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Modeling three-dimensional hip and trunk peak torque as a function of joint angle and velocity

Allison Anne Stockdale
University of Iowa

MODELING THREE-DIMENSIONAL HIP AND TRUNK PEAK TORQUE AS A FUNCTION OF JOINT ANGLE AND VELOCITY

by

Allison Anne Stockdale

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Thesis Supervisors: Associate Professor Laura Frey Law
Associate Professor Nicole Grosland

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Allison Anne Stockdale

has been approved by the Examining Committee for this thesis requirement for the Master of Science degree in Biomedical Engineering at the July 2011 graduation.

Thesis Committee: ______________________________
Laura Frey Law, Thesis Supervisor

____
Nicole Grosland, Thesis Supervisor

____
Tim Marler

____
Madhavan Raghavan

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Significance

Back pain is the number one musculoskeletal complaint among the American population. It is also the 5th most common reason for missed work and doctor visits. (Deyo 2006) With so many people experiencing back pain, healthcare costs have risen above 100 billion dollars a year in the treatment of chronic pain. (USNew 2009) This number is only expected to increase because it is estimated that 80% of the American population will experience back pain in their lifetime. (Acute 1985)

Ergonomists have begun to investigate ways to reduce back pain by assessing work environments and redesigning equipment. The work place is one of the most common places for back injuries, and assessing this risk will reduce healthcare costs at large. Digital human modeling is one of the most effective ways to recognize and assess these risks. However, digital human modeling is currently limited to predicting certain joints and positions.

Digital Human Modeling

Advances in digital human modeling are rooted in developing a deeper understanding of how to predict human kinematics and kinetics. The University of Iowa's Virtual Research Soldier (VSR) program is diligently developing the digital human model, Santos®. Santos is design to predict kinetics and kinematics for static and dynamic tasks. This tool is useful for ergonomic applications as it may provide a unique ability to predict high risk situations. Ultimately, digital human modeling may reduce the costs associated with musculoskeletal injuries in the work place especially back pain.

However, current digital human models are limited in their resources for predicting normal human capability. Often times, it is unclear whether the model population is an average population or the strongest population available. In addition, a large normative population is needed for accurate predictive modeling, which some models lack. Another limit current digital human models have is that they can either predict dynamic or static strength, never both. A popular current model, Jack (Electronic Data System, Plano, TX), is capable of predicting static positions but, he lacks the ability to predict dynamic motion. This limitation inhibits ergonomists from fully understanding the possible environmental risks.

In order to have effective digital human modeling, models of joint strength for static and dynamic conditions are needed. Santos is developed to incorporate an average range of static and dynamic strength data. The knee and elbow (Laake 2008), shoulder (Pierce 2009), wrist (unpublished), and ankle (unpublished) are currently being implemented in Santos. The hip and trunk joints are the next crucial joints to be added.

Joint Strength

Joint strength is the type strength implemented into the University of Iowa's digital human model, Santos. Adding strength based on the joint provides the optimal estimation of whole body kinematic motion because it is based on combination of several muscle, bone, and soft tissue strength. If the individual muscle strength was implemented into a digital human model, there is a high probability that the strength would be over or under estimated during movement analysis.

The joint strength values in digital human models are based on the experimental static and dynamic strength. The static strength is the voluntary muscle strength available in a still position where as dynamic strength is voluntary muscle strength available when moving through a defined range of motion at a set speed. These types of strength provide the digital human models with limiting strength parameters.

Isometric Strength

Ergonomists used static strength to model and predict the amount of strength produced in a particular position. To measure static strength, voluntary isometric muscle contractions are performed in stilled positions. The maximum strength is usually found in the anatomical position, however as the length of a muscle changes the maximum strength also changes. Researchers have classified this as the torque-angle relationship. An example of a torque-angle relationship can be seen in figure 1.1. It can be observed that the torque is affected by angle varying between different directions. Ergonomists use torque-angle relationships to assess high risk angles during functional tasks.

Isokinetic Strength

Isokinetic strength is the strength available throughout a range of motion at a set speed. Ergonomists use this strength measurement to evaluate the force people utilize in work environments. Estimating force at different velocities enhances ergonomists abilities to predict and model speed at which harmful tasks may occur. Previous studies have proven that as velocities increase force decreases. This torque-velocity relationship is demonstrated in figure 1.2. Torque-velocity relationships aid ergonomists in predicting human dynamic strength capabilities.

Three-Dimensional Strength

As beneficial as torque-angle and torque-velocity relationships are to ergonomics, digital human modeling requires the most precise strength data possible. Implementing a torque-angle-velocity relationship into a digital human model provides strength based on joint position and joint velocity. This gives the most accurate predicted data available because it can provides a range of torques at different angles and the same velocity, or different velocities and the same angle. The University of Iowa, Santos, has already implemented this relationship for several joints. In addition to Santos using this model, Khalaf used the torque-angle-velocity relationship to model several joints for an interface between ergonomics and rehabilitation.(Khalaf 1997) Anderson also modeled torque-angle-velocity strength to provide a practical and widely acceptable model for the hip, knee, and ankle joints. (Anderson 2007) However, the results from neither of these studies were meant to be implemented into a digital human model.

Trunk and Hip Joint Modeling

Modeling the trunk and hip is crucial to having a usable digital human model because these joints are responsible for the stability and balance of the body. Developing and implementing normative strength data for these joints will enhance the digital human modeling, and give ergonomists standard strength averages needed for assessing functional tasks. In addition, a comparison of the hip and trunk joint has never been consider and could provide further insight on the kinematics and kinetics of the human body.

The trunk strength is measured in three planes of motion; the sagittal plane, the transverse plane, and the frontal plane. Each plane is measured independently of one another. Trunk flexion and extension movement is the most common trunk motion considered in biomechanics or ergonomic research because injury occurs most commonly in these motions. Ergonomic lifting standards have been developed based on flexion and extension isometric strength. However, trunk rotation is also believed to be an important risk factor for back injuries especially when coupled with lifting. (Chaffin 2006) Since flexion, extension and rotation provide the highest risk for back injury, they are the motions considered in this study.

While often considered independently, the hip and trunk muscles can act together in certain planes of motion. In particular, hip and trunk extension or flexion typically co-occur during normal functional tasks. While the hip also has three degrees of motion: flexion and extension in the sagittal plane, adduction and abduction in the frontal plane, and internal and external rotational in the transverse plane, only flexion and extension will be considered in this study due to its role with trunk flexion and extension.

Specific Aims

The overall goal of this need base research is to increase the hip and trunk strength data available for digital human modeling. More specifically the aims of this research include:

1. Model the hip and trunk strength as three dimensional surfaces based on torque, joint angle, and velocity.
    a. Measure static and dynamic strength for trunk flexion, extension and rotation in men and women.
    b. Measure static and dynamic hip flexion and extension strength for men and women.
    c. Compare experimental strength relationships with relationships presented in literature.
2. Determine the differences between the three-dimensional surfaces for the same joint.

a. Compare trunk extension surfaces to trunk flexion surfaces for men and women.
b. Compare trunk right rotational surfaces to trunk left rotational surfaces for men and women.
c. Compare hip extension surfaces to hip flexion surfaces for men and women.

3. Determine the differences between the three-dimensional surfaces for different joints.
    a. Compare trunk flexion surfaces to hip flexion surfaces for men and women.
    b. Compare trunk extension surfaces to hip extension surfaces for men and women.

These objectives will be addressed in the following methods, results and discussion chapters.

