may have influenced the ability of anthropomorphic measures to more accurately predict muscle size. Also, hand dominance was not considered as an inclusion criteria yet all subjects were right hand dominant. This may have influenced subject muscle size. On average, all muscles on the left side of the body had a larger area than the corresponding muscles on the right side of the body. The small sample size also influenced how statistical tests were run. In this experiment, regression analyses were not able to be run for the left and right side muscle groups independently. Only when data from the left and right side muscle groups were combined was it possible to conduct a regression analysis. It is recommended that, if this research is to be expanded upon, then a greater number of subjects who are both left–hand and right–hand dominant should be considered. This will allow for variations in muscle geometry to be better accounted for and for independent analysis of the left muscle groups and right muscle groups to be conducted as well as allow for statistical tests such as backward elimination regression.

5.6 Conclusions

This study proposed to investigate if a meaningful relationship exists between easy to measure gross anthropometric characteristics and an individuals back muscle size and location. Conceptually, the idea of using MRI data to "look in the body" to collect muscle information not readily available is an accepted practice to collect data to build regression models to estimate muscle size and locations as well as moment arm lengths.

Preliminary data suggest easy to collect anthropometric measures can act as predictors of muscle size and location in the L–3 region of the back. All muscle sizes, all but one muscle location and disc size and location could be predicted through use of easy to measure anthropometric data. The following anthropometric measures; height, weight, chest circumference and pectoral pinch were most prevalent muscle size and muscle location predictors. Also, rather than left and right hand, dominant and non-dominant hand should be considered.

The anthropometric variables used to build the equations are typically made up of different combinations of gender (assuming both genders are studied), trunk measurements, height and weight. In this study additional measures were considered that are traditionally not considered such as grip strength, measurements needed to create an Xsens model (measurements used in previous experiments to estimate of hand and back postures), measures used in the Jackson–Pollock 3–spot body fat test and the Army Body Fat Calculator. None of these "non-traditional" measures yielded significant results.

In conclusion, the results indicate that commonly used anthropometric data such as height, weight and trunk dimensions should still be considered as the "gold standard" for use in building regression equations of the low back and trunk muscles.

Future research could expand on this work by exploring muscle size and location at the L–4 and L–5 region of the back. Additional work should also Increase sample size to include a more heterogeneous population that includes females, subjects of various sizes, and subjects with diverse body composition. For instance, investigate differences in subjects whose BMI ranges from 30 – 40 lbs/in^2 and over 40 lbs/in^2.

5.7 Acknowledgments

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Chapter 6

Conclusions

6.1 Introduction

The annual national bill for the care of low back problems has been estimated to be $100 billion [OSHA, 2014]. The annual prevalence of low back pain in the United States has been estimated at more than one–quarter of the U.S. population and the lifetime prevalence has been reported at 80 percent [Rubin, 2007]. The costs associated with work–related low back pain is high. On average, low back pain costs over $8,000 per claim in direct costs, and accounts for one third of workers' compensation costs even though they make up only 16 percent of all claims [Webster and Snook, 1994]. Even with all the attention paid to back injuries and their cost, there is no consensus on how to prevent back injuries. Worker training, back schools, work hardening, back belts, use of multiple lifting techniques or administrative practices are all methods reported to minimize worker exposure and minimize the incidence of back injuries. Yet none of these alternatives have resulted in a long term decrease to back injury rates or costs [(Burgess-Limerick, 2003) and (van Poppel et al., 1997)].

There has been little research on one–hand lifting particularly when compared to the amount of attention paid to symmetric two-hand lifting. While there is established two hand lifting guidance from government and professional organizations such as NIOSH, ACGIH, and the DoD, there is no one-hand lift standard from these same organizations even though one-hand lifting has been anecdotally recognized as a frequently occurring task in industry. Some of the earliest one-hand studies concluded that physiological experimental methods were not the ideal method to develop one-hand lifting guidance and that psychophysical studies did not account for the BCF acting on the back. More recent biomechanical studies that have incorporated MRI technology have reported creating more accurate models as muscle size and lever arm lengths from healthy populations that more closely resemble the current workforce are better data sources than cadaver studies.

Based on the prevalence and costs of low back injuries and the lack of biomechanically based one-hand lifting models, there is an opportunity to provide information to organizations that may find guidance on one-hand lifting valuable to help maintain a healthy workforce.

6.2 Summary of Findings

Three experiments were performed in this dissertation. The first experiment was to determine the most accurate way to estimate back compressive force (BCF) during asymmetrical lifting activities. Measures under investigation were models that estimated muscle contribution as a function of Cross Sectional Area (CSA), Mechanical Lever Arm Length (MLAL), MLALxCSA and MLALx$CSA^{1.5}$. The second experiment compared and discussed BCF when laterally lifting with one hand or two hands. The final experiment considered the development of a regression model using easily measured gross anthropometric characteristics to predict an individual's back muscle size and location.

The summarized findings of the first experiment are:

1. The MLAL weighted model had the lowest average rank score and its rank order performance was significantly different the other models performance.

2. Based on anticipated co–contraction levels reported by the literature, the MLAL was the best predictor of BCF when perfoming asymmetrical one-hand and two-hand lifts.

3. The level of co-contraction impacts a model's performance. At low levels of co–contraction, ≤ 15 percent, the CSA weighted model was the best predictor of BCF, at levels between 15 – 21 percent, the MLALxCSA weighted model was the best predictor, and at levels > 21 percent, the MLAL weighted model was the best predictor.

4. At co–contraction levels of 30 percent, the CSA weighted model's absolute error was 66 percent higher that the MLAL weighted model's absolute error. This difference prevented any CSA weighted model to be the best predictor of BCF at levels greater than 30 percent co–contraction.

The summarized findings of the second experiment are:

1. On average, symmetrical lifting (weight divided equally in both hands) reduces back compressive force by 70% (at the heaviest weight, 50 lbs.) compared to lifting the same amount of weight asymmetrically (weight held in one hand).

2. On average, Symmetrical lifting (weight divided equally in both hands) of twice as much weight places up to 24% less compressive back force on the back (at the heaviest weight, 50 lbs.) than asymmetrical lifting (weight held in one hand) of half as much weight.

The summarized finding of the third experiment are:

1. Significant correlations between measured anthropometric variables and an individuals back muscle size and location exist.

2. Regression equations for every muscle group under consideration could be created using on average 1.80 predictors per equation. R^2 values ranged from 41.6 to 70.6.

3. Regression equations for four of five muscle lever arms under consideration could be created using on average 1.75 predictors per equation. No relationship exists for the rectus abdominis lever arm. R^2 values ranged from 32.5 to 50.2.

Co–contraction which has been identified in the literature as a contributor to BCF is an important factor to consider when evaluating the effectiveness of back models. The literature reports that co–contraction can increase spinal loads by up to 25 percent compared to values predicted by models that do not consider co–activity. Furthermore, co–contraction has been observed in lateral bending and lifting. The results of experiment three suggest that no one model acted as the best predictor of BCF at co–contraction levels between 0.0 – 0.30.

Using MRI scans to collect anthropometric data is a valuable tool in the creation of more accurate models. This technology allows for better understanding of the deeper regions of the body and provides researchers with an alternative to relying on less accurate muscle data derived from cadaver studies.

6.3 Limitations of the Research

Limitations associated with this research included:

1. During development of the lifting model not all muscle groups were considered, as there was concern that the MRI scans would not be able to differentiate the internal and external oblique or if the latissimus dorsi would be distinguishable from the obliques. Therefore, both oblique muscles and the latissimus dorsi were "lumped together" as one muscle group. This created a larger muscle group, thereby potentially overestimating the obliques relative muscle contribution, especially on measures that considered the CSA of a muscle. Also, muscles were assumed to pull directly in line with the spine. Future work should consider muscle fiber orientations.

2. The arm posture used to create the calibration curves may have influenced the predictive abilities of the model. The calibration trials were performed with the forearm at approximately a 90° angle from the upper arm. This posture resulted in higher muscle activity than what was observed in the experiment lifting trials in which the arm was in a resting by the side in a neutral posture resulting in an angle of 180°. This resulted in the model appearing to be less accurate in predicting muscle forces when EMG activity was relatively low. Also, co–contraction was not assumed during muscle calibration testing. Future models should consider the same co–contraction as the final model.

3. The study was limited to 10 participants due to the costs associated with obtaining an MRI scans. Future work should increase sample size.

4. The selected study participants had to meet multiple inclusion criteria which resulted a homogeneous test population. Future work should include a larger more heterogeneous population that includes females, subjects of various sizes, and subjects with diverse body composition.

6.4 Recommendation for Future Research Studies

Several opportunities have arisen from this study, namely future studies should include a larger more heterogeneous population. Specific recommendations for future studies include:

- Expand model to include the L4–L5, L5–S1, and other regions of the back in order to gain a better understanding of what is happening to the back during one–hand lifting.
- Expand the model to include arms extended in different planes.
- Run the model on different populations, such as females, BMI between 25-30, and BMI > 30.
- Investigate one–hand lifting impacts on the shoulder.
- Explore if there is an optimal container shape when performing one-handed lifting.
- Investigate one–handed lifting impacts on the lower extremities.
- Investigate back compressive force reduction in when carrying an item in each hand versus carrying an item in one hand.
- Expand regression analysis to entire torso as well as regression analysis of a larger more heterogeneous population that includes females, subjects of various sizes, and subjects with diverse body composition.

Davis, P. and Stubbs, D. (1980).

Appendices

Appendix A

One–Hand Lift Literature Search Results

Year: 1966 Authors: McConville and Hertzberg Title: A Study of one-handed lifting Synopsis: 15 subjects lifted 5 containers and 15 subjects lifted 5 different containers. The initial starting weight (30 pounds) was kept constant for all subjects. After a successful trial, the observer replaced the container on the floor and added an increment of weight; either 5 or 10 pounds, depending upon how easily the previous lift was carried out. The trials were continued until the subject had achieved his maximum possible one-handed lift. Amount of weight that can be safely lifted can be expressed as Y=60-X, where Y is the weight that can be lifted in pounds and X is the width of the object being held in one hand.

Year: 1971 Authors: Datta and Ramanathan Title: Ergonomic comparison of seven modes of carrying loads on the horizontal plane Synopsis: A comparative study of seven modes of carrying an identical load at ground level was conducted. Carrying modes are head, rucksack, double pack, rice bag, sherpa, yoke, and hands. 30kg carried at a rate of 5km/hr. Oxygen consumption, heat rate, minute ventilation, minute ventilation during recovery were measured. The double pack mode was ergonomically the best mode, followed closely by the head mode. Carrying by hands was the worse method and the other methods were intermediate as far as physiological economy is concerned.

Year: 1975 Author: Drury Title: Predictive models for setting safe limits in manual materials handling Synopsis: Dynamic carrying produced lower endurances that static holding. This reduction suggests that the extra muscular fatigue due to steadying the object against the applied forces of movement was greater than the potential gain in endurance from increased blood flow to the stressed muscles. Also, there is no difference in endurance between lifting a single weight (e.g. 25 kg) with one hand and two equal weights (e.g. 2 x 25 kg) with two hands. This implies that the two arms can be considered independent vs. additive.

Year: 1980 Authors: Davis and Stubbs Title: Force limits in manual work Synopsis: Considered to be the most comprehensive data on one-hand lift force. Recommendations are provided for males performing one-hand lifting tasks while standing, squatting, sitting, or kneeling. The authors recommend reductions based on the age of the lifter, use of dominant vs. non-dominant hand, and acromial-grip distance.

Year: 1980 Authors: Warwick et al. Title: Maximum voluntary strengths of male adults in some lifting, pushing and pulling activities Synopsis: Applying forceful exertions by both, left or right hand, in six different directions, in 8 body positions. Six positions are vertically upward (lift), vertically downward (press), push forward, pull backward, push left push right. Strength depends markedly on body configuration, direction of force exertion, and hands used in task execution.

Year: 1980 Authors: Yates et al. Title: Static lifting strength and maximal isometric contractions of back, arm, and shoulder muscles Synopsis: Single predictor for lifting strength varies between sexes as well as substantial variation occurring from position to position. No multivariate predictor of lifting strength could be found.

Year: 1981 Authors: Schultz and Andersson Title: Analysis of Loads on the Lumbar Spine Synopsis: Study presents procedures to calculate loads on the lumbar spine and the contraction forces in the trunk muscles during one–hand lifts.

Year: 1982 Authors: Schultz et al. Title: Loads on the lumbar spine. Validation of a biomechanical analysis by measurements of intradiscal pressures and myoelectric signals Synopsis: The study attempted to validate predictions of compressive loads on the lumbar spine and contraction forces in lumbar trunk muscles based on a biomechanical model. The predictions were validated by quantitative measurements of myoelectric activities at twelve locations on the trunk and of the pressure in the third lumbar disc. Model did a good job predicting compressive loads on the lumbar spine and for one-hand lifts while the subjects were seated the forces on the left oblique muscles (contralateral to the hand holding weight) were higher than the oblique muscle forces on the right side.

Year: 1983 Author: Garg Title: Physiological responses to one-hand lift in the horizontal plane by female workers Synopsis: Two lifting distances of 38 and 63.5 cm and three weights (2.3, 4.5, and 5.7 kg for 38 cm) (1.2, 2.3, and 4.5 kg for 63.5 cm). The degree of effort involved in a one-handed lift in the horizontal plane is not accurately reflected by physiological responses. Psychophysical responses offer a greater potential to determine a "safe" workload for one-handed lifts.

Year: 1983 Author: Mital Title: Subjective Estimates of One-Handed Carrying Tasks Synopsis: Three task variables, shape of container (plastic bucket, galvanized iron bucket, tool box, radiator can), volume of container (8.5 and 12.3 liters), and carrying distance (30.48, 60.96, and 91.44 meters). Shape of the container significantly influenced the amount of weight subjects were willing to carry in one hand.

Year: 1985 Authors: Legg et al. Title: Comparison of different methods of load carriage Synopsis: The energy cost of four modes of load carriage used to repeatedly move 30kg boxes over 10 meters were compared. Bimanually and anteriorly at waist height, on one shoulder, clasped to the chest, and in one hand. The most inefficient way to lift of the four techniques was one hand lift.

Year: 1985 Author: Mital Title: Preliminary guidelines for designing one-handed material handling tasks Results of a literature search indicate that for optimum performance, one-handed tasks should elicit a RPE of about 12 on the Borg scale. Males and females should not carry more than 9.95 and 7.1 kg load, respectively, in their stronger arm, by the side, for distances up to 91.5 m.

Year: 1987 Authors: Cook and Neumann Title: The effects of load placement on the EMG activity of the low back muscles during load carrying by men and women. Synopsis: Two different magnitude loads (10% and 20% of the subject's body weight) and four different carrying positions were compared with walking without an external load. EMG activity showed slight decreases when loads were carried in a backpack position or in the hand ipsilateral to the muscle. EMG activity contralateral to the hand carrying the load was significantly increased. Significant increases occurred when loads were carried anterior to the chest with the arms and a significant difference was found between male and female subjects for this carrying position. These findings have implications for the selection of carrying methods.

Year: 1988 Authors: Garg et al. Title: One-handed dynamic pulling strength with special application to lawn mowers Synopsis: Maximum stresses were perceived on the shoulder and upper arm with a mean rating between fairly light and somewhat hard. Dynamic pulling strength for women is 62 percent of strength for men.

Year: 1989 Authors: Strasser et al. Title: Local Muscular Strain Dependent on the direction of Horizontal Arm Movements Synopsis: Subjects were seated and performed lifting at a distance of 38 cm. Direction of movement from the frontal plane was between 20 to 230 degrees; weight handled was 0, 1, 2, and 4 kg, frequency was 12, 24, or 48 lifts per minute. The direction of movements in a horizontal plane implies considerable variations of the strain on the hand-arm-shoulder system.

Year: 1990 Authors: Cook et al. Title: Dynamic comparison of the two-hand stoop and assisted one-hand lift methods Synopsis: The initial distance of the handles from the floor was 31 cm. The final distance of the handles from the floor was 114.4 cm when the box was rested on the top edge of the container for a total vertical excursion of 83.4 cm. The horizontal distance from the midpoint of the box in its initial location to the top edge of the container was 36.6 cm for all lifts. Three loads, 3.75 kg, 6.81 kg, and 13.64 kg, were used in randomly ordered blocks of six lifts each. Within each block, subjects randomly varied the type of lift, using one-hand assisted lift or two-hand stoop lift. Consequently, all subjects performed a total of 18 lifts. Under certain circumstances, the (supported) one-hand lift is a less stressful method of lifting than the two-hand stoop method.

Year: 1990 Authors: Mital and Faard Title: Effects of sitting and standing, reach distance, and arm orientation on isokinetic pull strengths in the horizontal plane Synopsis: Three independent variables (1) Posture (sitting and standing) (2) reach distance (25, 40, and 55 cm for sitting, 45, 65, 85 for standing) and (3) angle of the stronger arm relative to the frontal plane (0, 30, 60, 90, 120, and 150 degrees). Isokinetic pull strength of males is almost 37% greater in the standing posture than in the sitting posture. Maximum isokinetic pull strength is exerted when the arm is in the sagittal plane.