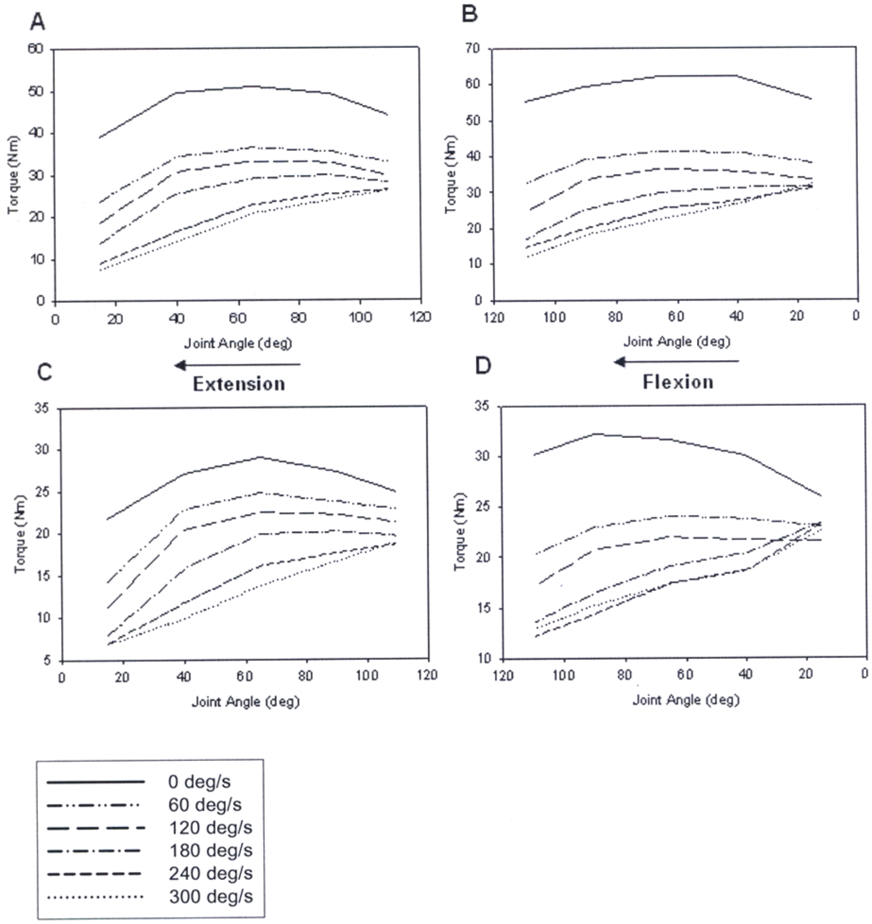

Figure 1.1. Joint torque-angle relationship for the male elbow flexion and extension (A and B) and female elbow flexion and extension (C and D).

Source: Laake, Andrea (2008). Modeling three-dimensional knee and elbow joint strength as a function of velocity and position.

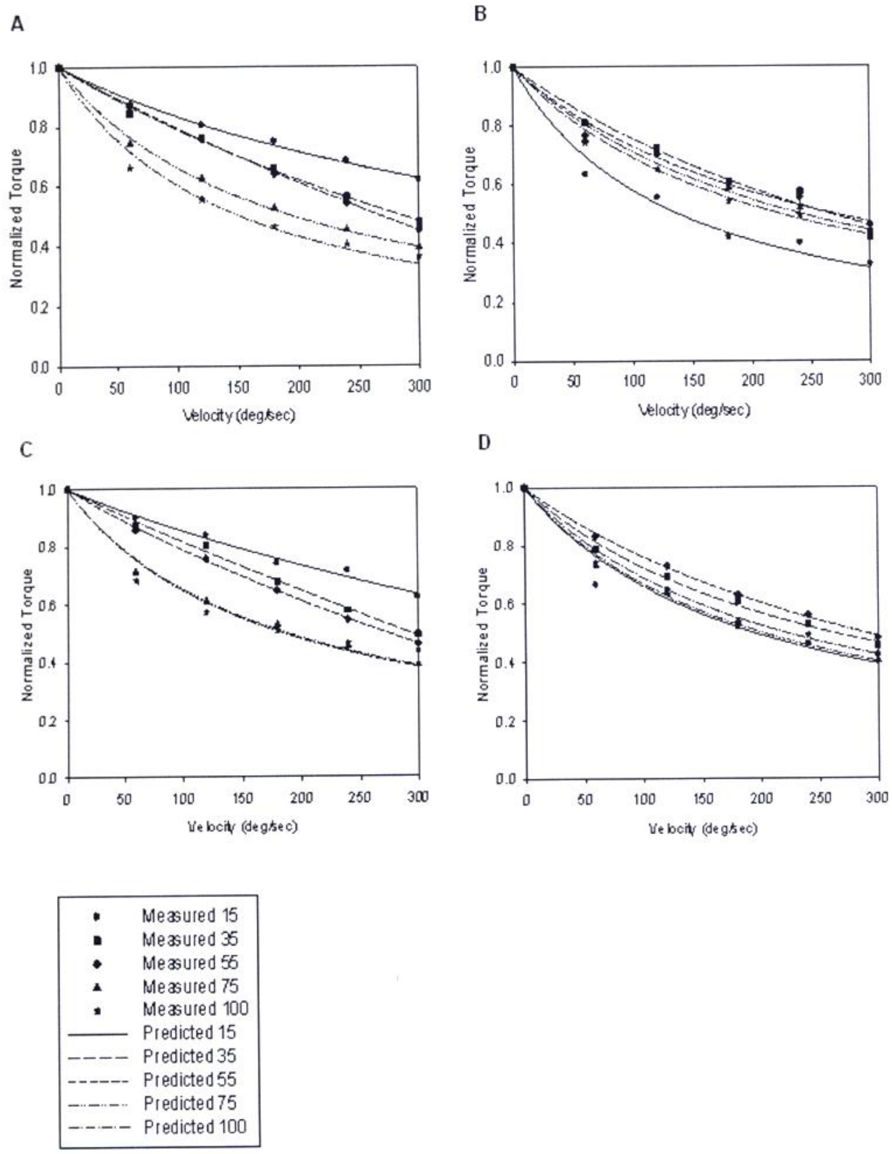

Figure 1.2. Joint torque-velocity relationship for the male knee flexion and extension (A and B) and female knee flexion and extension (C and D).

Source: Laake, Andrea (2008). Modeling three-dimensional knee and elbow joint strength as a function of velocity and position.

CHAPTER 2

LITERATURE REVIEW

Populations

Ergonomists are interested in the kinematic and kinetic motion of the hips and trunk since it is a large cause of occupational health injuries and illnesses (Chaffin, 2006). A method to reduce injury while maintaining human safety is to model a functional task (Chaffin, 2006). Specifically, modeling the trunk and hip joint would be particularly useful for reducing risk of injury during a functional task. Collecting a normative database among an average population provides ergonomists with a reliable range of available strength for the development of these models. However diseased populations are often the focus of research, which makes identifying normative capabilities quite difficult. For instance, Shirado (1992) investigated chronic low back pain, and provided little information about the healthy control. In order to have successful joint strength models, ergonomists need a large average population which current research lacks.

Isokinetic Strength

Isokinetic strength testing is one way to qualify dynamic motion. The torque-velocity relationship provides the peak torques people can produce at a variety of speeds. Previous studies have shown that as the force decrease as the velocity increases. In addition, a number experimental factors can impact the torque-velocity relationship produced.

The peak torques produced from isokinetic testing are influenced by the positions the joints are tested in. Hip positions for isokinetic testing have included prone, supine, seated, and standing. Figures 2.1.-2.4. compare the different testing positions, and the standing position appears most common in current literature. Cahalan et.al 1989 used the standing position for hip because it allows for body weight to be evenly dispersed throughout the body and is considered the natural functional position. (Cahalan et al., 1989). Like hip, the standing position is optimal for trunk isokinetic strength collection. As it is seen in figures 2.5.-2.8, the data is consistent for the same position, but varies between testing position. Finley et al. (2000) investigated the difference between seated and standing positions for the flexion and extension motion. No variation existed for extension torques between positions, but the flexion torque for the standing position was statistically greater than the seated. According to Finley, one reason for the differences is that the muscle length between the hip and trunk is longest in the standing position. (Finley et al., 2000) In addition, the standing position is also the safest position to test in because the seated position increases the risk of lumbar injury. (Davis, 1998) Testing position for the hip and trunk is sensitive to generating peak torques.

In literature, investigators often compare the joint strength between men and women. For the hip and trunk joints, a comparison of normative strength data between men and women were the focus of several studies. According to Claiborne et.al 2006, women produce less absolute peak torque then men do for isokinetic flexion and extension. The hip flexion and extension peak torques for men and women can be seen in figures 2.1-2.4. Similar to hip, men have higher peak torque values for trunk flexion and extension. It is speculated that men have higher peak torques because men have greater fat-free or muscle-mass than women. (Cowley, 2009) The desire to understand the hip and trunk strength between men and women has lead to the development of many current normative strength databases.

Isometric Strength

The torque-angle relationships depicts hip and trunk torque for a given angle under isometric conditions. During isometric testing, the highest voluntary muscles contractions are reached in a static position.

The peak torques for isometric testing often occur at a neutral angle, and most investigators only focus on that particular angle. Isometric testing for trunk flexion, extension, and rotation occur at the anatomical position zero for many studies. (Smith 1987, Tanaka 1998, McNeil 1980, Kondraske 1987, Keller 2002, McIntyre 1989, Yasserli 2007, Lariviere 2003, Parnianpour 1989, Madsen 1996, Levene 1989, Hakkinen 2003 , Gomez 1991, Lee and Kuo 2000, Kumar 2003, Malchaire and Masset 1995, Azghani 2008, Kumar 2001, Kumar 1995) The highest torques for both hip and trunk isometric testing happens at the zero degree angle, however, a zero degree angle for the hip is more difficult to test. Researchers have found that angles, 0, 10, and 15 produce the highest peak torques depending on anatomical reference. (Arokoski 2002, Calahan et.al 1989, Dean 2004, Wojcik 2000) Investigators for both the trunk and hip believe the zero degree angle is the optimal angle to test at.