Year: 1991 Authors: Jager et al. Title: Lumbar load during one-handed bricklaying Synopsis: The lumbar load during bricklaying increases (a) with decreasing grasp height (90, 50, 10 cm), (b) with decreasing execution time, (c) and with increasing weight of the brick.

Year: 1992 Authors: Kilbom et al. Title: One-handed load carrying - cardiovascular, muscular and subjective indices of endurance and fatigue Synopsis: Participants carried varying loads that were to fatigue them while on a treadmill. Treadmill was set at 4 km/hr. Walking times were 3, 5, 9, 11, and 13 minutes. Prolonged carrying in one hand of more than 6 kg or 10 kg for young healthy women and men respectively should not be recommended, since it could lead to cardiovascular non-steady states and EMG signs of fatigue.

Year: 1995 Authors: Wilkinson et al. Title: Relationships between one-handed force exertions in all directions and their associated postures Synopsis: Subjects performed maximal force exertions at three heights and 26 force directions. Knowing the limits of the exertable force due to deployment of bodyweight may be of use in training so that workers may be made aware of how a change in posture may improve their ability to carry out a task.

Year: 1996 Authors: Allread et al. Title: Trunk kinematics of one-handed lifting, and the effects of asymmetry and load weight Synopsis: Each subject performed every lift. Independent variables were (lift technique, one or two hands), (load asymmetry at the beginning of the lift, sagittally symmetric, 45 deg, 90 deg, and 135 deg to the right of the mid-sagittal plane) and (box weight 3.4, 6.8, 10.2 kg). Unsupported one-handed lifting loads the spine more than two-handed lifts due to the added coupling. One-handed lifts also increase the risk of suffering a low back disorder.

Year: 1997 Authors: Marras and Granata Title: Spine loading during trunk lateral bending motions Synopsis: Subjects performed static and isokinetic lateral exertions while standing on a force plate. Static and dynamic exertions were performed while subjects held weights in their right hand i.e. left lateral exertion, or left hand, i.e. right lateral exertion.

Independent variables consisted of three isometric lateral trunk angle conditions (15 degree left, 0 degree (upright), 15 degree right), three-isokinetic lateral trunk velocity conditions (15,30, and 45 s-), two weight levels (13.6,27.3 kg), and two exertion directions (right, left). Compression and lateral shear increased monotonically as trunk velocity increased. It is expected that this combined (compression and lateral shear) loading is the mechanism for increased risk observed in industry.

Year: 1998 Authors: Yoon and Smith Title: Psychophysical and physiological study of one-handed and two-handed combined tasks Synopsis: Two different task variables were studied: task frequency, and hand condition for performing a task. Three different frequencies (6/min, 1/min, and 1/5 min), and two-hand conditions (one- handed and two-handed) were investigated. For one-handed tasks, each subject used his right hand, which was his preferred hand. The capacity of one-hand combined tasks was over 75% of the capacity of two-handed combined tasks at the same handling frequency. High correlations were observed between one-hand and two-handed task capacities at the same handling frequency, indicating that a positive, linear relationship may exist between the capacities of one-hand and two-handed tasks.

Year: 1999 Authors: Strasser and Muller Title: Favorable movements of the hand-arm system in the horizontal plane assessed by electromyographic investigations and subjective rating Synopsis: Subjects performed one-handed lifting task in the horizontal plane, moving repetitively objects of approximately 0 kg and of 1 kg on a table. Thirteen different directions in the frontal area had been provided. The direction of the movements is an important parameter for the muscular strain. Both static and dynamic components of the muscular activity show a strong dependence on the moving direction. The directions around 30 (measured from the body plane) cause less than half of the muscular load in comparison with directions between 90 and 160, which are often found in real work situations. The strain in the relevant muscle groups dependent on the working direction is not neglectable.

Year: 2001 Authors: Kothiyal and Kayis Title: Workplace layout for seated manual handling tasks: an electromyography study Synopsis: Seated manual handling tasks performed with one hand. Subject used the dominant hand to perform the task and handled weights of magnitude 1 and 2 kg at the work rates of 10 and 20 movements/min. Starting positions were fixed at 45, 90 and 150 degrees with respect to the body midline. The distance over which weights were moved was fixed at 38 cm. Results of the study show that muscular strain as measured by EMG activity was in general sensitive to variations in magnitude of load and work rate. Work rate had relatively large influence on muscular strain as compared to magnitude of load. The results of the study indicate that the total muscle load was dependent on the direction of movement.

Year: 2001 Author: Wilke et al. Title: Intradiscal pressure together with anthropometric data - A data set for the validation of models Synopsis: Subject performed a variety of tasks including one-hand lift (19.8 kg), lifting 19.8 kg in each hand, and a two-hand lift of 19.8 kg. and two hand lifting of the same weight. Intradiscal pressure was less when lifting 19.8 kg in each hand then just lifting 19.8 kg in one hand.

Year: 2002 Author: Ferguson et al. Title: Spinal loading when lifting from industrial storage bins Synopsis: Workers lifting from the lower regions or upper back region of a bin should be encouraged to use one-handed supported lifting styles to minimize spinal loading. Supporting body weight on the side of the bin with one hand reduces spinal loading by at least 15

Year: 2003 Author: Institute of Occupational Medicine for the Health and Safety Executive 2003 Title: The principles of good manual handling: Achieving a consensus literature review of one-hand lifting studies. Synopsis: When lifting to the side of the body, a one-handed lift is preferable. However, when lifting in front of the body a two-handed lift is to be preferred. If only one hand can be used for some reason then using the second hand to support the body confers some benefit.

Year: 2003 Authors: Kingma and van Dieen Title: Lifting over an obstacle: effects of one-handed lifting and hand support on trunk kinematics and low back loading Synopsis: Two-handed lifting is compared to one-handed lifting (with and without supporting the upper body with the free hand) while lifting over an obstacle. A 3-D linked segment model was combined with an EMG-assisted trunk muscle model to quantify kinematics and joint loads at the L5S1 joint. The hypothesis that one-handed lifting with support of the free hand causes substantial reduction of low back loading was supported. The support force at the free hand and the reduction of the distance of L5S1 to the trunk COM and to the load appear to be the major factors causing this reduction. In addition, one-handed lifting was found to result in increased asymmetry in movements in and moments about the lumbar spine.

Year: 2003 Authors: Sesek et al. Title: Evaluation and quantification of manual materials handling risk factors Synopsis: Database consisting of 667 manufacturing jobs and historical injury data, symptom interviews, and basic medical exams for approximately 1,100 participants. The RNLE can be modified to allow analysis of one-handed and two-handed asymmetric lifts without hindering performance.

Year: 2004 Authors: Gall and Parkerhouse Title: Changes in physical capacity as a function of age in heavy manual work Synopsis: The physical test battery administered consisted of eight separate test modules, with the physical capacity of the right and left hands being assessed in three of the eight modules, for a total of 11 assessments. Among the test were static one-handed lifts and static one-hand pull downs. Based on the principal of specificity for muscle training and testing, this study has demonstrated that heavy manual work appears to maintain physical capacity specific to the task as age progresses.

Year: 2004 Author: Gielo-Perczak Title: Maximum one-handed pull force and its relation to shoulder geometry Synopsis: Individual joint geometry influences the maximum acceptable load that can be applied to the hand during pulling. Also an area determined by the height and width of the glenoid fossa closely relates to the mean force during pulling.

Year: 2004 Author: Lee Title: Static lifting strengths at different exertion heights Synopsis: Two-handed lifting should be encouraged for its higher lifting strength and less strains on load-bearing shoulder, elbow and wrist structures compared with one-handed lifting.

Year: 2005 Authors: MacKinnon and Vaughan Title: Effect of reach distance on the execution of one-handed sub maximal pull forces Synopsis: As forward reach increases the greater the flexion movements and increased range of motion of the trunk. Also EMG activity of the trapezius and deltoid muscles decreases with increasing reach distance.

Year: 2006 Authors: Garg et al. Title: Short-cycle overhead work and shoulder girdle muscle fatigue Synopsis: The simulation consisted of four tasks in a 1-min job-cycle. Each cycle was repeated 50 times. The four tasks were varied with different predetermined combinations of two weights (W1 signifying a workpiece and W2 signifying the hand-tool weight), three exertion times and three shoulder postures. W1 was either 1.36 or 2.73 kg (3 and 6 lb.), and W2 was 0.45, 0.91 or 1.82 kg (1, 2 and 4 lb.). Exertion time was with the arm up for 2 seconds and down for 2 s (22) for ten exertions per minute, arm 3 s up and 3 s down (33) for seven exertions/min, or arm 5 s up and 3 s down (53) for five exertions/min. An analysis of variance showed that all four variables (workpiece weight (W1), tool weight

(W2), arm up and down time, exertion time and shoulder posture) were statistically significant (pp0.01), although the tool weight and workpiece weight were most predictive of capabilities. As expected, the RPE, fatigue and pain increased with an increase in the weights of the workpiece (W1) and hand tool (W2). NOTE: Tasks performed included one hand carry, one hand lift, and working with each hand above shoulder height.

Year: 2008 Authors: Hoffman et al. Title: Postural behaviors during one-hand force exertions Synopsis: Analysis of one-handed exertions indicates that, when possible, people tend to align their bodies with the direction of force application, converting potential cross-body exertions into sagittal plane exertions.

Year: 2009 Authors: Faber et al. Title: Low-back loading in lifting two loads beside the body compared to lifting one load in front of the body Synopsis: Comparison of low-back loads in lifting two 10 kg objects on either side of the body to lifting 20 and 10kg objects in front of the body. Lifting a 20-kg split-load instead of a 20-kg single-load resulted in most cases in a reduction (832%) of peak L5/S1 compression forces. The magnitude of the reduction was roughly comparable to halving the load mass and depended on lifting technique and load width. The effects of load-splitting could largely be explained by changes in horizontal distance between the load and L5/S1.

Year: 2010 Authors: Mo et al. Title: Literature Review on One-Handed Manual Material Handling Synopsis: Authors found 37 research articles and plan on using the data as a basis for one-hand guidance.

Year: 2012 Authors: Arjmand et al. Title: Predictive equations for lumbar spine loads in load-dependent asymmetric one- and two-handed lifting activities Synopsis: A finite element biomechanical model is used to estimate spinal loads during one- and two-handed asymmetric static lifting activities. It is concluded that the NIOSH AM multiplier should depend on the trunk posture and be defined in terms of the load vertical and horizontal positions.

Year: 2012 Authors: McGill et al. Title: Low back loads while walking and carrying: comparing the load carried in one hand or in both hands Synopsis: The participants were instructed to walk carrying buckets containing various weights (5 kg both hands, 10 kg 1 hand, 10 kg both hands, 15 kg both hands, 20 kg 1 hand, 30 kg 1 hand, 30 kg both hands). The weight was either distributed evenly in two buckets held in either hand or in one bucket carried in the right hand. Carrying a load in one hand (30 kg) resulted in more spine load than splitting the same load between both hands (15 kg). When carrying double the load in both hands (30 kg in each hand vs. 30 kg in one hand), spine load decreased, suggesting merit in balancing load when designing work.

Year: 2012 Authors: Sevene et al. Title: Physiological and psychophysical comparison between a one and two-handed identical lifting task Synopsis: Participants performed three, 5-minute work bouts with the milk crate. Order (i.e., right hand, left hand, or both hands) was determined randomly. Three minutes of rest was allowed between work bouts. Pace was constant at eight lifts per minute. Lifting technique was self-selected by the participant and no foot placement instructions were given. There were no differences in metabolic cost or perceived exertion when performing a paced, one- or two-handed identical lifting task with self-selected lifting technique.

Year: 2012 Authors: US Department of Defense Title: Department of Defense Design Criteria Standard Human Engineering Synopsis: Provides one-hand carrying limits for male and female Soldiers. Males 82 lbs. for carries 33 feet or less, 30 lbs. for carries greater than 33 feet. Females 42 lbs. for carries 33 feet and less, 30 lbs. for carries longer than 33 feet.

Year: 2013 Authors: Jones et al. Title: The effect of bracing availability on one-hand isometric force exertion capability Synopsis: Participants exerted one-handed isometric backward, forward and upward exertions at four task handle configurations(1. No brace: no contact with the structure permitted other than at the task hand. 2. Hand only: hand bracing permitted, no contact with thigh structure. 3. Thigh only: thigh bracing permitted, no hand bracing. 4. Hand and thigh: both thigh and hand bracing permitted). Analyses of one-hand maximal push, pull and lift tasks demonstrated that bracing surfaces available at the thighs and non-task hand enabled participants to exert an average of 43% more force at the task hand.

Appendix B

IRB Approval Letter

AUBURN
UNIVERSITY

Office of Research Compliance
115 Ramsay Hall, basement
Auburn University, AL 36849

Telephone: 334-844-5966
Fax: 334-844-4391
IRBadmin@auburn.edu
IRBsubmit@auburn.edu

May 29, 2015

MEMORANDUM TO:	Dr. Richard Sesek Mr. John Pentikis Department of Industrial and Systems Engineering
PROTOCOL TITLE:	"Low Back Muscle Modeling During One-Hand Lifting Tasks"
IRB AUTHORIZATION NO:	15-110 EP 1503
APPROVAL DATE: EXPIRATION DATE:	March 2, 2015 March 1, 2016

Your protocol was approved as "Expedited" by Auburn University's IRB #1 under 45 CFR 46.110(4) and (7):

> "(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)
> (7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies."

Note the following:

1. RECORDS: Keep this and all protocol approval documents in your files. Please reference the complete protocol number in any correspondence.
2. MODIFICATIONS: You must request approval of any other changes to your protocol before implementation. Some changes may affect the assigned review category.
3. RENEWAL: Submit a renewal a month before expiration. If your protocol expires and is administratively closed, you will have to submit a new protocol to continue your research.
4. FINAL REPORT: When your study is complete, please submit a final report to the Office of Research Compliance, Human Subjects.

If you have any questions concerning this Board action, please contact the Office of Research Compliance.

Sincerely,

Dr. Bernie Olin, Phar.D.
Chair of the Institutional Review Board #2
for the Use of Human Subjects in Research

Appendix C

IRB Approval Email

From: IRB Administration <irbadmin@auburn.edu>
Date: November 3, 2015 at 3:48:54 PM CST
To: Richard Sesek <rfs0006@auburn.edu>
Cc: John Pentikis <jsp0013@auburn.edu>, Jorge Valenzuela <valenjo@auburn.edu>
Subject: Modification request - approved, Protocol # 15-110 EP 1503

Use IRBsubmit@auburn.edu for protocol-related submissions and IRBadmin@auburn.edu for questions and information. The IRB only accepts forms posted at https://cws.auburn.edu/vpr/compliance/humansubjects/?Forms and submitted electronically.

Dear Rich,

Your request for modification of your protocol entitled " Low Back Muscle Modeling During One-Hand Lifting Tasks " has been approved. The review category continues as "Expedited" under federal regulation 45 CFR 46.110(9).
You are approved to include female participants and to reduce the size of the weights for them.

Official notice:
This e-mail serves as official notice that your protocol has been modified. A formal approval letter will not be sent unless you notify us that you need one. By accepting this approval, you also acknowledge your responsibilities associated with this approval. Details of your responsibilities are attached. Please print and retain.

Consent document:
Attached is a scan of your new, stamped consent and flyer. (The original paper documents will only be sent upon request.) Provide a copy for each participant to keep. Also attached is the approved

modification request.

Expiration:
Your protocol will still expire on March 1, 2016. About three weeks before that time you will need to submit a final report or renewal request.

If you have any questions or concerns, please let us know.

Best wishes for success with your research!
Susan

Susan Anderson, IRB Administrator
IRB / Office of Research Compliance
115 Ramsay Hall, basement
Auburn University, AL 36849
(334) 844-5966
IRBadmin@auburn.edu *(for general queries)*
IRBsubmit@auburn.edu *(for protocol submissions)*

Appendix D

Sample Advertisement Flyer

Low Back Modeling Research Study
Be part of an important research study

Are you a male?
Are you between 19 and 25 years old?
Can you lift 50 pounds with one hand?
Are you willing to participate in an MRI procedure?

If you answered ***YES*** to these questions, you may be eligible to participate in the following study: Low Back Muscle Modeling During One-Hand Lifting Tasks.

The purpose of this research study is to model the muscles of the low back and trunk to estimate compressive forces in the lumbar spine. To create the model, muscle sizes and positions will be estimated using magnetic resonance imaging (MRI). Muscle activity will be measured using electromyography (EMG) sensors. Together, the use of MRI and EMG technology can help model the muscle activity of the low back.

There is no direct benefit to you for participating in the study. Participants will receive monetary compensation of up to $75.00 for participating.

This study is being conducted by the Industrial and Systems Engineering Department at Auburn University. MRI images will be captured at the Auburn University MRI Research Center.

Please contact Mr. Akash Shettannavar at **ADS0045@auburn.edu** to schedule an appointment.

Appendix E

Initial Screening Form

I am calling on behalf of the Industrial and Systems Engineering Department. You had previously expressed an interest in participating in a research study. I would like to ask you a few screening questions to determine if you are eligible for an upcoming study on one–hand lifting.

If, at any point, you have a question for me or any concerns please let me know what they are. I will do my best to answer them.

The first set of questions will be asked to determine if you meet the anthropometric and other eligibility requirements.

Y N Are you an Auburn University student?