In order to create a torque-angle relationship, isometric testing must be performed at a number of angles. For trunk flexion and extension, Keller et al. 2002 was the only investigator to perform isometric testing at several different angles. The torque-angle relationship can be seen in figures 2.12-2.16. Similar to Keller et. Al 2002, Kumar 1995 presented a torque-angle relationship for trunk rotation, which is seen in figures 2.16.-2.20. However, the only torque-angle relationship for hip was presented by Cahalan which is presented in figures 2.9-2.12. (Cahalan et.al 1989) Cahalan's torque-angle relationship however, lacks many other different angles. The use of several different angles provide the most reliable torque-angle relationships.

In hip and trunk isometric testing, several researchers have investigated whether or not both sides of the joint have equal strength. For trunk rotation, it can be seen from figures 2.16.-2.20, that the trunk appears to be bilateral. Kumar proved that there are no sizable differences between right and left muscle pairs. (Kumar 1995) Like trunk rotation, the hips are also bilateral. Arokoski concluded that the right and left side of the hips had no significant differences for men in flexion and extension isometric testing. (Arokoski et.al 2002) Since both the hip and trunk can be considered bilateral either side of the joint can be tested.

Three Dimensional Strength Data

In the past decade, researchers started to present joint strength as a combination of joint angle and velocity. Presenting strength as combination includes the force-length and force-velocity relationships making a more realistic model to human motion. Khalaf (1997), the first to model strength as a combination of joint angle and velocity, modeled trunk flexion and extension in order to provide ergonomists with a better tool for determining trunk strength. The three-dimensional strength surfaces for trunk flexion and extension are seen in figure 2.21. Similar to Khalaf, Anderson et.al (2007) modeled the knee and ankle. His surfaces can be seen in figures 2.22. Both studies provide models that predict joints strength as a function of joint angle and angular velocity. However, neither study can be implemented into a digital human model because only a limited number of motions and directions were tested.

In order to aid in the development of the University of Iowa's digital human model, Santos, Laake (2008) and Pierce (2009) created three-dimensional surfaces of peak torque as a function of joint angle and velocity. Laake created three-dimensional strength surfaces for the knee and elbow; she tested each joint at 5 different isokinetic velocities and 5 different isometric angles for 28 male and 26 female subjects. She concluded that many models are needed to describe the motions at the knee and elbow. Pierce (2009) produced similar three-dimensional surfaces for the shoulder based on 22 male and 27 female subjects. He tested the shoulder's flexion/extension and adduction/abduction at 4 different velocities, and 5 isometric angles. For the shoulder internal/external rotation, he tested at 5 different velocities and 5 isometric angles. He concluded that any Taylor Series equation can successfully model shoulder motion. Laake and Pierce, all found differences between planar motions and between men and women. They also concluded all the motions model can be implemented into a digital human model, and will enhance this ergonomic tool.

<u>Literature Limitations of Digital Human Modeling</u>

The current joint strength data available on the hip and trunk is used for other purposes besides digital human modeling. Since studies have a wide variety of goals, the type of strength collection is different from study to study. Several strength dynamometers are currently available however, each dynamometer measures torque slightly differently making a large range of maximum peak torques. Each study also analyzes the strength differently, influencing the maximum peak torques presented. Gravity correction is one of the most influential factors in data analysis, and must be used for digital human modeling to be effective. The gravity corrected strength prevents digital human models from under or over estimating joint strength. Most current literature available does not provide information on whether or not gravity correction was used. The limitations literature currently has lead to inaccurate digital human models.

In addition to strength literature limiting digital human modeling, the current digital human models such as Teechnomatix's Jack and Process Simulate Human, the University of Michigan's Three-Dimensional Static Strength Posture Prediction, Anybody Technology software programs are also limited. These digital human models are only designed to predict static positioning and posture. Although these software programs are successful at static prediction, dynamic prediction is important to include. This static and dynamic strength must be added into the University of Iowa's Santos.

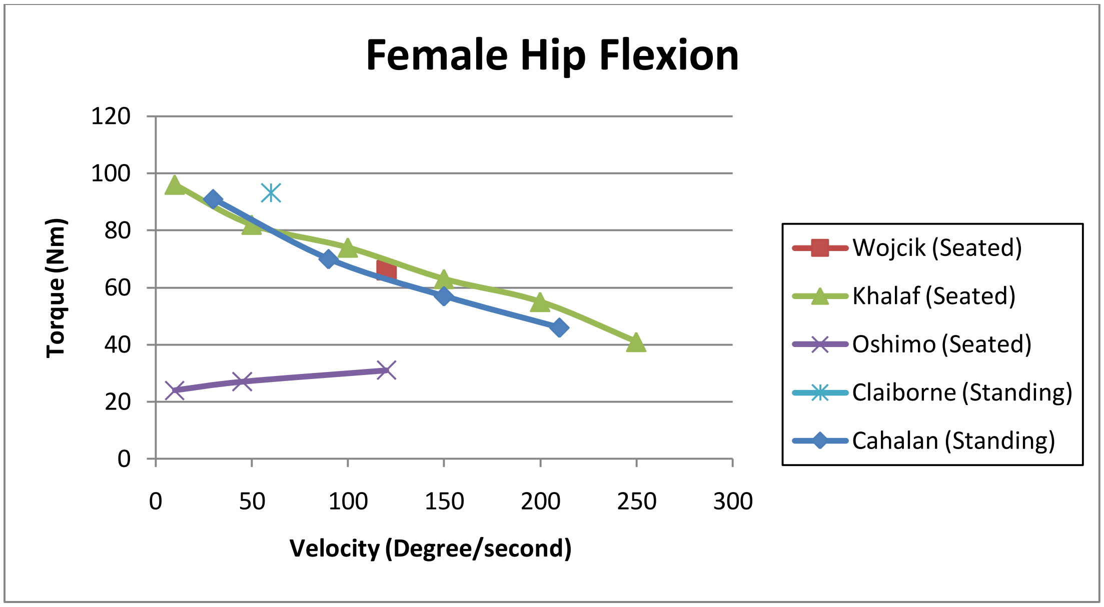

Figure 2.1. Female hip flexion from 5 studies. Note that position that testing was done is listed.

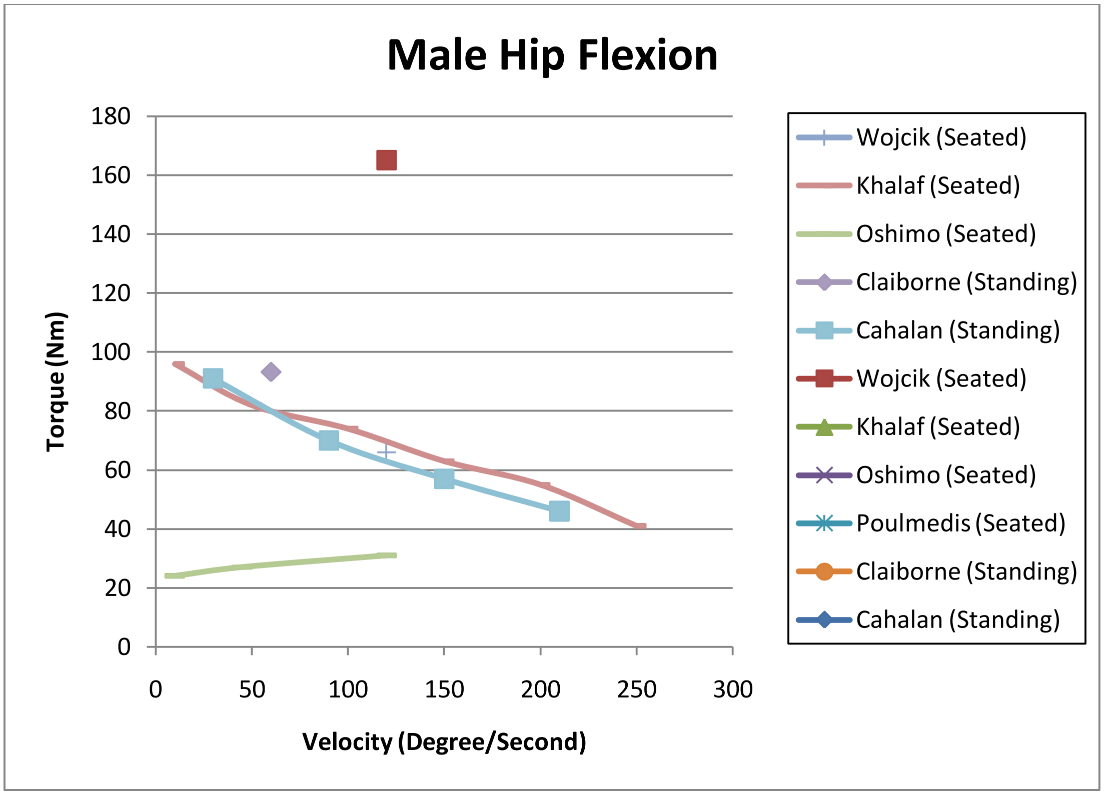

Figure 2.2. Male hip flexion from 7 studies. Note that position that testing was done is listed.

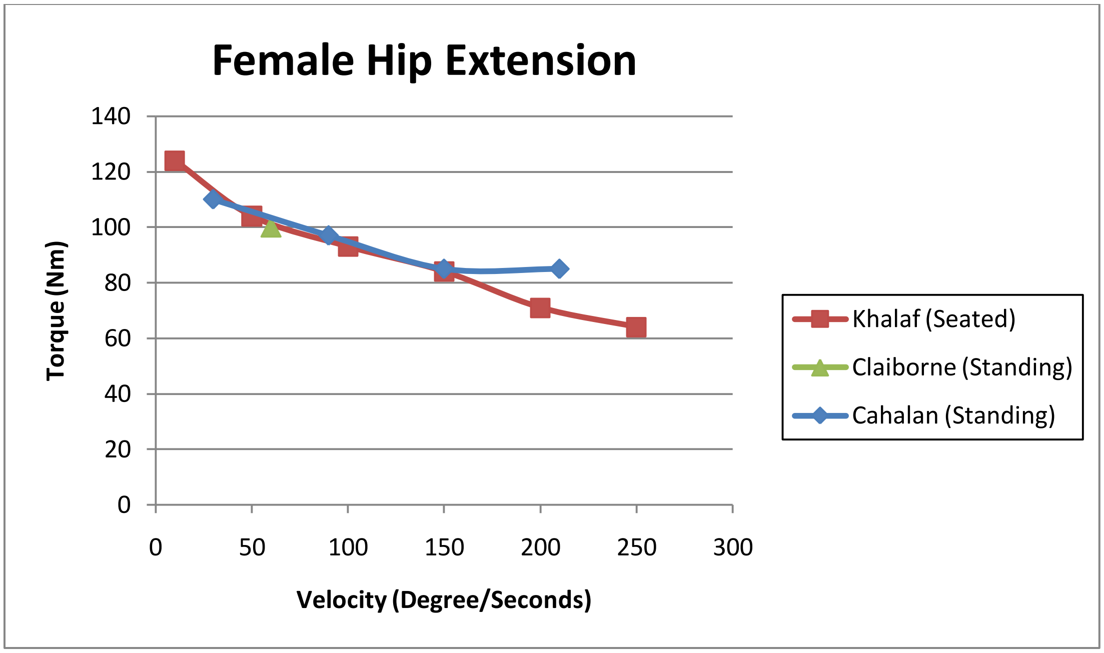

Figure 2.3. Female hip extension from 3 studies. Note that the position that testing was done is listed.

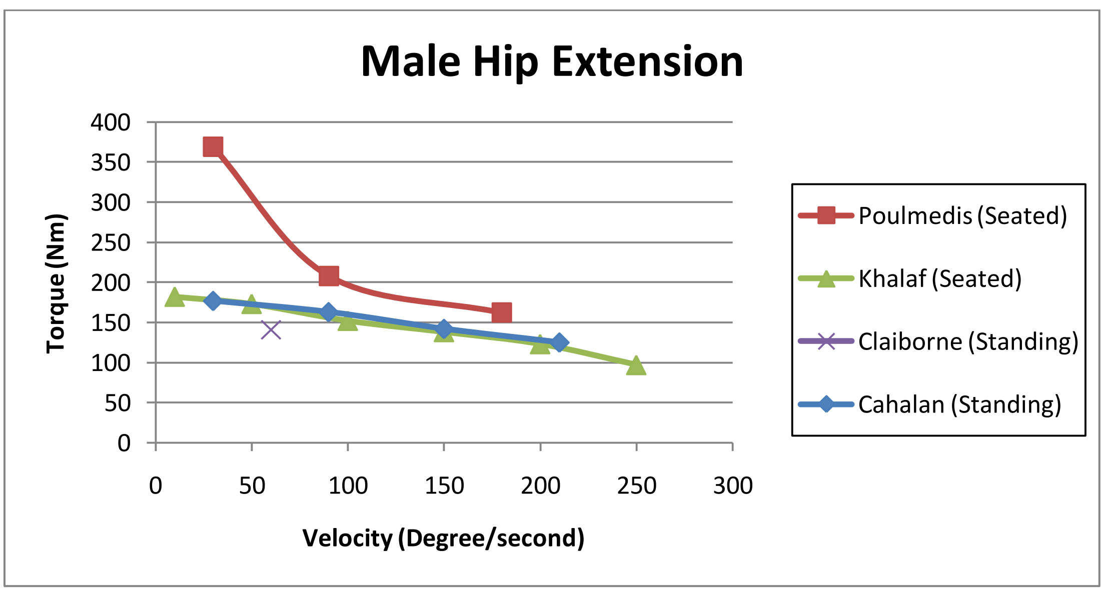

Figure 2.4. Male hip extension from 4 studies. Note that the position that testing was done is listed.

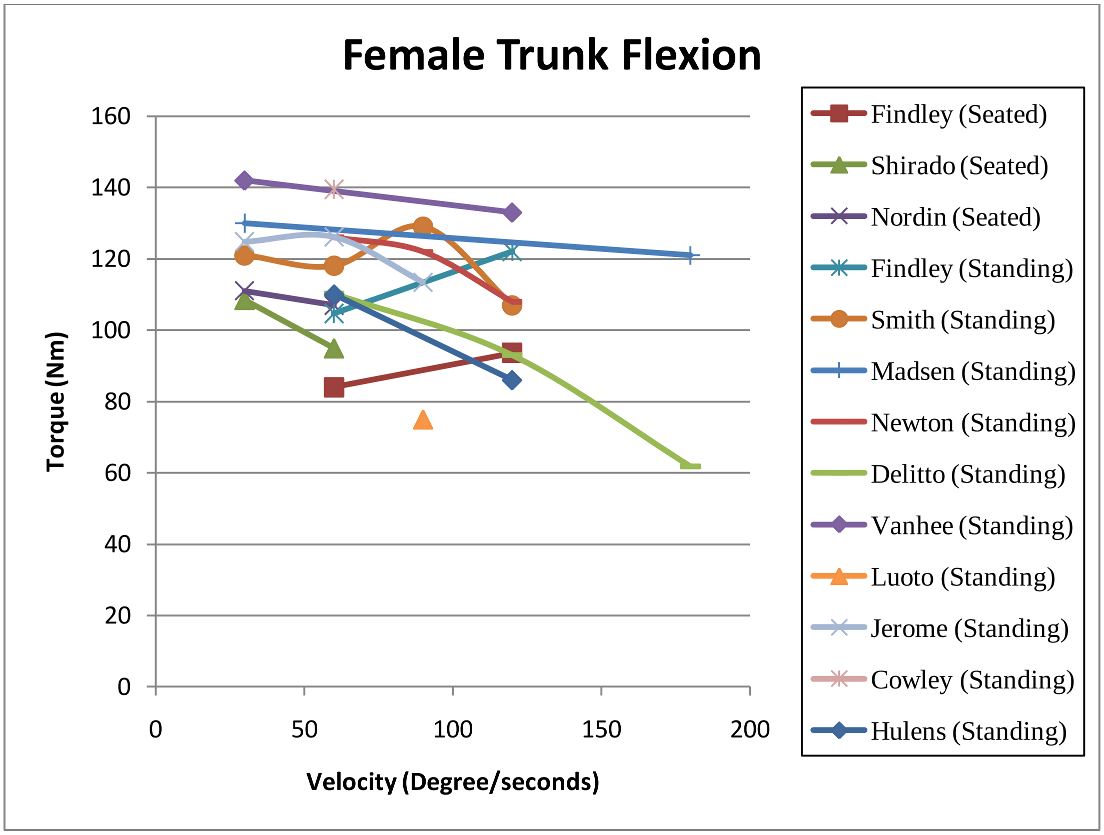

Figure 2.5. Female trunk flexion from 12 studies. Note that the position that testing was done is listed.