What is your:

Age: *Must be between 19-25 to meet eligibility requirements.*

Gender: *Must be male to meet eligibility requirements.*

Height:

Weight:

BMI: *Must be* ≤ 30 *to meet eligibility requirements.*

Calculate participants BMI.

BMI = (Weight (pounds) x 0.45) ÷ (Height (inches) x 0.025)^2

For example someone 74in tall and weighting 225lbs has a BMI of 29.6

(225lbs x .45) ÷ (74in x 0.025) ^{2} = 101.25 ÷ 3.42 = 29.6

What is your shoe size (American size chart)? *Shoe size must be between 9 11 to be eligible.*

The next set of questions will be asked to determine if you meet the MRI eligibility requirements. Please answer honestly. Although an MRI procedure is a safe practice permanent injury can result if you have metal in your body.

Must answer No to all questions to be eligible.

Y N Do you have a cardiac pacemaker or implemented cardioverter defibrillator (ICD)?

Y N Is there a possibility of metal in your head (for example aneurysm clips)?

Y N Do you have metal dental work such as braces or non removable retainers?

Y N Have you had an injury to the eye involving a metallic fragment (for example, metallic slivers, shavings, foreign body) or have you ever needed an eyewash having worked with metals?

Y N Do you have an implanted medical device that is electrically, magnetically, or mechanically controlled or activated?

Y N Do you have a breathing or motion disorder?

Y N Are you claustrophobic?

Y N Do you have inner ear disorders or experience vertigo or dizziness?

Y N Do you have tattoos or permanent makeup that contains metal?

Y N Do you have body piercing jewelry that cannot be removed?

Y N Do you have any metal in your body: For instance artificial joint, dental work such as a permanent retainer?

Y N Have you ever been injured by a metallic object, for instance BB, bullet, shrapnel?

Y N Do you have an implanted medical device?

Appendix F

IRB Informed Consent Form

AUBURN UNIVERSITY

MAGNETIC RESONANCE
IMAGING CENTER

(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
"Low Back Muscle Modeling During One-Hand Lifting Tasks "

You are invited to participate in a research study that uses electromyography (EMG) data to measure back muscle activity during lifting tasks as well as magnetic resonance imaging (MRI) to accurately measure the size of the low back and trunk muscles. These two pieces of information when used together will help create a better way of estimating the forces acting on the back during a one-hand lifting task. The study is being conducted by John Pentikis, Auburn University PhD. Candidate, under the direction of Dr. Richard Sesek, Associate Professor, Auburn University Department of Industrial and Systems Engineering. You were selected as a possible participant because you are age 19 or older. Please note that
you will not be considered for the study if you do not meet all of the following requirements:

- must be male
- between 19-25 years old at time of the study
- currently asymptomatic from low back pain
- have no previous low back injury history
- have no current low back pain symptoms
- have a body mass index of no greater than 30 (non obese)
- currently enrolled as an Auburn University student

Also please be aware that de-identified MRI pictures, lab data and anthropometric data will be shared with the US Army Institute of Public Health (USAIPH). USAIPH is partnering with Auburn University during this study.

What will be involved if you participate (EMG portion)? If you decide to participate in this research study, you will have anthropometric data collected. After that, you will be asked to preform one-hand and two-hand lifts in a laboratory while being monitored for changes in electromyography (EMG) activity, force, and posture. After the EMG portion of the experiment is completed you will undergo a magnetic resonance imaging (MRI) procedure at a later time. Please note, however, that the MRI procedure can be completed first if that better fits your schedule.

You will first be asked screening questions to make sure it is safe for you to perform lifting activities as well as participate in a magnetic resonance imaging (MRI) procedure. You will then be asked if you object to the procedure required to:

- prepare your skin for EMG sensor placement (wipe with alcohol and possible shaving)
- place EMG sensors on your body
- place motion capture sensors on your body

 Participant's initials____

- place a foot force insert in your shoes
- collect anthropometric data (height, weight, body mass index via skin caliper measurement)

Once you have answered the screening questions you will have your anthropometric measurements taken, be fitted with EMG and motion capture sensors, and, finally you will have foot pressure measuring insoles inserted in your shoes. Immediately following that, you will then begin the lifting trials. You will be asked to lift between 10 and 50 pound dumbbells in either one hand or both hands. You will be given at least one-minute rest period between each lifting trial. Your total time commitment will be approximately 1.5 hours for the EMG portion of the study. Please note part two of the study, the MRI procedure, will require an additional 1.5 hours. Your total time commitment for this study will be 3 hours. Again, you may participate in part two (MRI portion) first if that better fits your schedule.

Are there any risks or discomforts (EMG portion)?

The risks associated with participating in the EMG portion of the study are:

1. The most obvious personal risk from lifting is musculoskeletal injury.
2. There may be minor skin irritation as part of the EMG sensor placement procedure.

To minimize these risks, we will:

1. Have you fill out a screening form to determine if you are healthy enough to perform lifting tasks.
2. Ensure investigators have been trained and are adept at preparing the skin for EMG placement.
3. Allow you to decline ANY lifting task you feel uncomfortable performing.
4. You will only have to lift the weight 3 inches from a platform at waist level.

What will be involved if you participate (MRI portion)? If you decide to participate in this research study, you will be asked to undergo magnetic resonance imaging (MRI) scans.

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 at these times. To help you keep your head perfectly still, we will put cushions around your head.

Two scans will be performed in a single session with approximately five minutes between scans. Each set of scan lasts about 15 minutes and should not exceed 30 minutes in the bed. Each scan will obtain MRI pictures of the low back and trunk muscles from the lumbar 1 to the

 Participant's initials____

lumbar 5 region of the back. Your total time in the scanner will be no more than 50 minutes. Your total time commitment will be approximately 1½ hours.

Please note that 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.

Are there any risks or discomforts (MRI portion)?

The risks associated with the MRI portion of 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.

To minimize these risks, we will:

1. Have you fill 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
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.

 Participant's initials____

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.

Are there any benefits to yourself or others? If you participate in this study, you can expect to receive no direct benefits. Your participation, however, provides the investigator with a greater understanding of the geometry of the low back and trunk muscles in the lumbar region of the back. This may be useful in developing regression equations that can estimate the relative contribution of each back muscle during lifting activities.

Will you receive compensation for participating? To thank you for you time you will be offered monetary compensation in the amount of $50.00 to participate in the EMG portion of the study and an additional $25.00 to participate in the MRI portion of the study for a total compensation of $75.00.

Are there any costs? If you decide to participate, you will not incur any costs. If you require medical attention, you will be responsible for all costs for medical treatment.

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. You may cease participation at any point. You will receive prorated compensation for the percentage of the experiment you complete.
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, or the Department of Industrial and Systems Engineering.

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 used to fulfill an educational requirement, 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 condition you may have. Furthermore, the investigators who will analyze these images are not medical doctors and are not trained to evaluate these scans.

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

Participant's initials____

Auburn University Medical Clinic, who will discuss the results of the scan with you at your expense.

If you have questions about this study, *please ask them now or* contact 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

Participant's initials____

Appendix G

Samuel Ginn College of Engineering Photo Release Form

AUBURN
UNIVERSITY

SAMUEL GINN COLLEGE OF ENGINEERING

INDUSTRIAL & SYSTEMS ENGINEERING

PHOTO RELEASE - Adult

During your participation in this research study, "LOW BACK MUSCLE MODELING DURING ONE-HANDED LIFTING TRIALS." you will be photographed. Your signature on the Informed Consent gives us permission to do so.

Your signature on this document gives us permission to use the photographs for the additional purposes of *(publication, training, etc...)* beyond the immediate needs of this study. These photographs will not be destroyed at the end of this research but will be retained *(indefinitely for* 1 year *months, years, etc....)*.

In addition, the following persons or groups will have access to the photographs:

Your permission:

I verify that I am of legal age in my state and give my permission for photographs produced in the study, "LOW BACK MUSCLE MODELING DURING ONE-HANDED LIFTING TRIALS" to be used for the purposes listed above, and to also be retained *(indefinitely,* 1 year *months, years, etc.*).

[signature]	4-22-2016	[signature]
Participant's Signature	Date	Investigator's Signature
MENEKSE SALAR	4-22-2016	JOHN PENTIKIS
Participant's Printed Name	Date	Investigator's Printed Name

SHELBY CENTER FOR
ENGINEERING TECHNOLOGY
SUITE 3301
AUBURN, AL 36849-5346

TELEPHONE:
334-844-4340

FAX:
334-844-1381

www.auburn.edu

AUBURN UNIVERSITY

SAMUEL GINN COLLEGE OF ENGINEERING

INDUSTRIAL & SYSTEMS ENGINEERING

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[signature]	11-5-2015	[signature]
Participant's Signature	Date	Investigator's Signature
Tyler Gattis	11-5-2015	JOHN PENTIKIS
Participant's Printed Name	Date	Investigator's Printed Name

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AUBURN UNIVERSITY

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Robert Granzow 4-22-2016

Participant's Signature Date Investigator's Signature

Robert Granzow 4-22-2016 John Pertiko

Participant's Printed Name Date Investigator's Printed Name

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[signature] Participant's Signature — 4-22-2016 Date — [signature] Investigator's Signature

JOHN PENTIKIS Participant's Printed Name — 4-22-2016 Date — JOHN PENTIKIS Investigator's Printed Name

SHELBY CENTER FOR ENGINEERING TECHNOLOGY

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ABHISHEK RAO	4/22/2016	
Participant's Signature	Date	Investigator's Signature
ABHISHEK RAO	4/22/2016	John Pentikis
Participant's Printed Name	Date	Investigator's Printed Name

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[signature]	4-22-2016	[signature]
Participant's Signature	Date	Investigator's Signature
AKASH SHETTANNAVAR	4-22-2016	JOHN PENTIKU
Participant's Printed Name	Date	Investigator's Printed Name

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[signature]	4-22-2016	[signature]
Participant's Signature	Date	Investigator's Signature
Fehmi CAPANOGLU	4-22-2016	JOHN Pentikis
Participant's Printed Name	Date	Investigator's Printed Name

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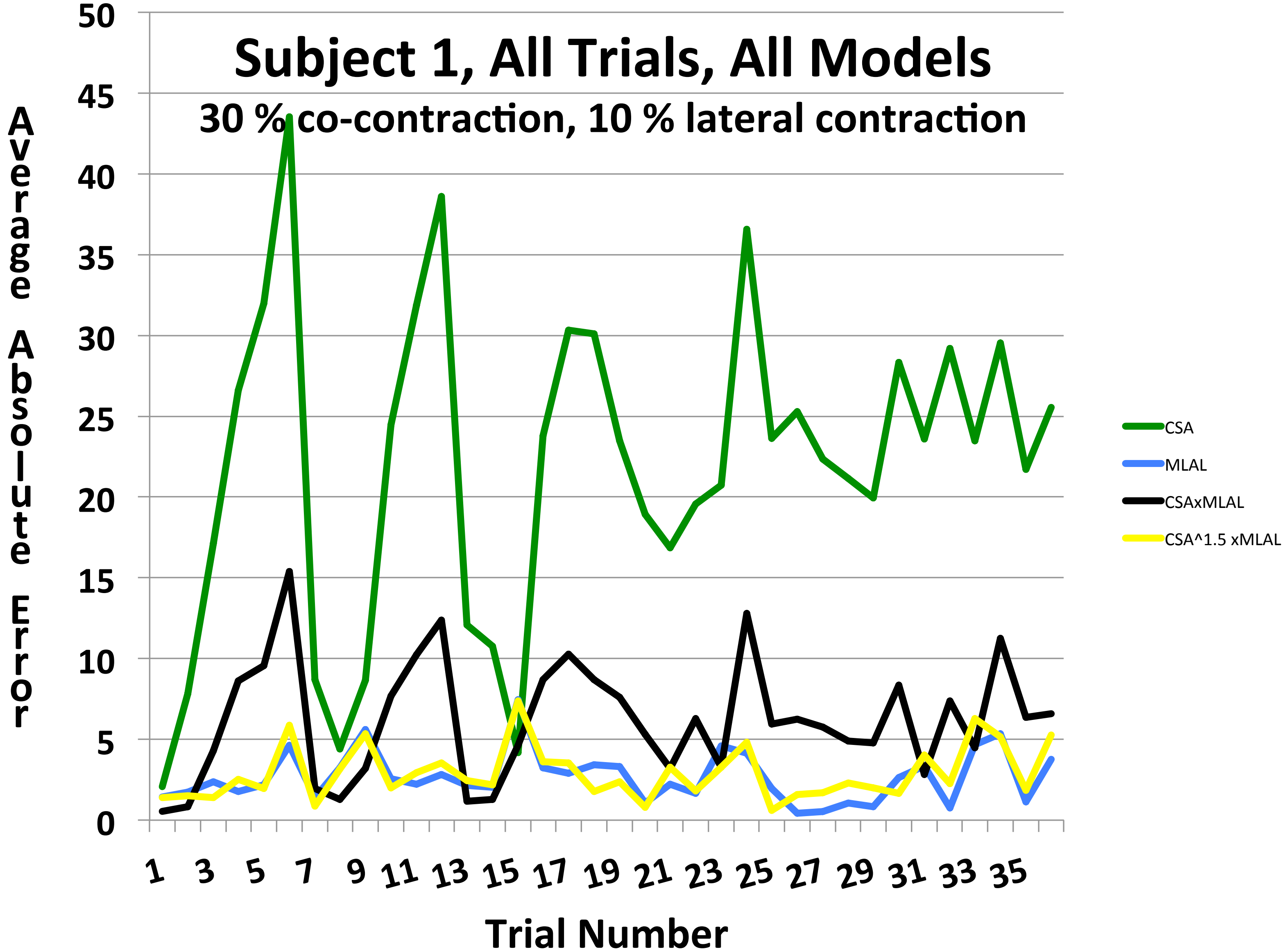
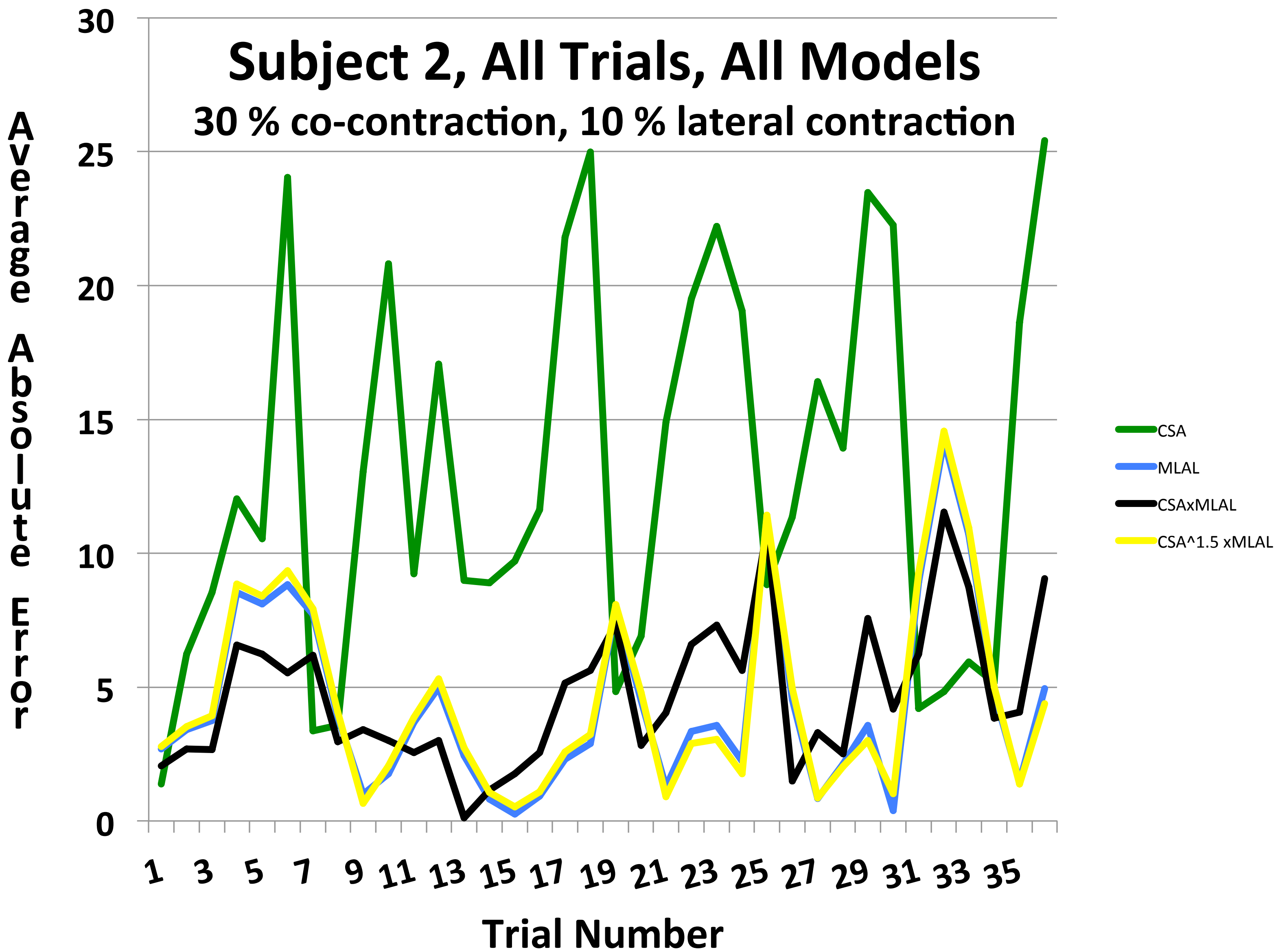
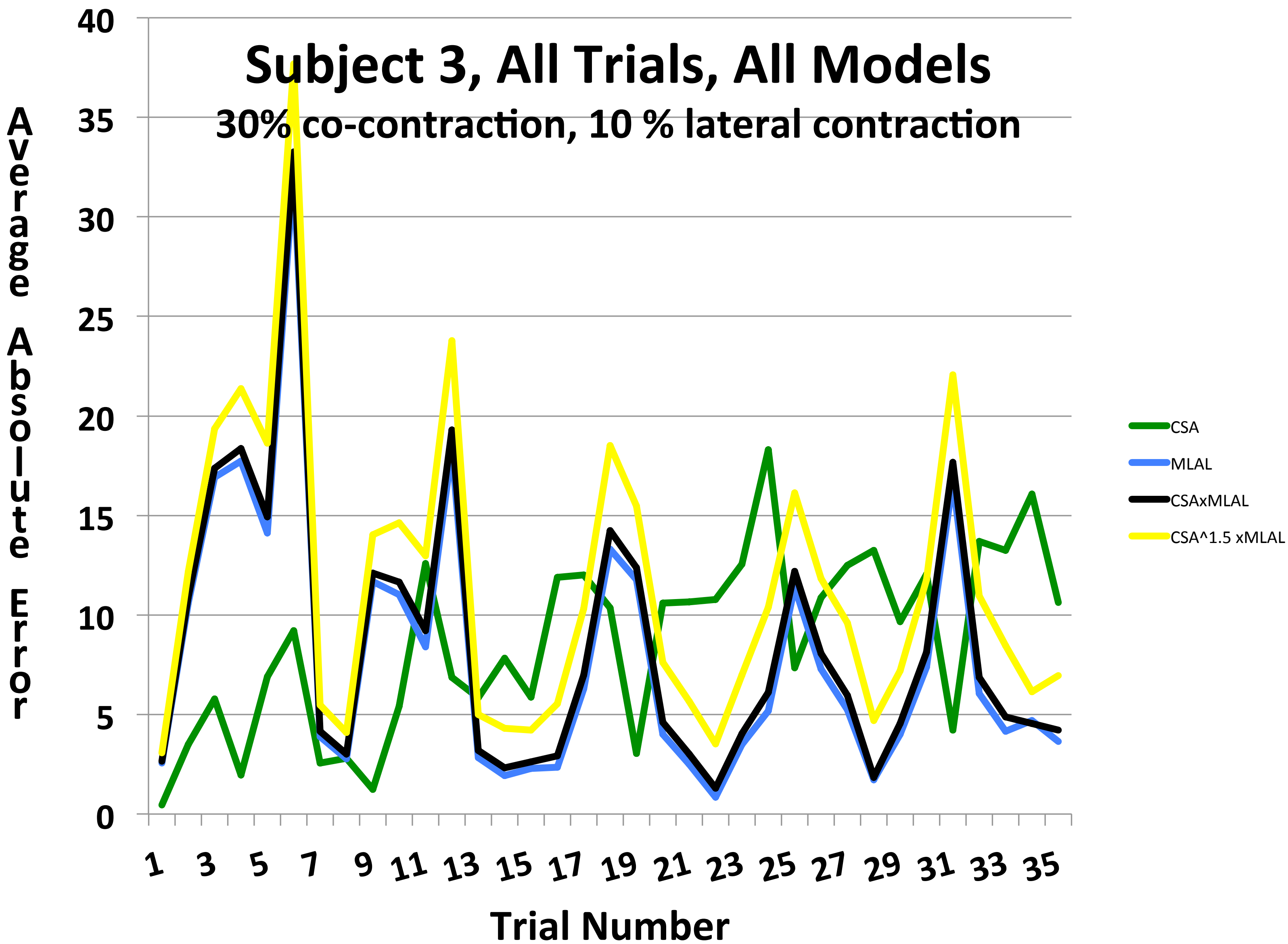
Appendix H