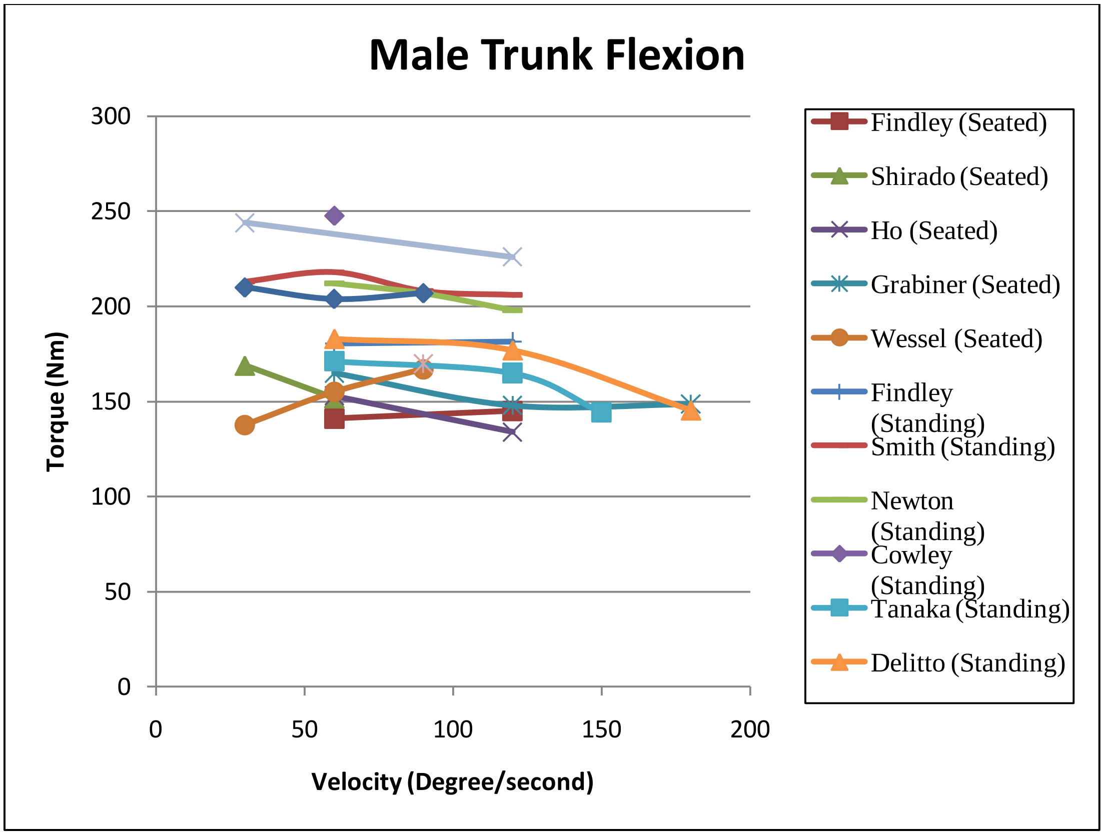

Figure 2.6. Male trunk flexion from 13 studies. Note that the position that testing was done is listed.

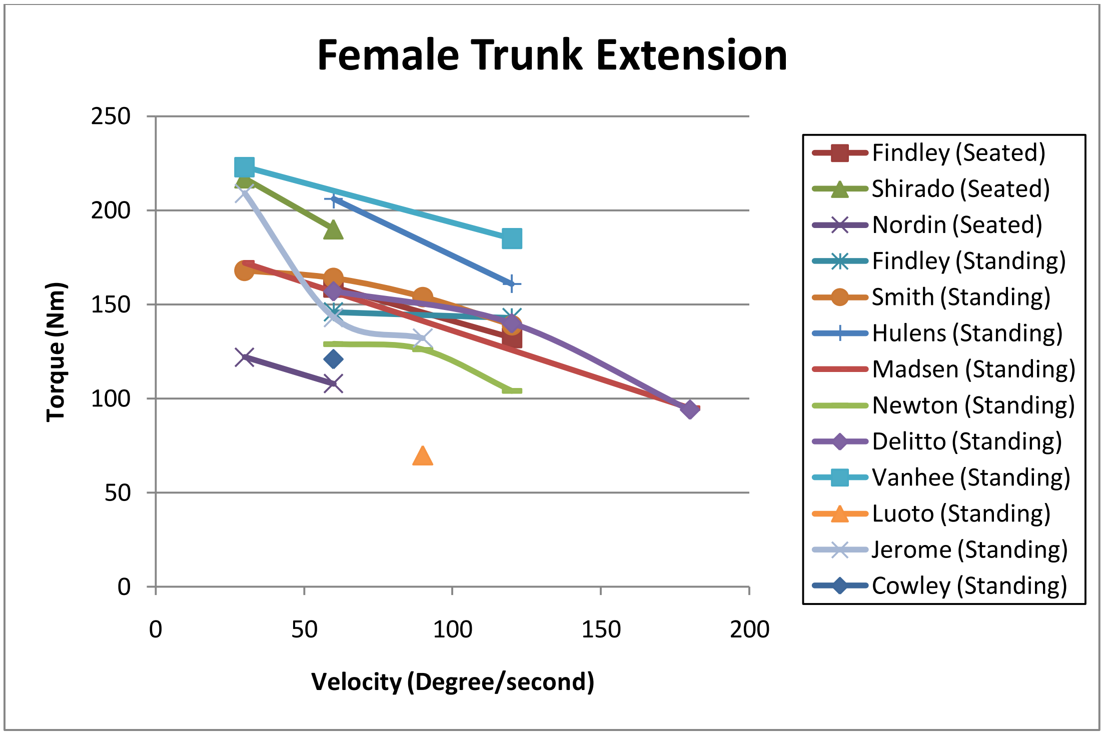

Figure 2.7. Female trunk extension from 12 studies. Note that the position that testing was done is listed.

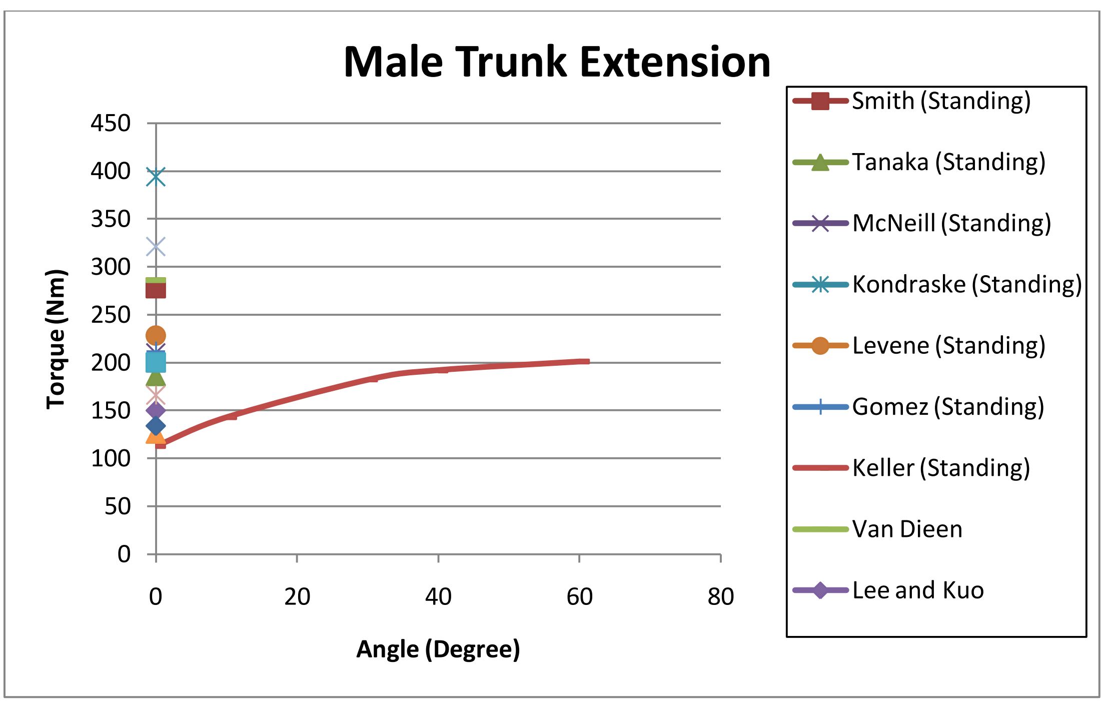

Figure 2.8. Male trunk extension from 13 studies. Note that the position that testing was done is listed.

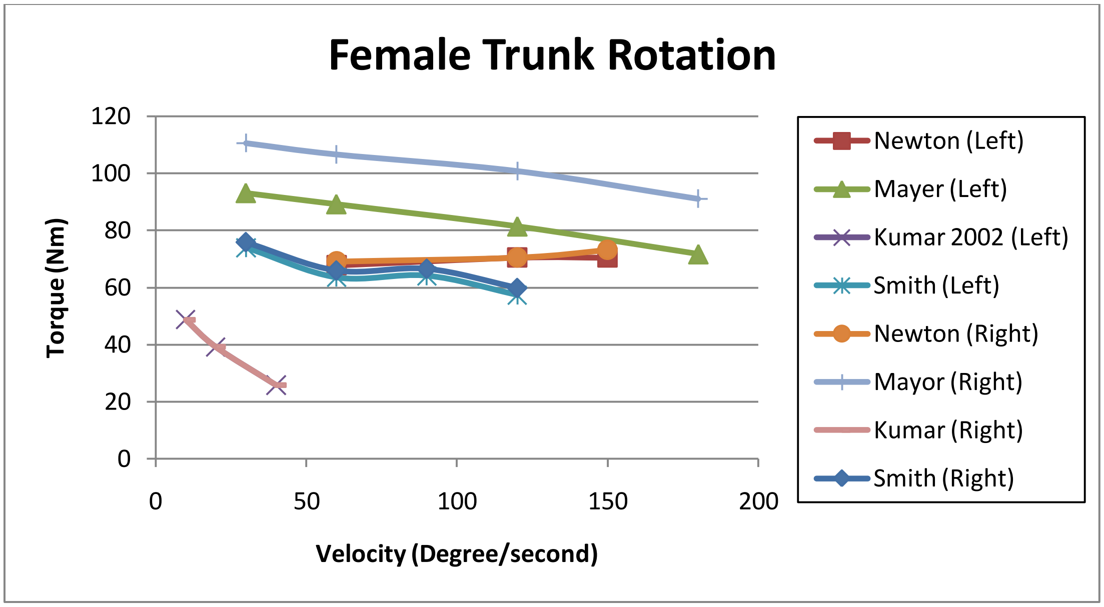

Figure 2.9. Female trunk rotation strength from 4 studies. Note that the side that was tested is denoted by Left or Right.

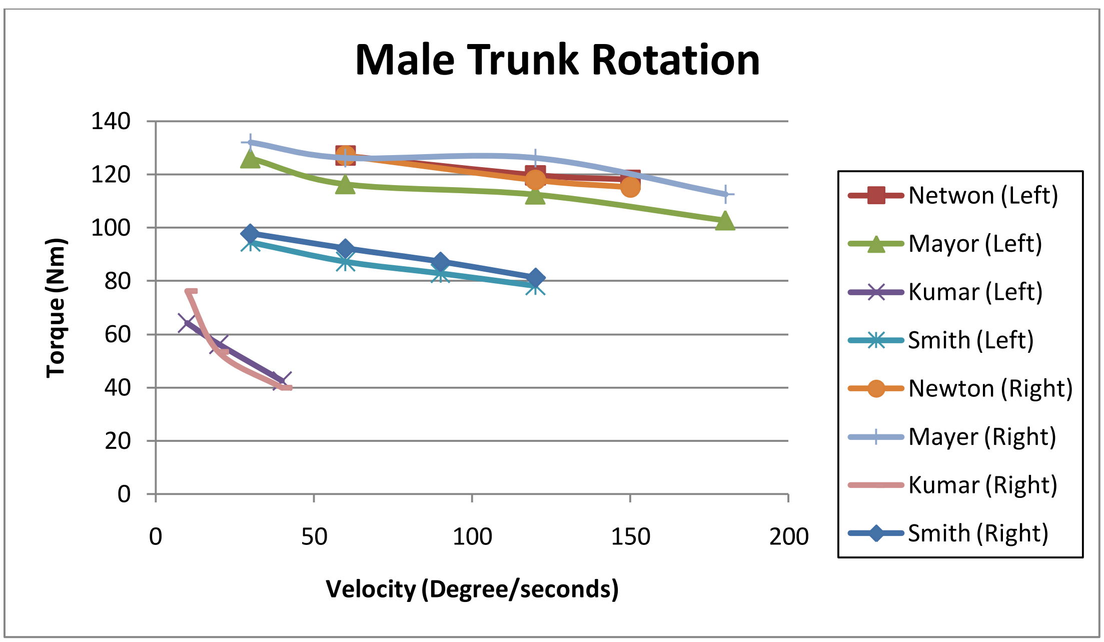

Figure 2.10. Male trunk rotation from 4 studies. Note that the side that was tested is denoted by Left or Right.

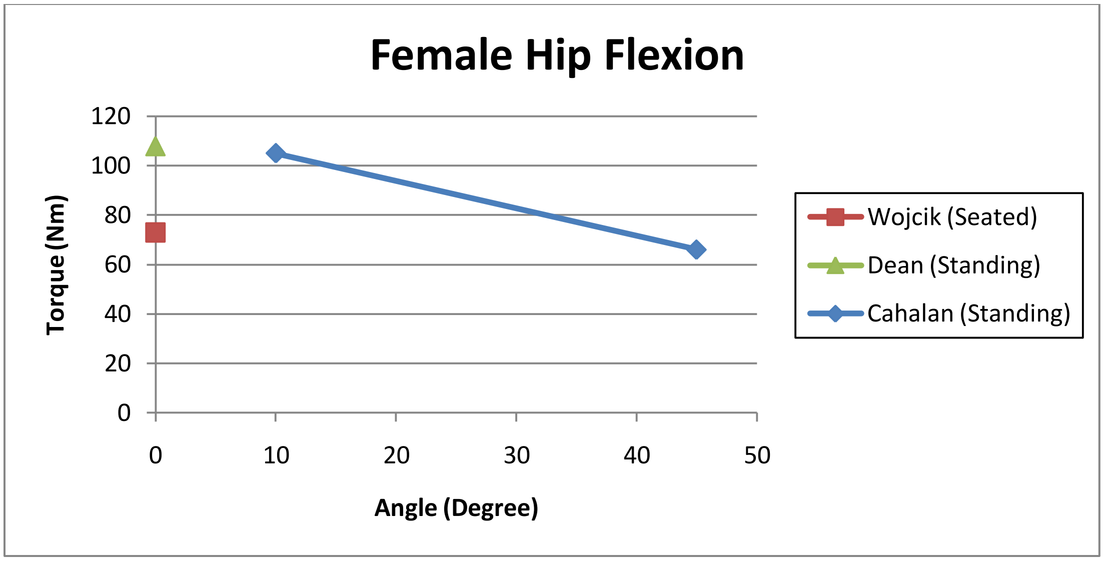

Figure 2.11. Female hip flexion from 3 studies. Note that the position that testing was done is listed.

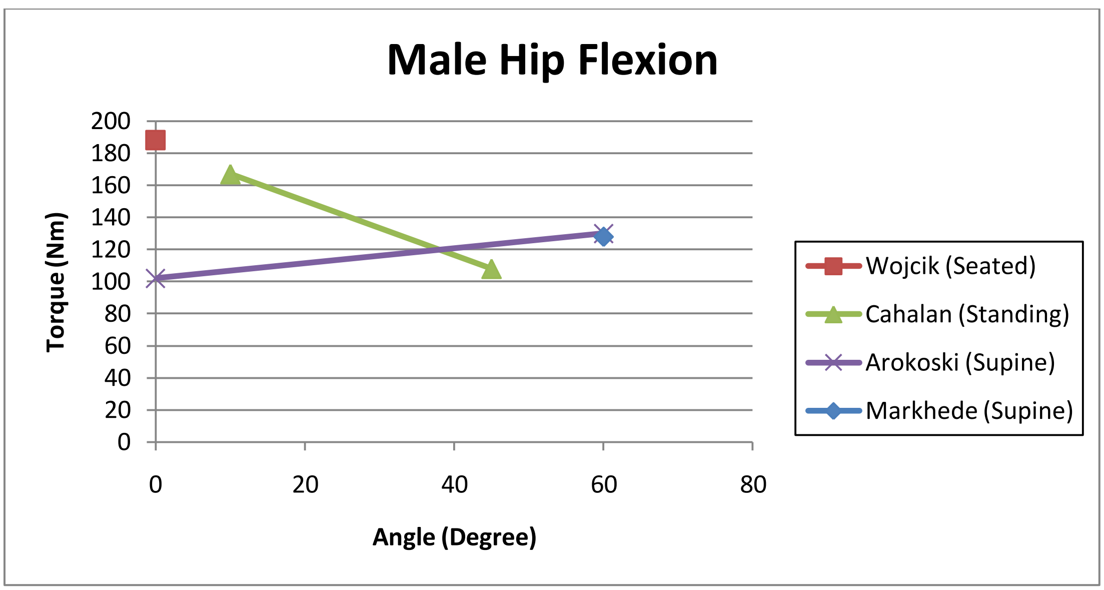

Figure 2.12. Male hip flexion from 4 studies. Note that the position that testing was done is listed.