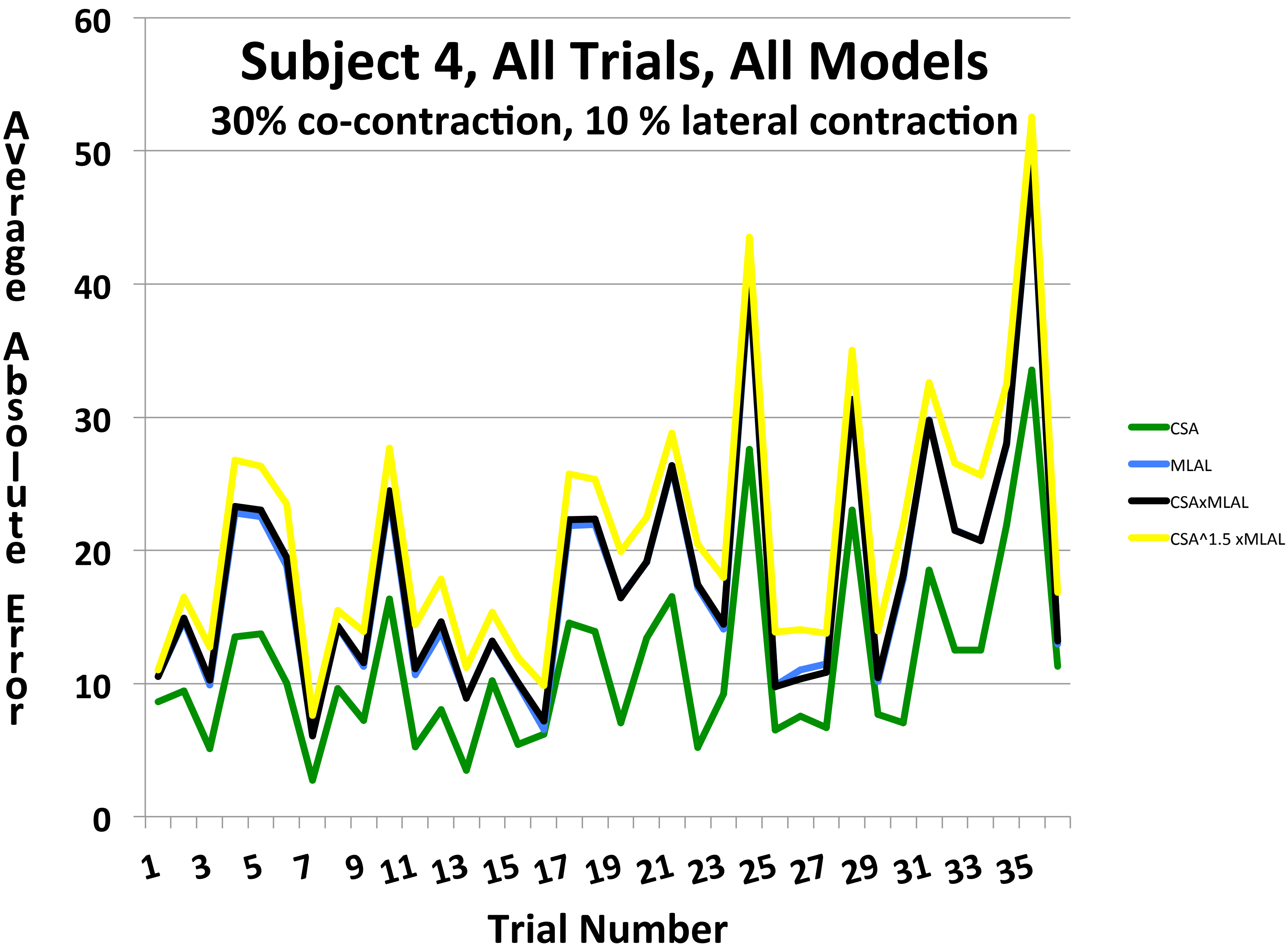
Models Perfomance at Co-Contration of 30 % and Lateral Contraction of 10 %



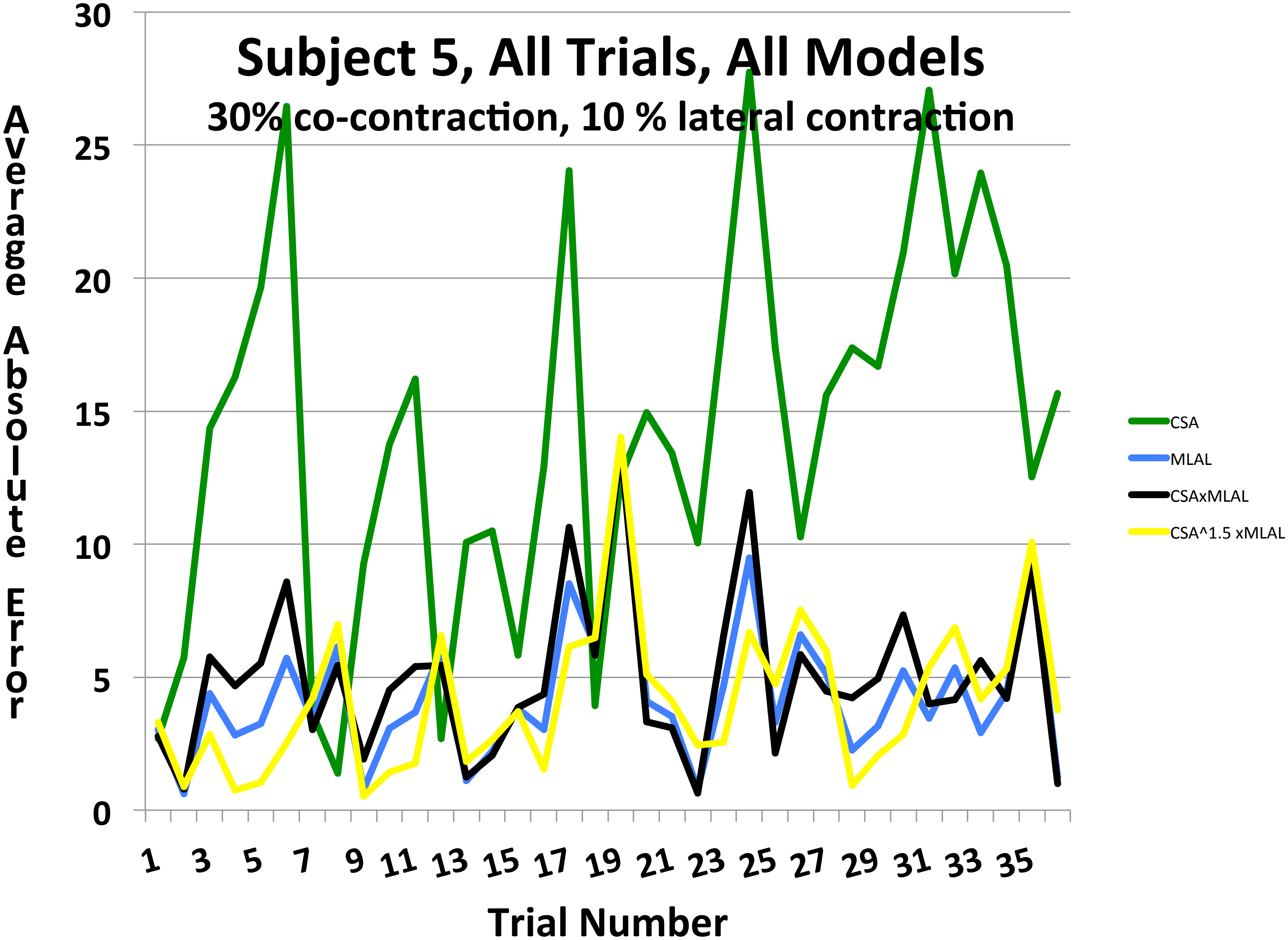
Subject 1, All Trials, All Models
30 % co-contraction, 10 % lateral contraction
Average Absolute Error
0
5
10
15
20
25
30
35
40
45
50
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Trial Number
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL

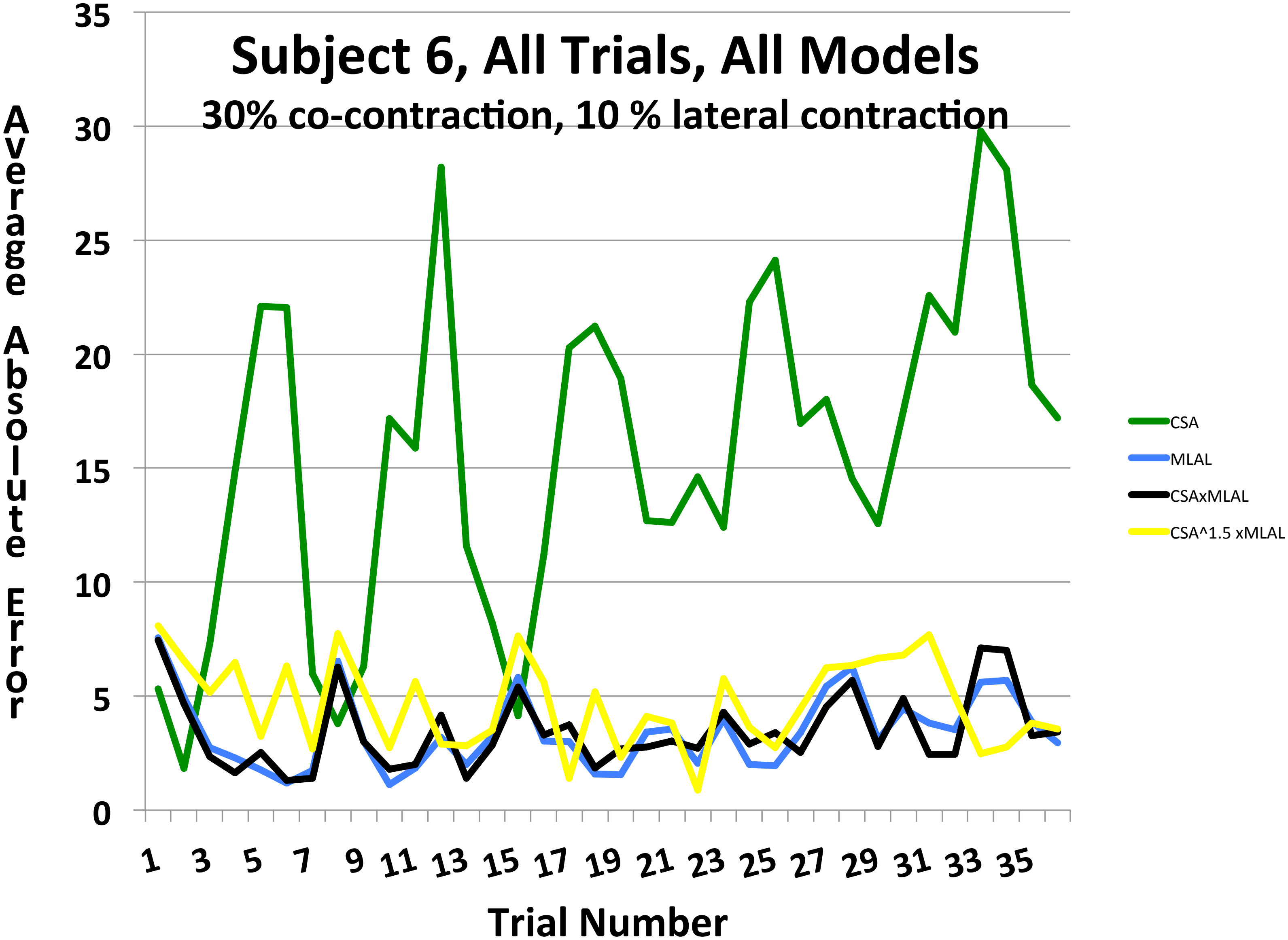

Subject 2, All Trials, All Models
30 % co-contraction, 10 % lateral contraction
Average Absolute Error
Trial Number
0
5
10
15
20
25
30
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL


Subject 3, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
Trial Number
0
5
10
15
20
25
30
35
40
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL