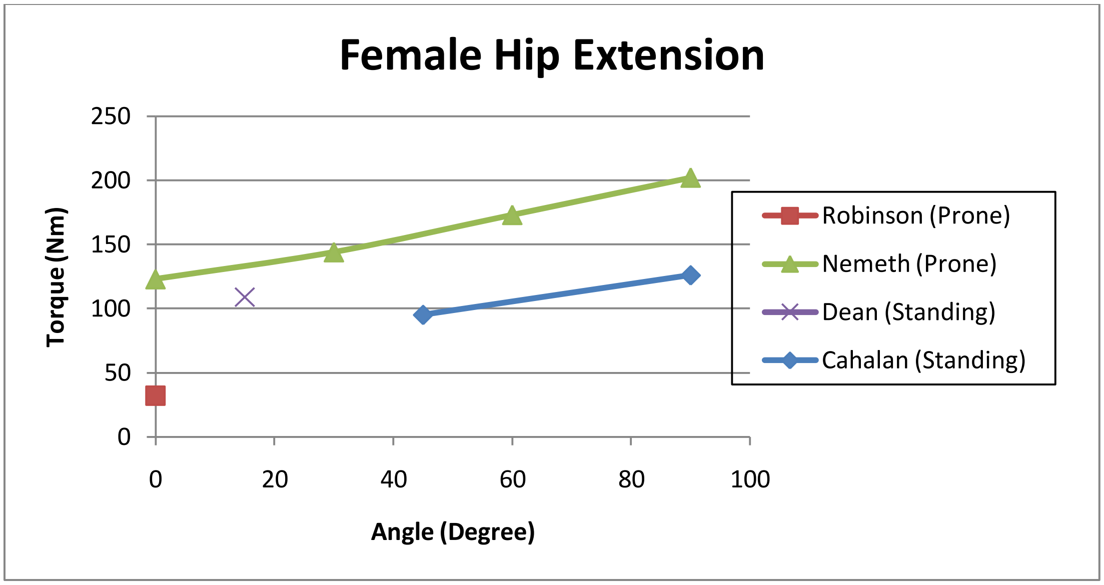

Figure 2.13. Female hip flexion from 4 studies. Note that the position that testing was done is listed.

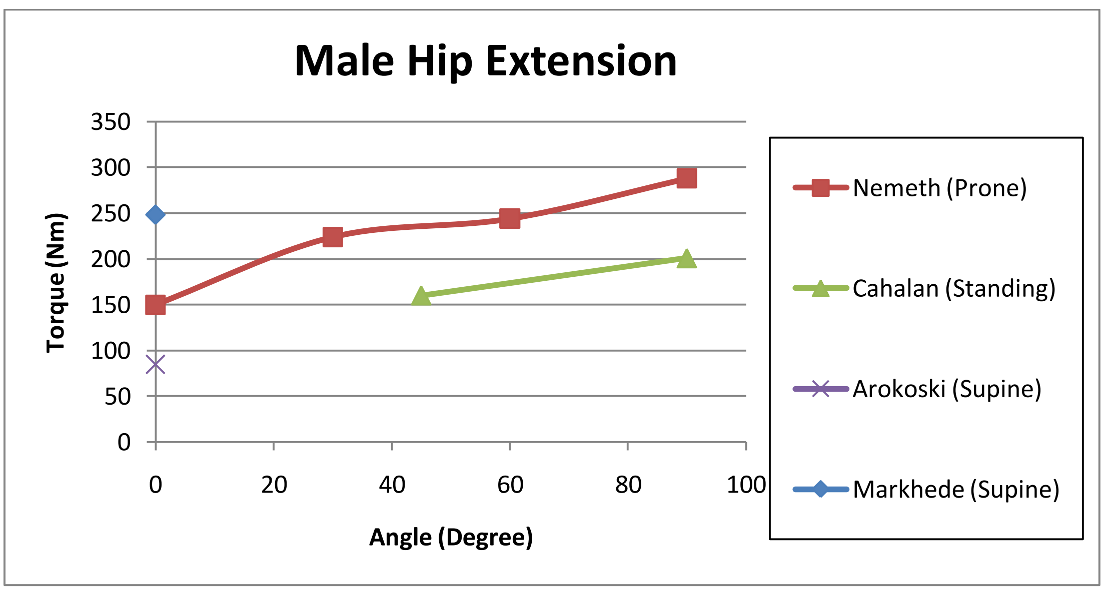

Figure 2.14. Male hip flexion from 4 studies. Note that the position that testing was done is listed.

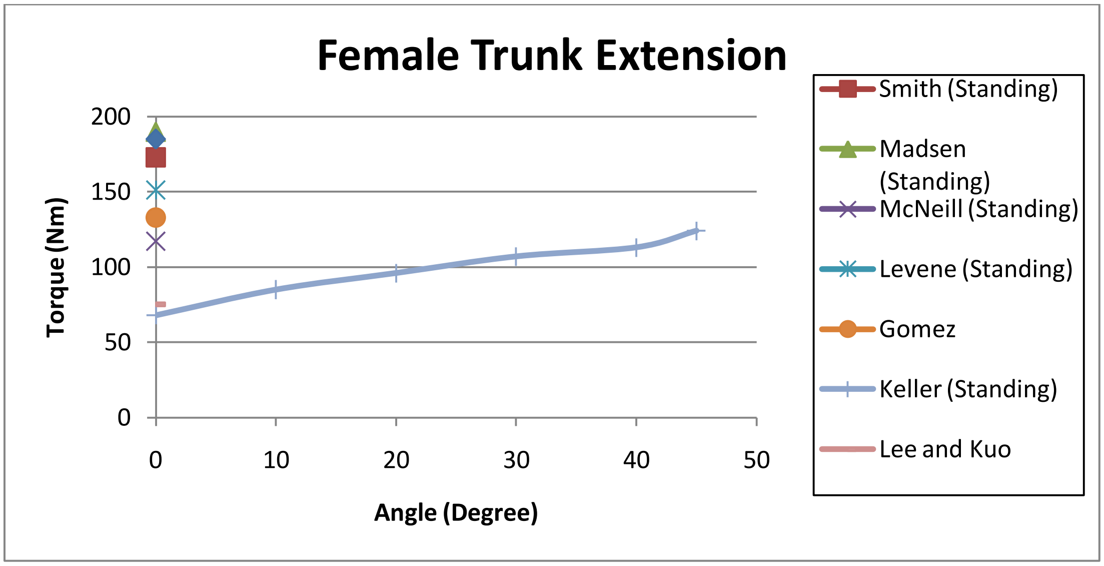

Figure 2.15. Female trunk extension from 8 studies. Note that the position that testing was done is listed.