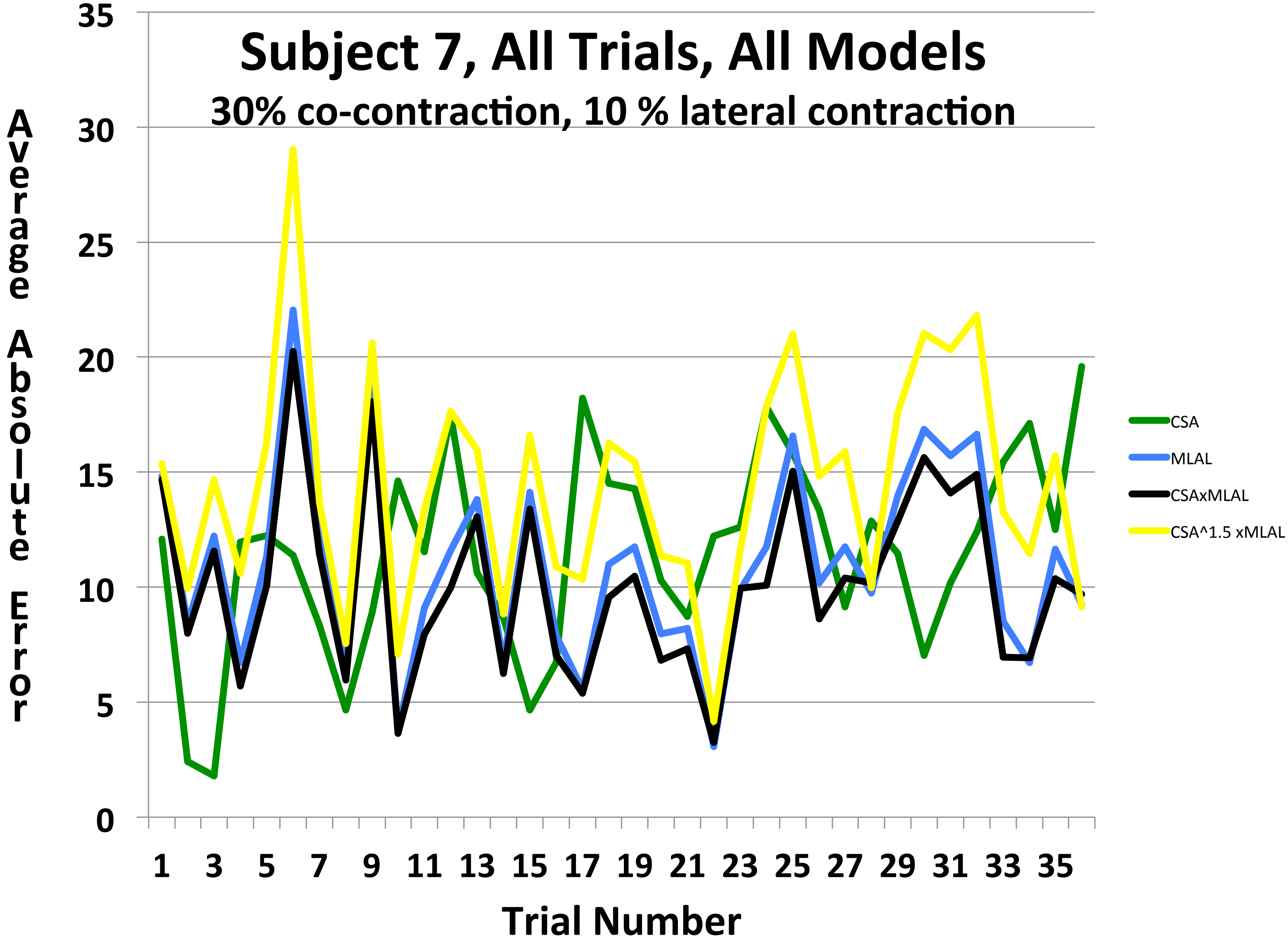


Subject 4, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
60
50
40
30
20
10
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Trial Number
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL

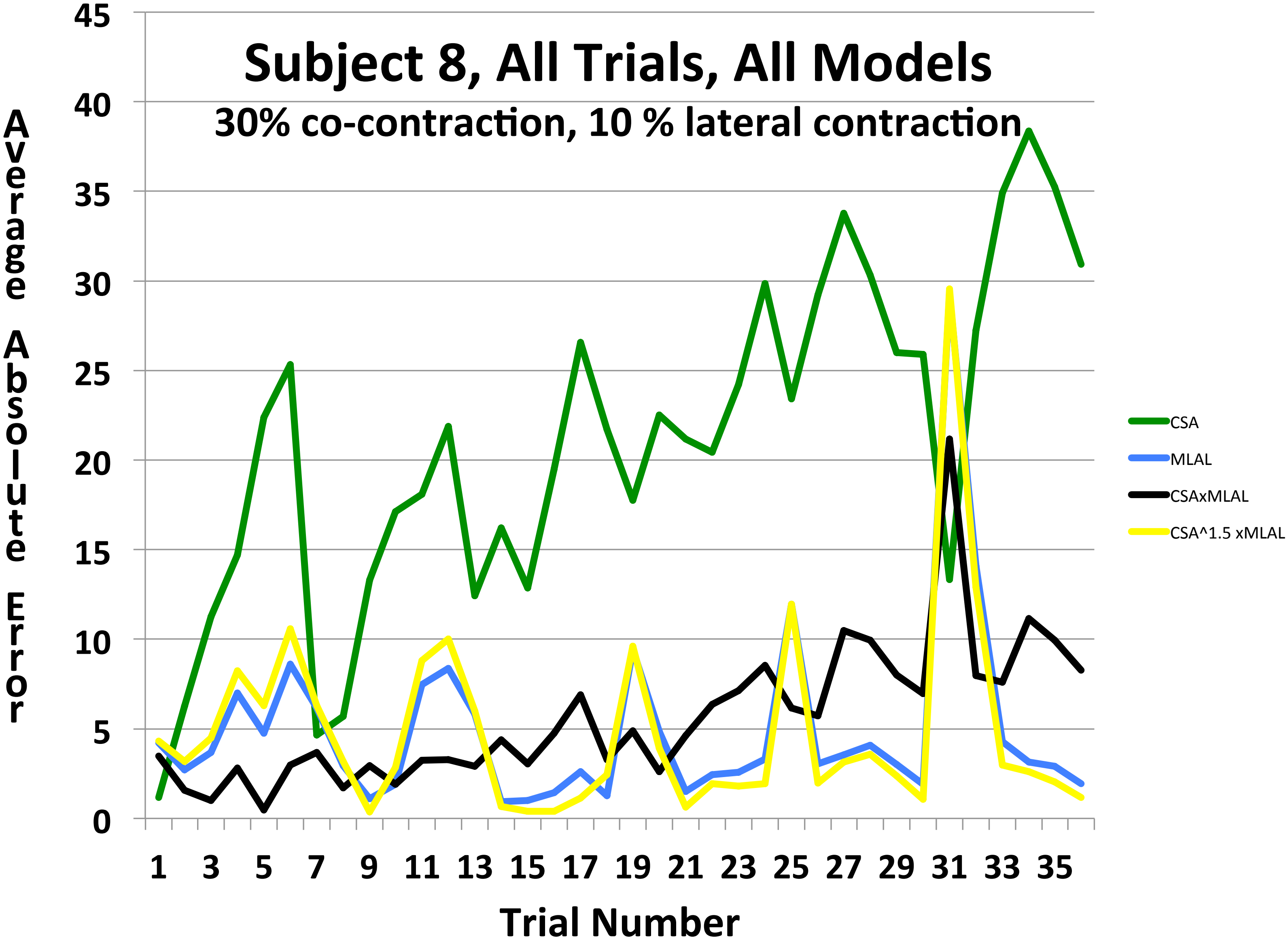

Subject 5, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
0
5
10
15
20
25
30
Trial Number
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL

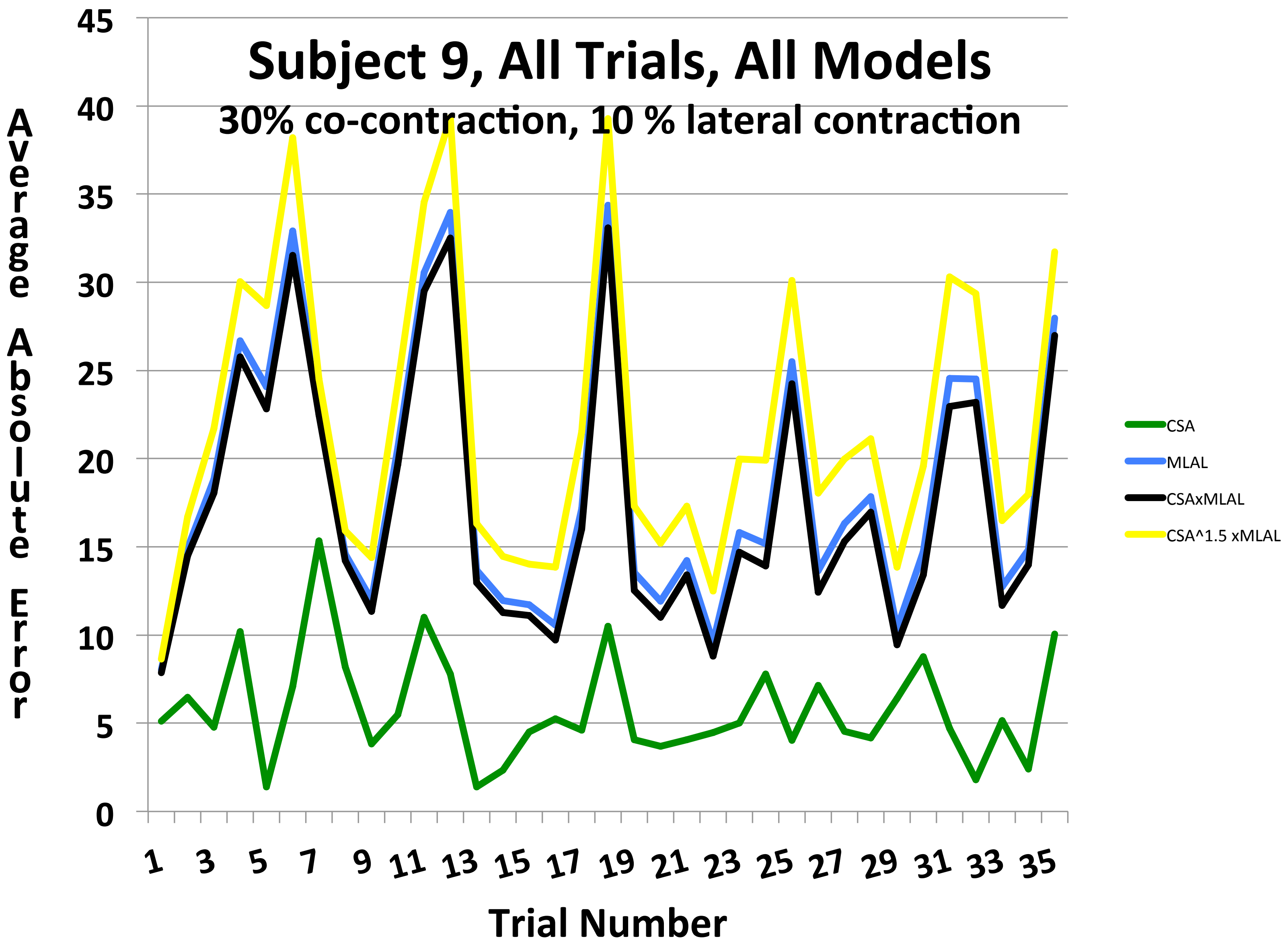


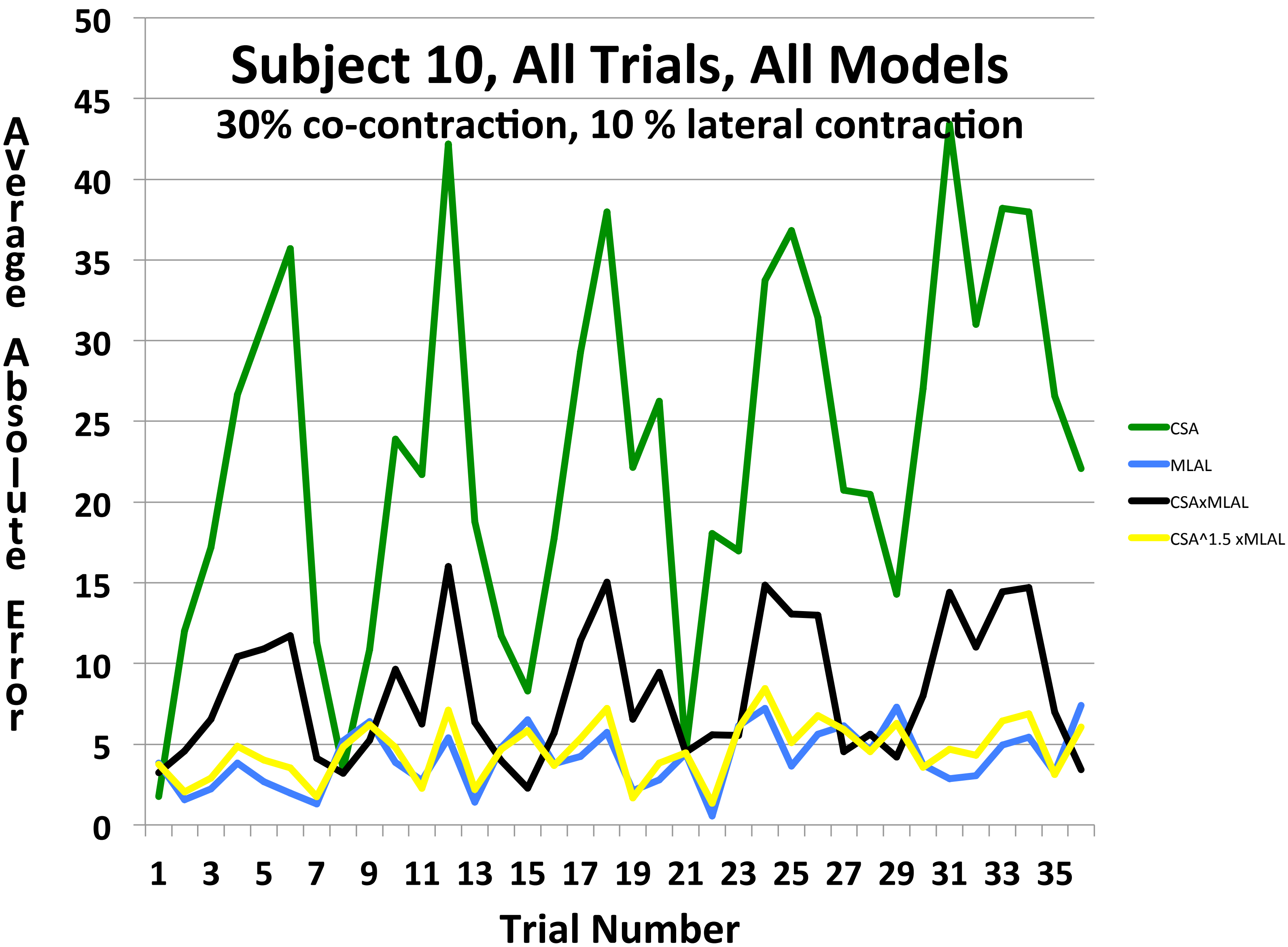
Subject 6, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
Trial Number
35
30
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL



Subject 7, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
0
5
10
15
20
25
30
35
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Trial Number
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL


Subject 8, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
Trial Number
0
5
10
15
20
25
30
35
40
45
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL


Subject 9, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
0
5
10
15
20
25
30
35
40
45
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Trial Number
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL


Subject 10, All Trials, All Models
30% co-contraction, 10 % lateral contraction
Average Absolute Error
Trial Number
0
5
10
15
20
25
30
35
40
45
50
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
CSA
MLAL
CSAxMLAL
CSA^1.5 xMLAL

Appendix I

Wilcoxon Signed–Rank Test Calculations

Wilcoxon Sign Test
CSA vs. MLAL

H_0: There is no difference between the models
H_1: There is a difference between the models

Critical value: Signed rank table, two tailed test, sample size = .05

z value greater than 3.291 indicates statistical significance greater than .001

One "0" value, thus N = 358 - 1 = 357

Max W = (N*(N+1))/2, =(357*358)/2 = 63,903
Min W = -(N*(N+1))/2, = -(357*358)/2 = -63,903

Net positive sum = 26,818, indicates CSA average rank is higher than LA average rank
σw=sqrt[N(N+1)(2N+1)/6] = sqrt[357*358*715/6] = sqrt 15,230,215 =+/- 3,902
W = 26,818
μw = 0
z = ((W - μw)+/- .5)/σw = (26,818 - 0 -.5)/3,902 = 6.873

Level of significance for a directional test at the .0005 level is 3.291

6.873 > 3.291, we reject the null hypothesis of no difference between the models.

CSA average rank order is higher than MLAL average rank order

Wilcoxon Sign Test
CSA x MLAL vs. MLAL

H_0: There is no difference between the models
H_1: There is a difference between the models

Critical value: Signed rank table, two tailed test, sample size = .05

z value greater than 3.291 indicates statistical significance greater than .001

Twelve "0" values, thus N = 358 - 12 = 346

Max W = (N*(N+1))/2, =(346*347)/2 = 60,031
Min W = -(N*(N+1))/2, = -(348*349)/2 = -60,031

Net positive sum = 39,849, indicates LAxCSA average rank is higher than LA average rank
σw=sqrt[N(N+1)(2N+1)/6] = sqrt[346*347*693/6] = sqrt 13,867,161 =+/- 3,724
W = 39,849
μw = 0
z = ((W - μw)+/- .5)/σw = (39,849 - 0 -.5)/3,724 = 10.700

Level of significance for a directional test at the .0005 level is 3.291

10.700 > 3.291, we reject the null hypothesis of no difference between the models.

CSAxMLAL average rank order rank is higher than MLAL average rank order

Wilcoxon Sign Test
$CSA^{1.5}$ x MLAL vs. MLAL

H_0: There is no difference between the models
H_1: There is a difference between the models

Critical value: Signed rank table, two tailed test, sample size = .05

z value greater than 3.291 indicates statistical significance greater than .001

Ten "0" values, thus N = 358 - 10 = 348

Max W = (N*(N+1))/2, =(348*349)/2 = 60,726
Min W = -(N*(N+1))/2, = -(348*349)/2 = -60,726

Net positive sum = 41,316, indicates LAxCSA^1.5 average rank is higher than LA average rank
σw=sqrt[N(N+1)(2N+1)/6] = sqrt[348*349*697/6] = sqrt 14,108,674 =+/- 3,756
W = 41,316
μw = 0
z = ((W - μw)+/- .5)/σw = (41,316 - 0 -.5)/3,756 = 11.000

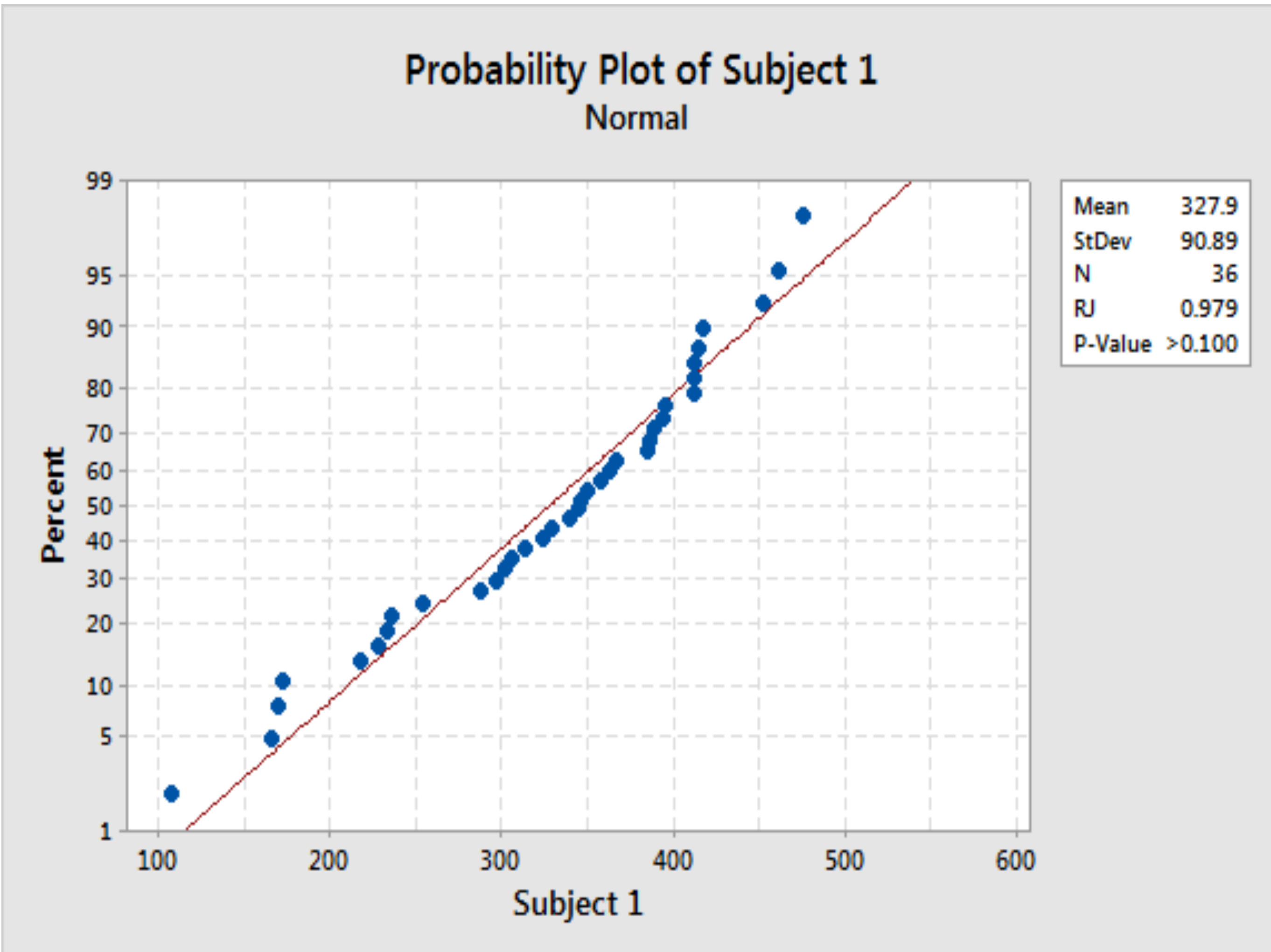
Level of significance for a directional test at the .0005 level is 3.291

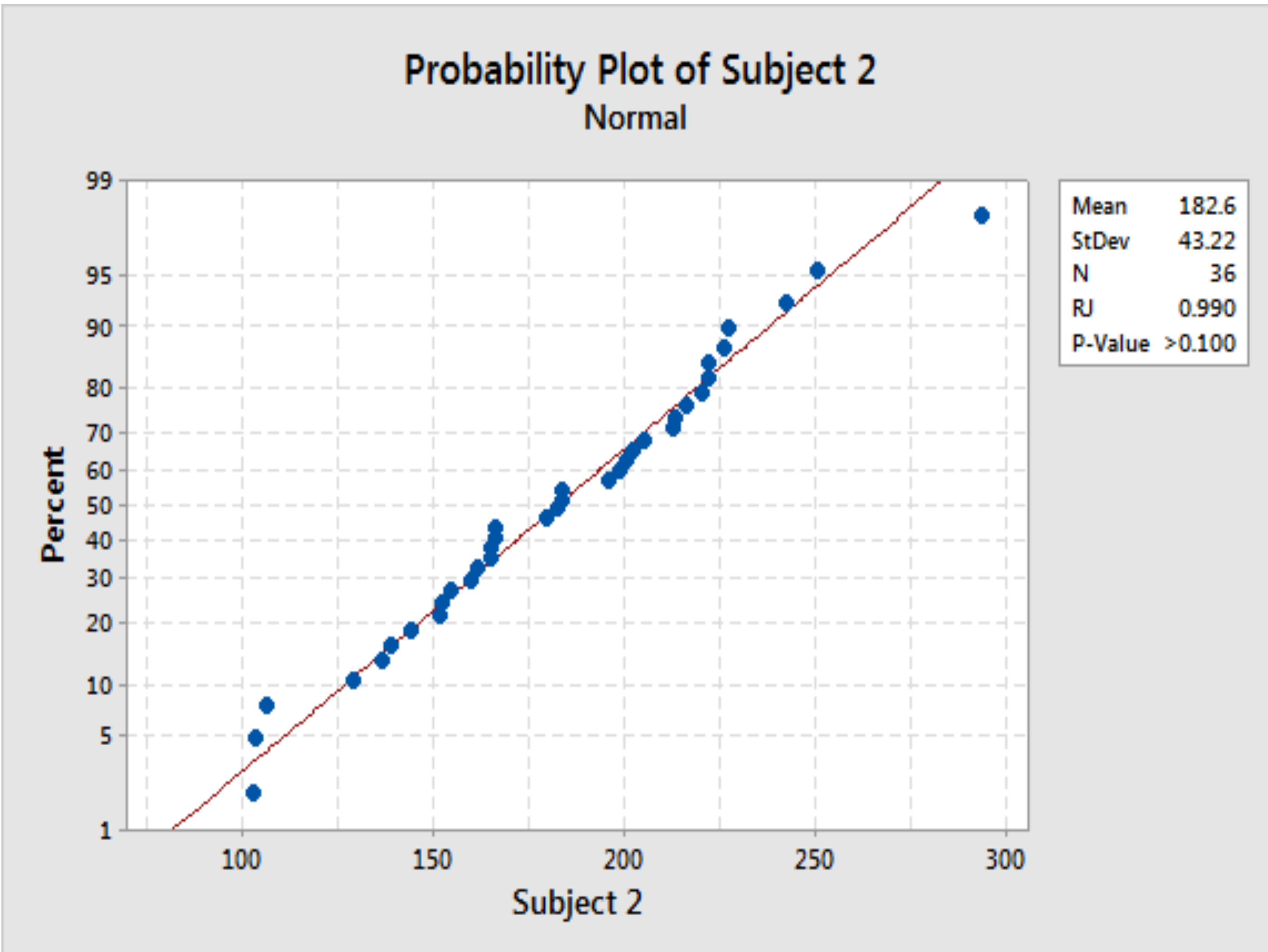
11.000 > 3.291, we reject the null hypothesis of no difference between the models.

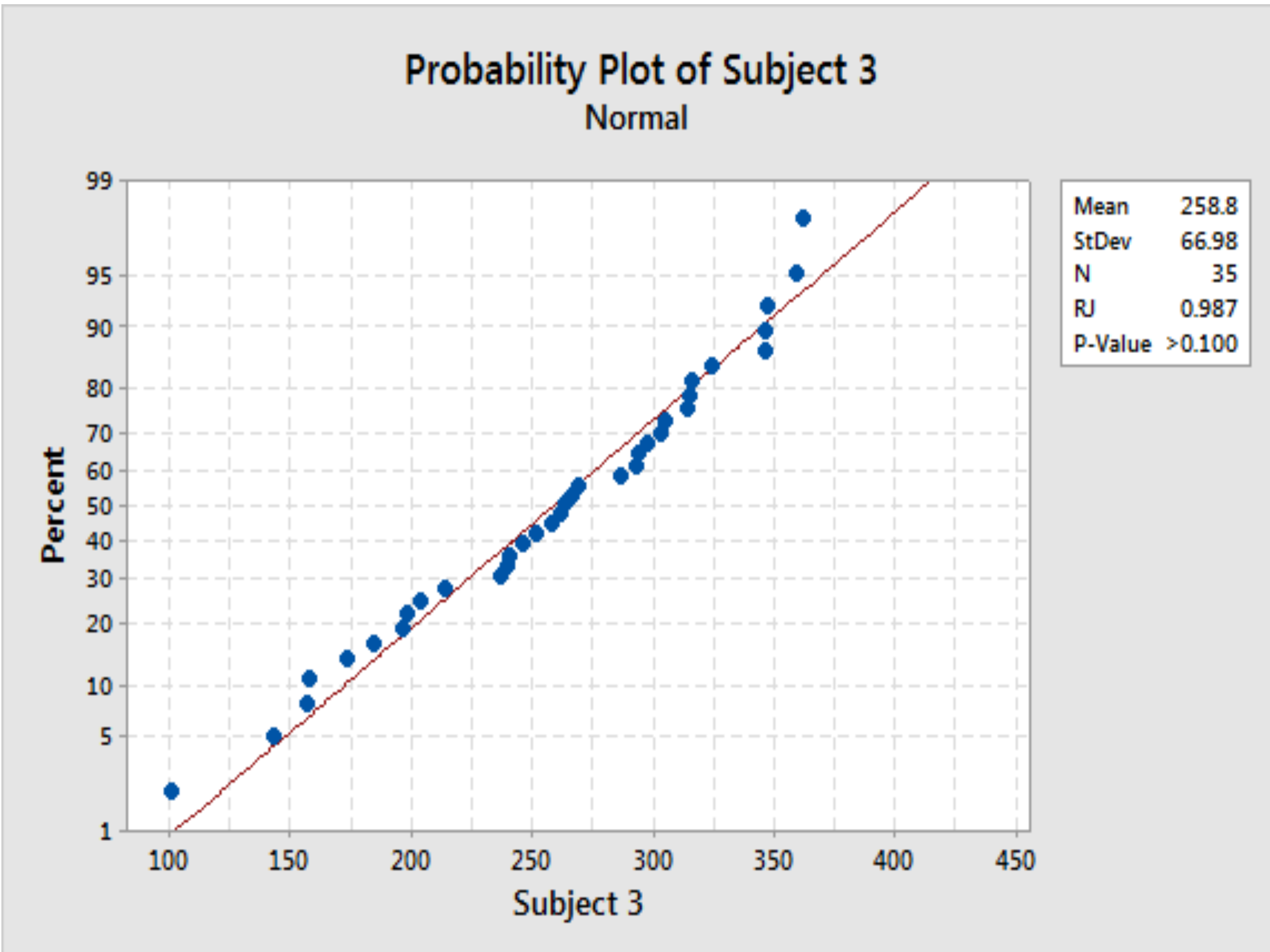
$CSA^{1.5}$ x MLAL average rank order is higher than MLAL average rank order

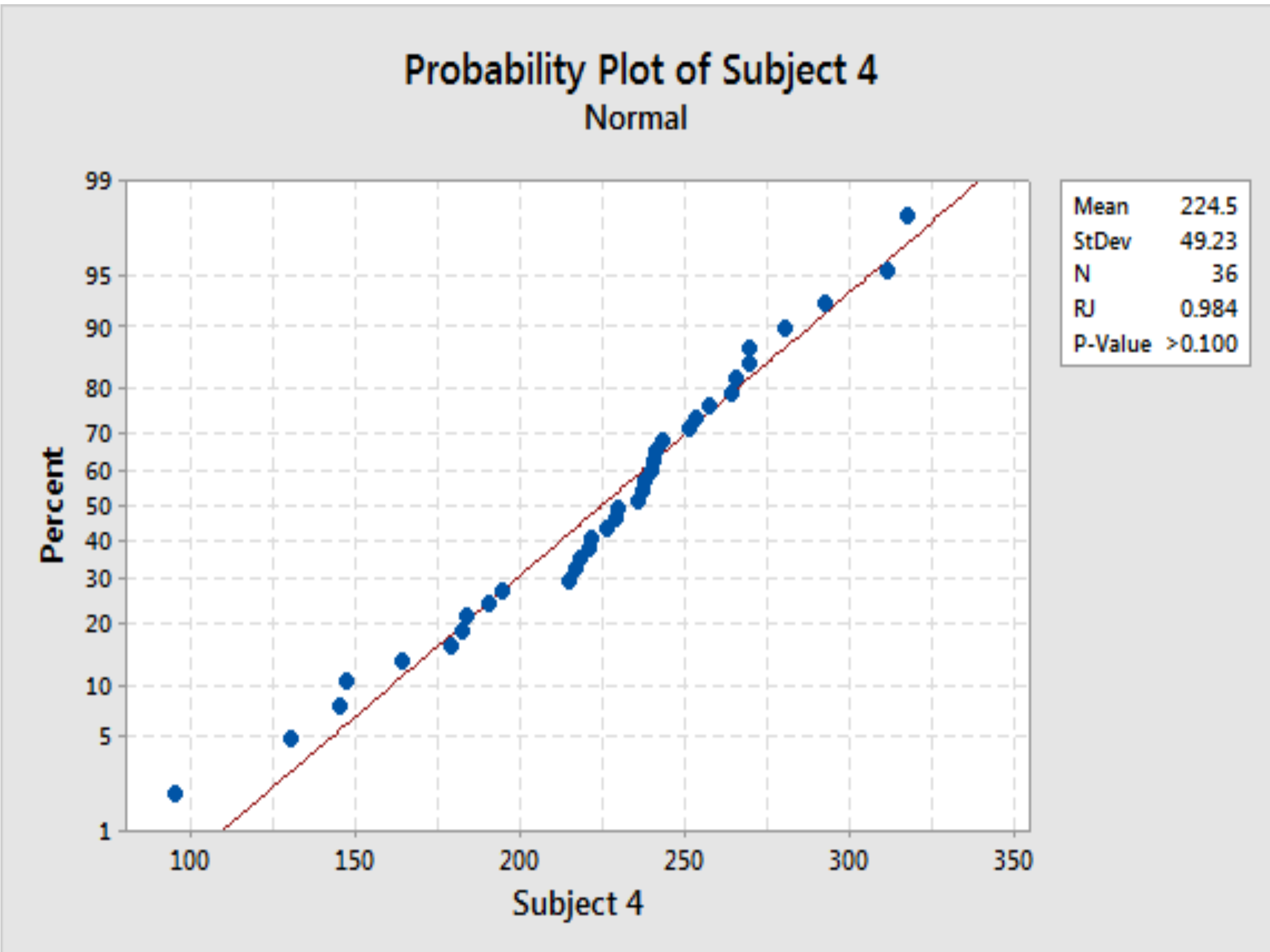
Appendix J

Ryan-Joiner Normality Tests for All Subjects

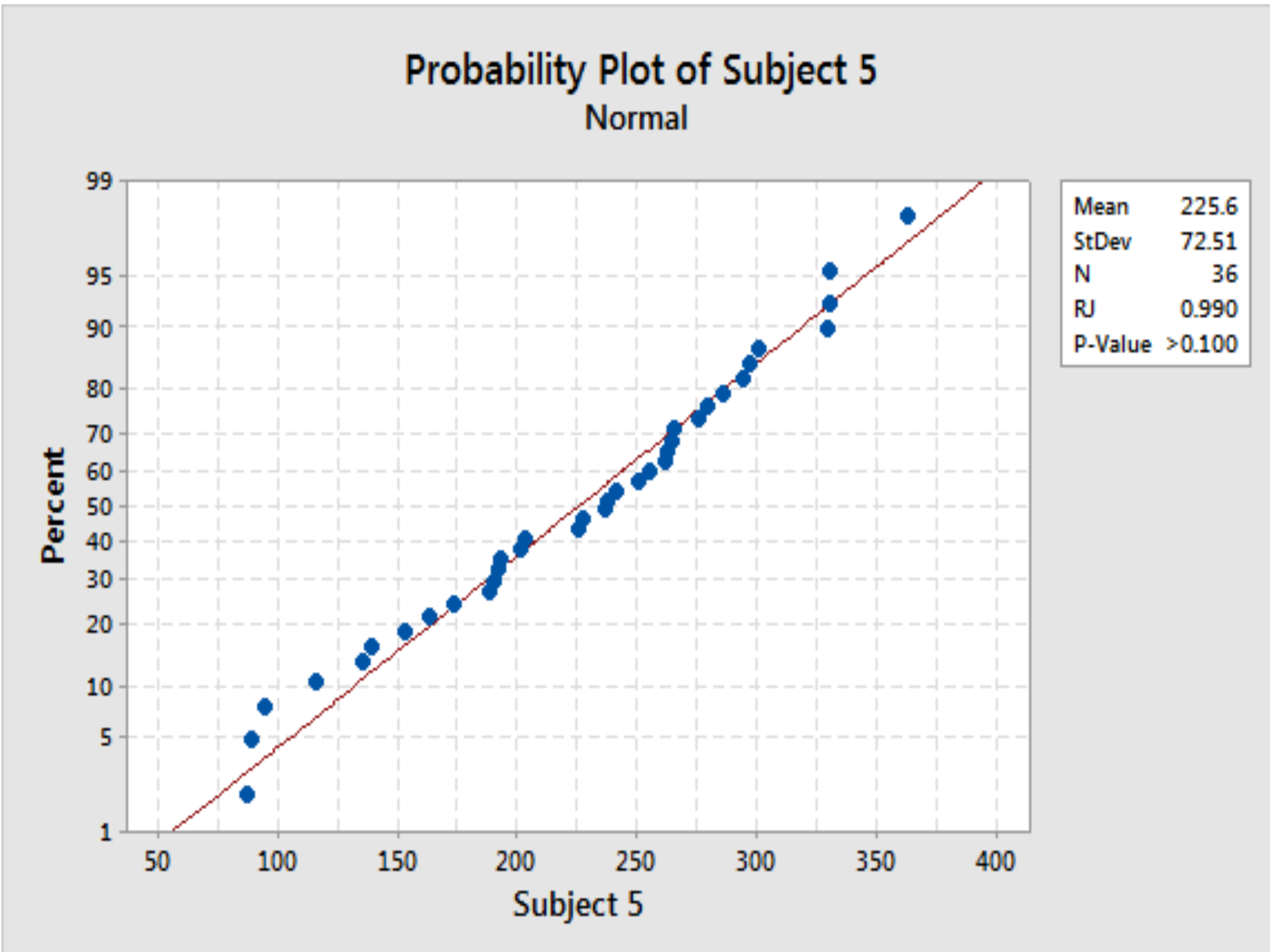

Probability Plot of Subject 1
Normal
Mean 327.9
StDev 90.89
N 36
RJ 0.979
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
200
300
400
500
600
Subject 1


Probability Plot of Subject 2
Normal
Mean 182.6
StDev 43.22
N 36
RJ 0.990
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
Subject 2

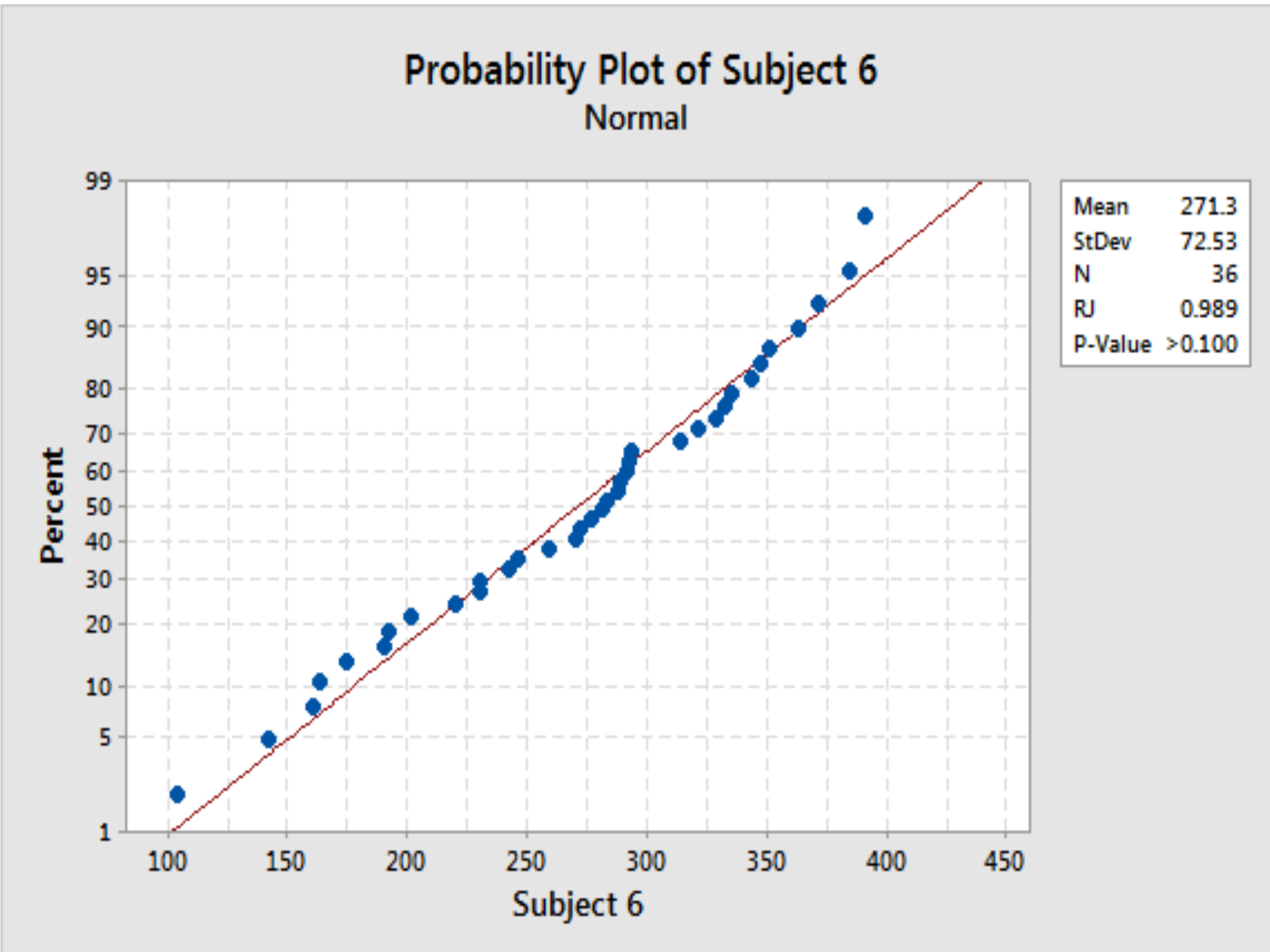

Probability Plot of Subject 3
Normal
Mean 258.8
StDev 66.98
N 35
RJ 0.987
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
350
400
450
Subject 3

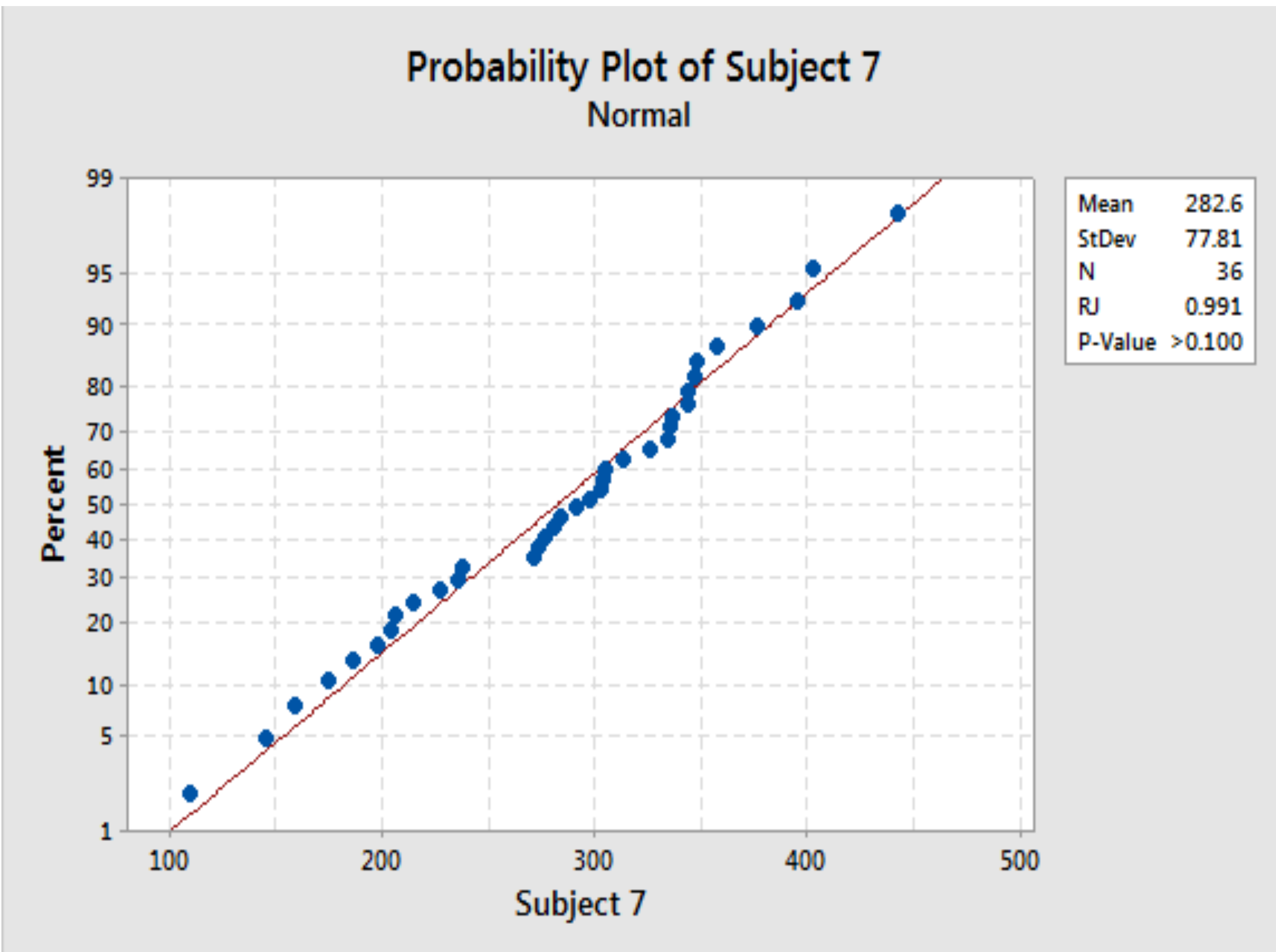


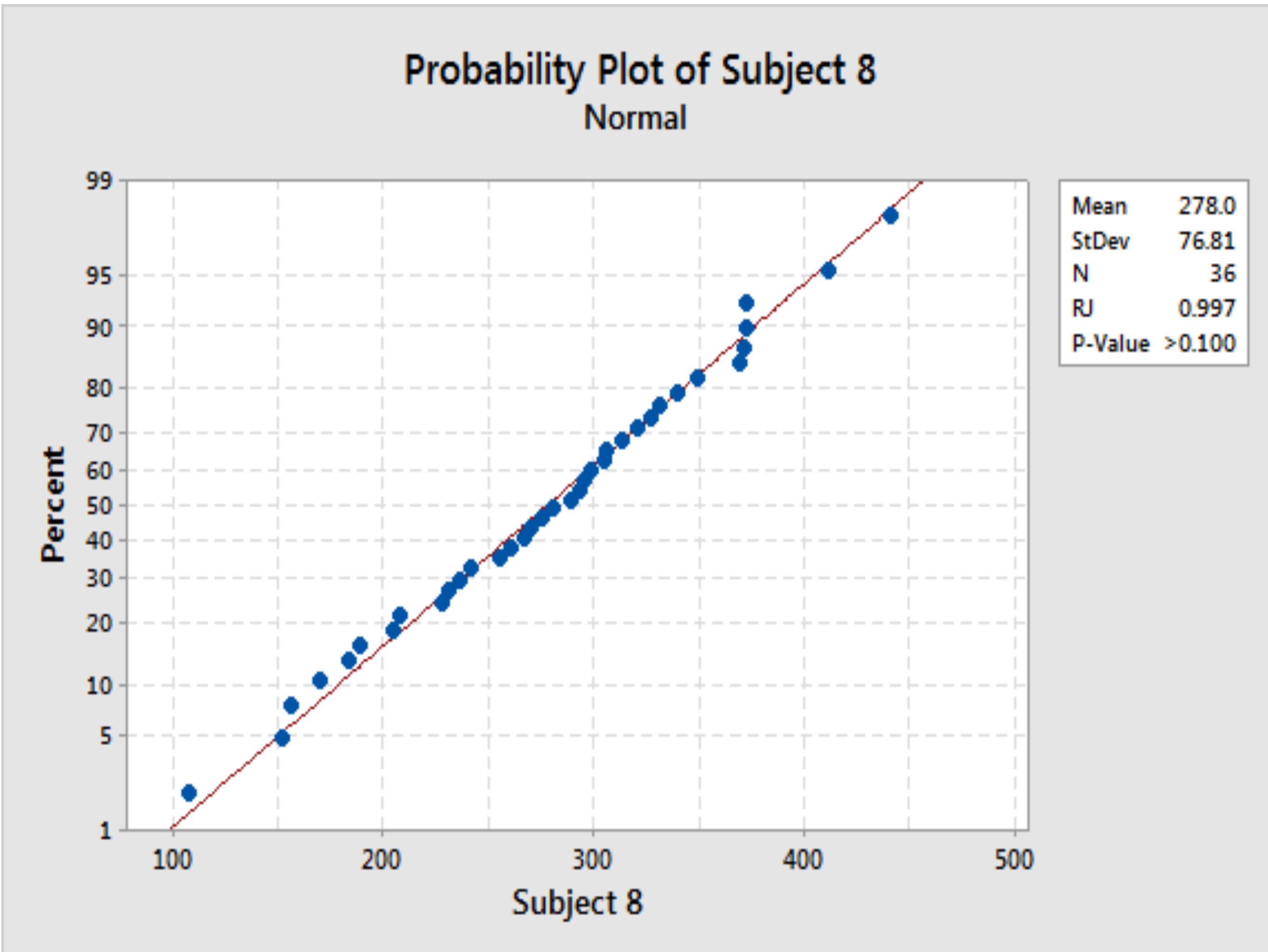
Probability Plot of Subject 4
Normal
Mean 224.5
StDev 49.23
N 36
RJ 0.984
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
350
Subject 4

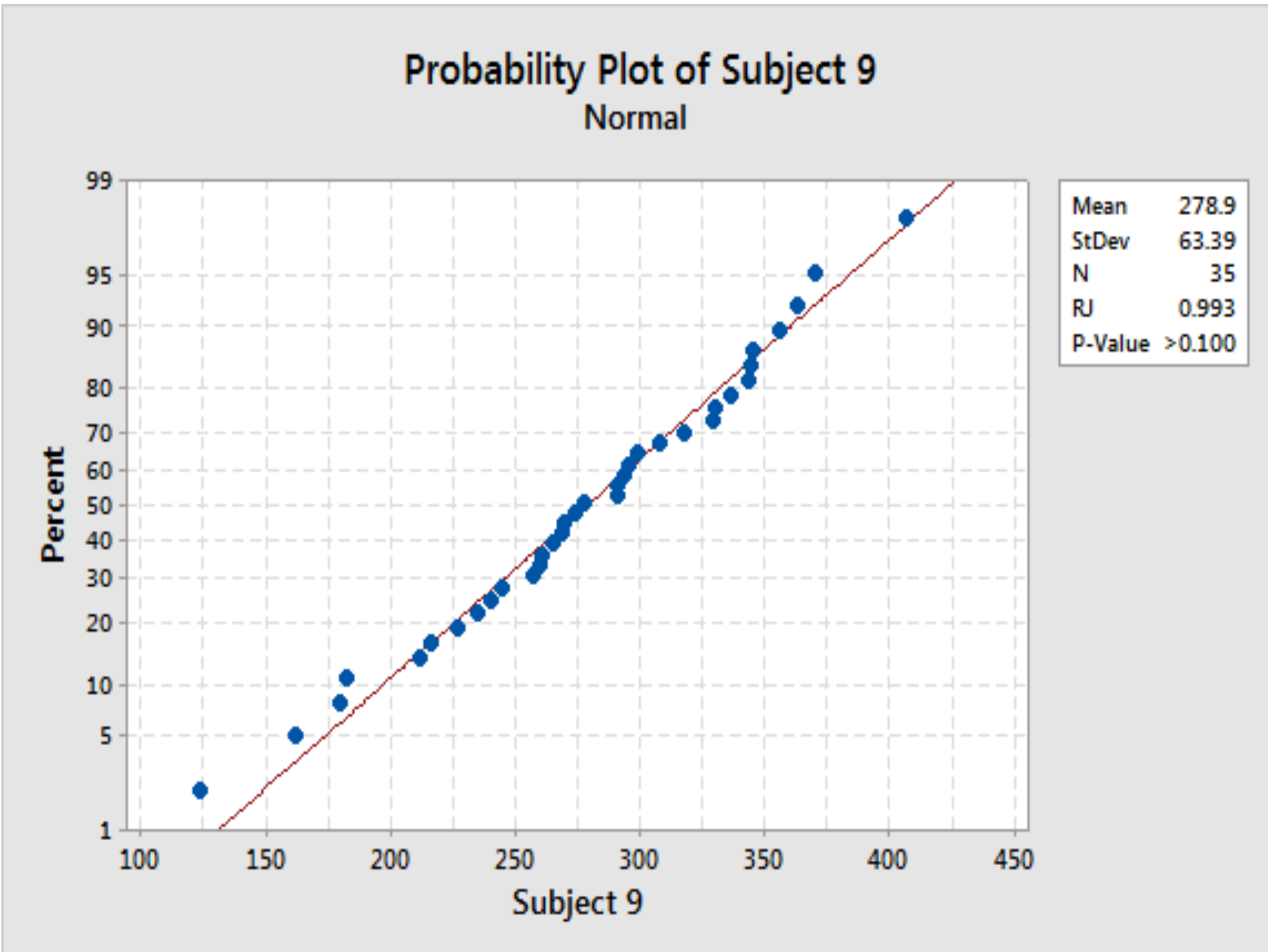


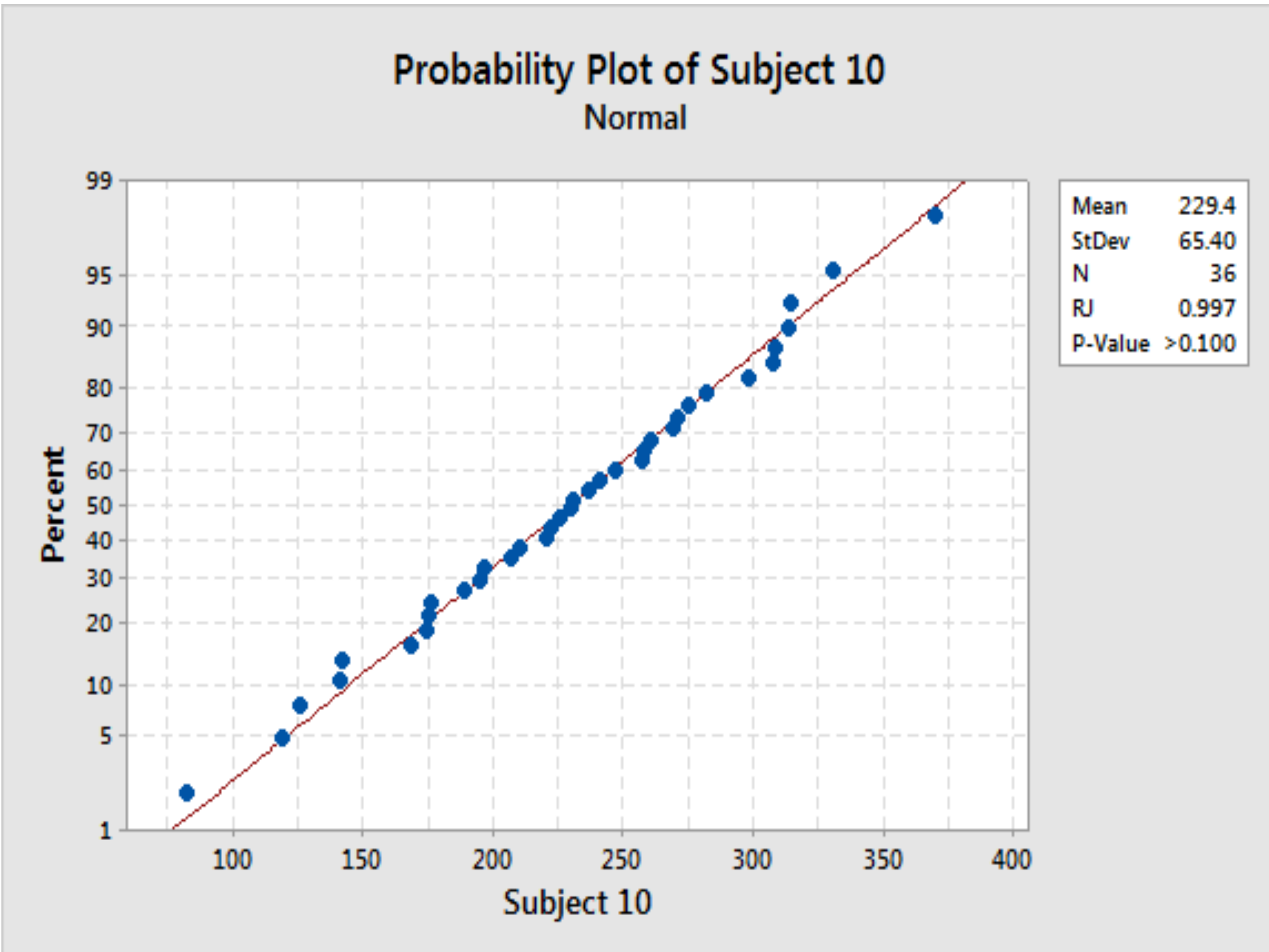
Probability Plot of Subject 5
Normal
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
50
100
150
200
250
300
350
400
Subject 5
Mean 225.6
StDev 72.51
N 36
RJ 0.990
P-Value >0.100

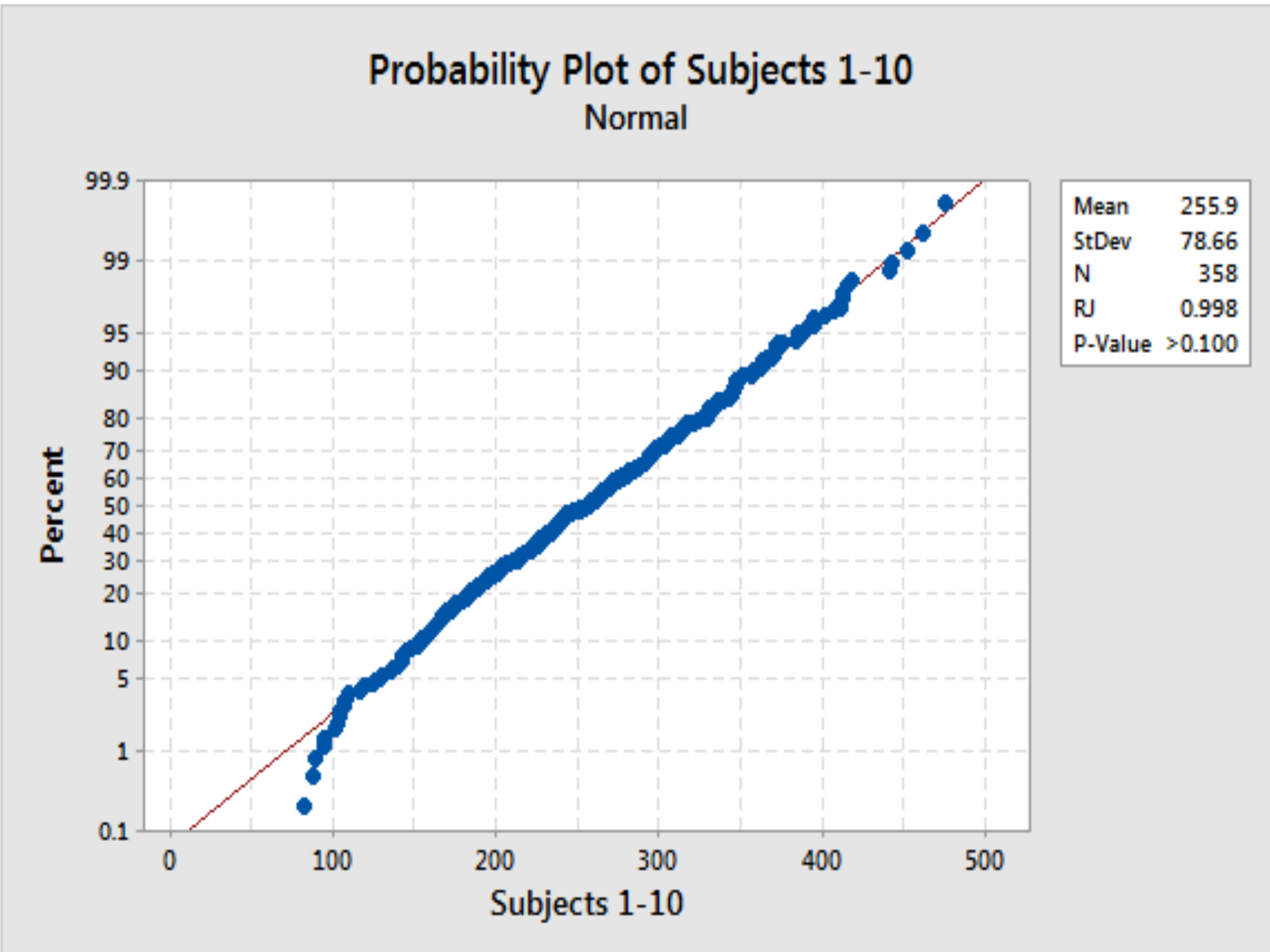

Probability Plot of Subject 6
Normal
Mean 271.3
StDev 72.53
N 36
RJ 0.989
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
350
400
450
Subject 6


Probability Plot of Subject 7
Normal
Mean 282.6
StDev 77.81
N 36
RJ 0.991
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
200
300
400
500
Subject 7


Probability Plot of Subject 8
Normal
Mean 278.0
StDev 76.81
N 36
RJ 0.997
P-Value >0.100
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
100
200
300
400
500
Subject 8


Probability Plot of Subject 9
Normal
Percent
Subject 9
Mean 278.9
StDev 63.39
N 35
RJ 0.993
P-Value >0.100
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
350
400
450


Probability Plot of Subject 10
Normal
Percent
Subject 10
Mean 229.4
StDev 65.40
N 36
RJ 0.997
P-Value >0.100
99
95
90
80
70
60
50
40
30
20
10
5
1
100
150
200
250
300
350
400


Probability Plot of Subjects 1-10
Normal
Mean 255.9
StDev 78.66
N 358
RJ 0.998
P-Value >0.100
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0
100
200
300
400
500
Subjects 1-10

Appendix K

Summary of All Subject Trials

Trial Number	Left Load (lbs)	Right Load (lbs)	Subject 1 BCF (lbs)	Subject 2 BCF (lbs)
1	0	0	103.5	103.1
2	10	0	148.7	143.8
3	20	0	209.0	161.3
4	30	0	262.7	216.0
5	40	0	308.4	204.8
6	50	0	367.8	293.6
7	0	10	151.8	138.8
8	10	10	137.6	128.4
9	20	10	186.9	164.7
10	30	10	251.4	220.2
11	40	10	301.9	164.9
12	50	10	349.0	222.0
13	0	20	202.2	166.2
14	10	20	185.7	151.4
15	20	20	166.5	151.8
16	30	20	235.4	159.7
17	40	20	286.5	226.8
18	50	20	301.5	250.4
19	0	30	258.4	105.8
20	10	30	230.9	165.9
21	20	30	230.5	179.4
22	30	30	219.9	195.6
23	40	30	262.1	212.6
24	50	30	327.2	198.8
25	0	40	281.1	102.3
26	10	40	295.2	200.1
27	20	40	264.0	201.8
28	30	40	257.2	183.7
29	40	40	241.9	222.0
30	50	40	290.3	242.2
31	0	50	319.0	182.0
32	10	50	328.4	183.5
33	20	50	319.9	154.1
34	30	50	280.3	136.4
35	40	50	244.3	213.0
36	50	50	287.2	225.7

Trial Number	Left Load (lbs)	Right Load (lbs)	Subject 3 BCF (lbs)	Subject 4 BCF (lbs)
1	0	0	23.2	94.6
2	10	0	32.3	146.8
3	20	0	36.3	190.4
4	30	0	48.6	237.3
5	40	0	46.1	229.0
6	50	0	66.0	265.1
7	0	10	31.2	145.1
8	10	10	28.9	129.8
9	20	10	37.0	183.1
10	30	10	49.5	225.9
11	40	10	37.1	228.7
12	50	10	49.9	242.9
13	0	20	37.4	181.7
14	10	20	34.0	178.7
15	20	20	34.1	163.9
16	30	20	35.9	220.5
17	40	20	51.0	235.5
18	50	20	56.3	214.2
19	0	30	23.8	239.1
20	10	30	37.3	236.7
21	20	30	40.3	193.9
22	30	30	44.0	217.5
23	40	30	47.8	239.8
24	50	30	44.7	221.3
25	0	40	23.0	268.9
26	10	40	45.0	280.0
27	20	40	45.4	269.2
28	30	40	41.3	257.1
29	40	40	49.9	240.8
30	50	40	54.4	252.6
31	0	50	40.9	216.6
32	10	50	No Data	317.2
33	20	50	34.7	311.3
34	30	50	30.7	292.0
35	40	50	47.9	263.7
36	50	50	50.7	251.1

Trial Number	Left Load (lbs)	Right Load (lbs)	Subject 5 BCF (lbs)	Subject 6 BCF (lbs)
1	0	0	21.3	103.2
2	10	0	33.0	160.1
3	20	0	42.8	201.4
4	30	0	53.4	292.0
5	40	0	51.5	331.9
6	50	0	59.6	363.1
7	0	10	32.6	163.1
8	10	10	29.2	141.4
9	20	10	41.2	191.6
10	30	10	50.8	276.6
11	40	10	51.4	293.2
12	50	10	54.6	390.5
13	0	20	40.8	219.6
14	10	20	40.2	189.6
15	20	20	36.9	174.6
16	30	20	49.6	245.5
17	40	20	52.9	291.6
18	50	20	48.1	342.9
19	0	30	53.7	288.0
20	10	30	53.2	241.7
21	20	30	43.6	230.4
22	30	30	48.9	230.2
23	40	30	53.9	258.9
24	50	30	49.8	328.7
25	0	40	60.5	346.6
26	10	40	62.9	288.3
27	20	40	60.5	313.2
28	30	40	57.8	271.4
29	40	40	54.1	270.3
30	50	40	56.8	321.0
31	0	50	48.7	383.8
32	10	50	71.3	335.0
33	20	50	70.0	371.6
34	30	50	65.7	351.0
35	40	50	59.3	281.1
36	50	50	56.4	283.2

Trial Number	Left Load (lbs)	Right Load (lbs)	Subject 7 BCF (lbs)	Subject 8 BCF (lbs)
1	0	0	108.8	24.5
2	10	0	158.6	35.7
3	20	0	206.2	46.4
4	30	0	280.1	63.0
5	40	0	334.4	75.2
6	50	0	442.0	99.4
7	0	10	174.5	39.2
8	10	10	145.0	32.6
9	20	10	185.7	41.7
10	30	10	273.2	61.4
11	40	10	302.7	68.1
12	50	10	394.4	88.7
13	0	20	203.6	45.8
14	10	20	197.9	44.5
15	20	20	214.0	48.1
16	30	20	237.7	53.4
17	40	20	335.6	75.5
18	50	20	356.7	80.2
19	0	30	290.8	65.4
20	10	30	270.9	60.9
21	20	30	235.2	52.9
22	30	30	227.2	51.1
23	40	30	297.4	66.9
24	50	30	401.8	90.3
25	0	40	335.1	75.3
26	10	40	343.2	77.2
27	20	40	313.1	70.4
28	30	40	283.8	63.8
29	40	40	276.4	62.1
30	50	40	304.3	68.4
31	0	50	347.3	78.1
32	10	50	375.8	84.5
33	20	50	347.0	78.0
34	30	50	343.7	77.3
35	40	50	303.8	68.3
36	50	50	325.8	73.3

Trial Number	Left Load (lbs)	Right Load (lbs)	Subject 9 BCF (lbs)	Subject 10 BCF (lbs)
1	0	0	123.5	82.3
2	10	0	181.7	141.5
3	20	0	239.5	173.8
4	30	0	265.2	230.0
5	40	0	329.2	270.3
6	50	0	362.3	307.9
7	0	10	179.6	140.5
8	10	10	161.8	125.6
9	20	10	215.7	175.2
10	30	10	276.8	210.2
11	40	10	298.4	221.8
12	50	10	370.0	330.0
13	0	20	234.2	196.2
14	10	20	226.9	168.0
15	20	20	211.4	175.9
16	30	20	260.2	188.7
17	40	20	316.9	246.6
18	50	20	345.1	298.1
19	0	30	294.9	229.7
20	10	30	269.6	240.8
21	20	30	256.8	119.1
22	30	30	244.2	194.7
23	40	30	307.7	206.7
24	50	30	335.5	257.1
25	0	40	343.1	314.0
26	10	40	329.5	257.3
27	20	40	290.6	236.3
28	30	40	268.0	220.6
29	40	40	274.0	225.3
30	50	40	343.8	260.7
31	0	50	406.3	369.7
32	10	50	355.6	274.5
33	20	50	No Data	312.8
34	30	50	293.6	307.0
35	40	50	259.2	269.2
36	50	50	290.6	281.6

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