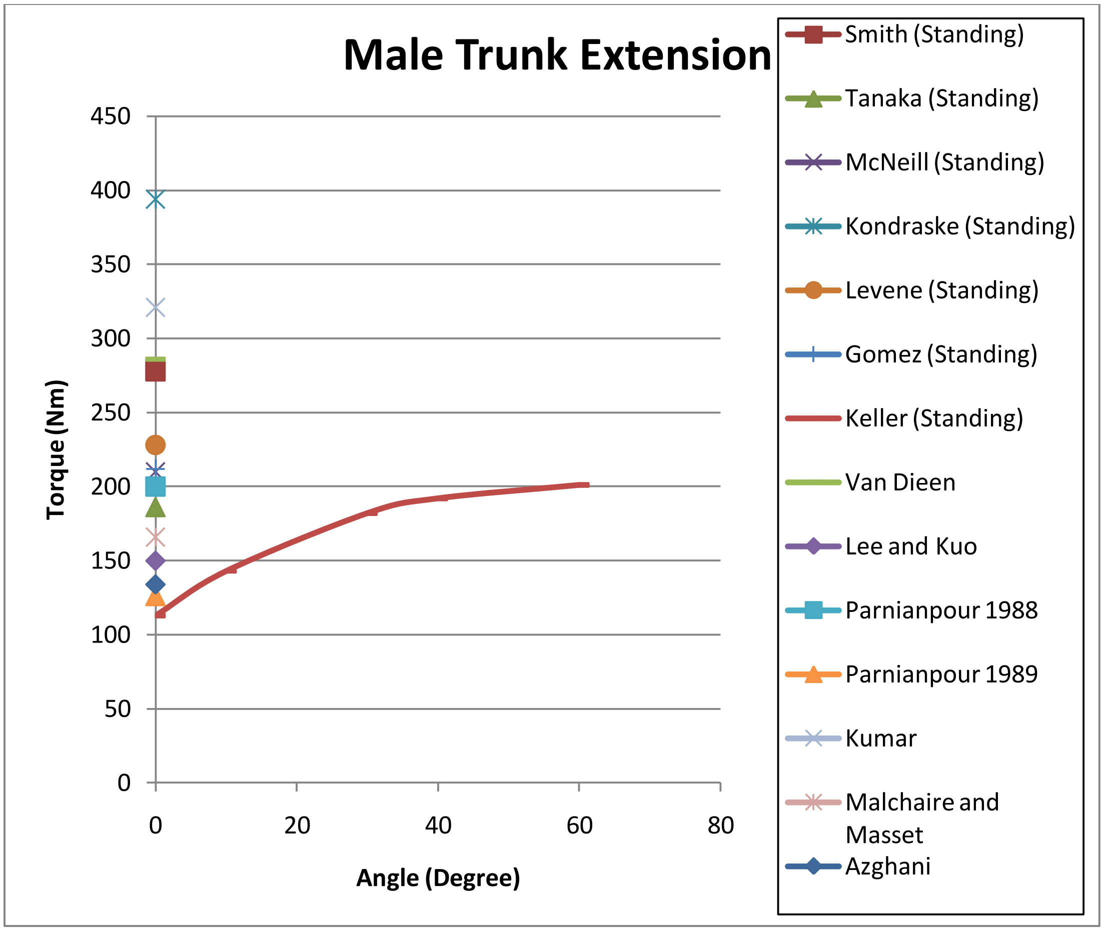

Figure 2.16. Male trunk extension from 14 studies. Note that the position that testing was done is listed.

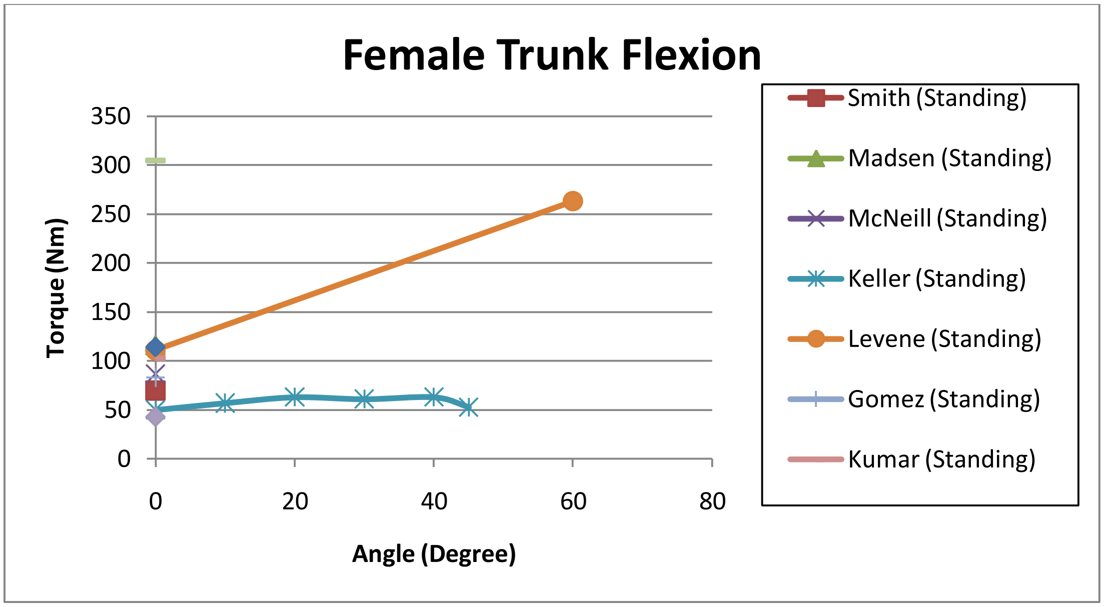

Figure 2.17. Female trunk flexion from 10 studies. Note that the position that testing was done is listed.

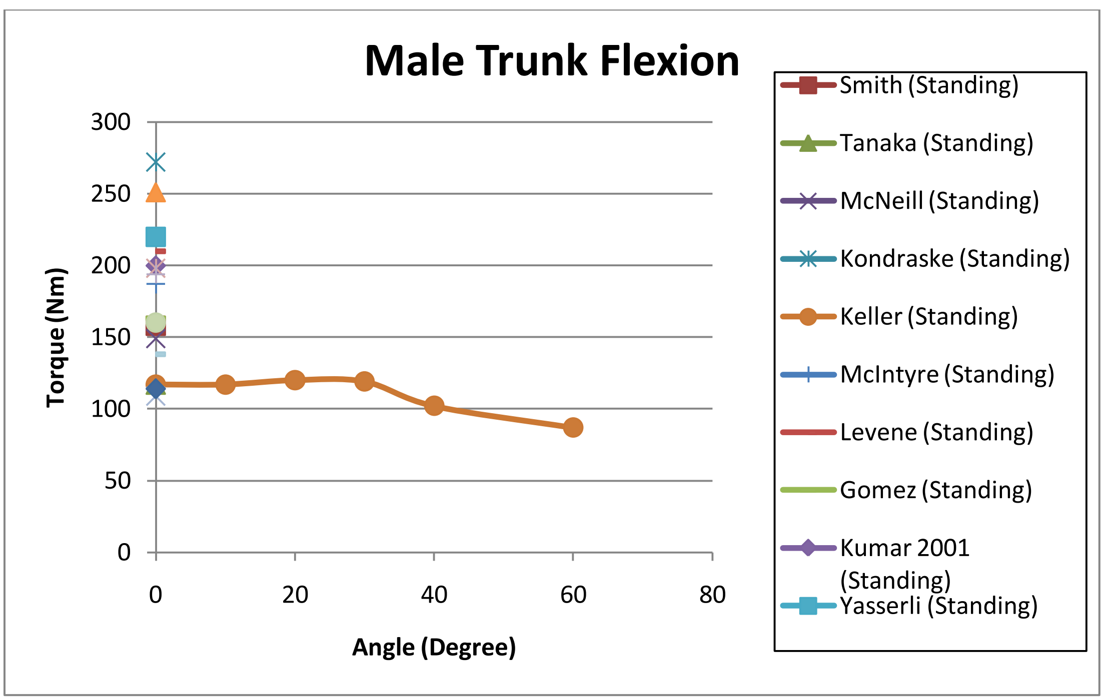

Figure 2.18. Male trunk flexion from 17 studies. Note that the position that testing was done is listed.

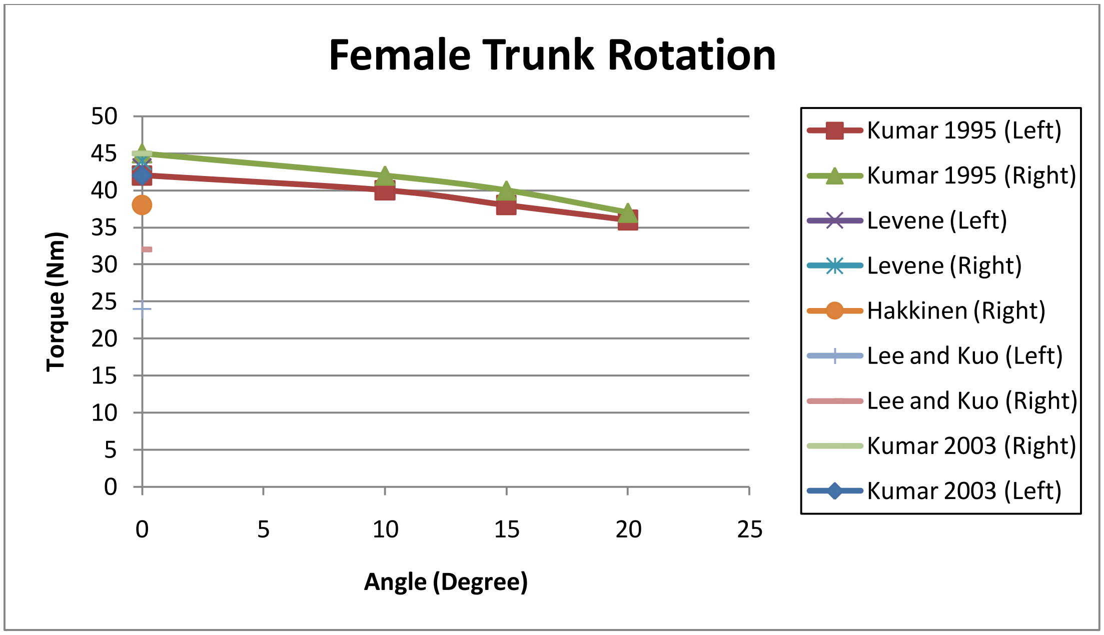

Figure 2.19. Female trunk rotation from 5 studies. Note that the side that was tested is indicated.

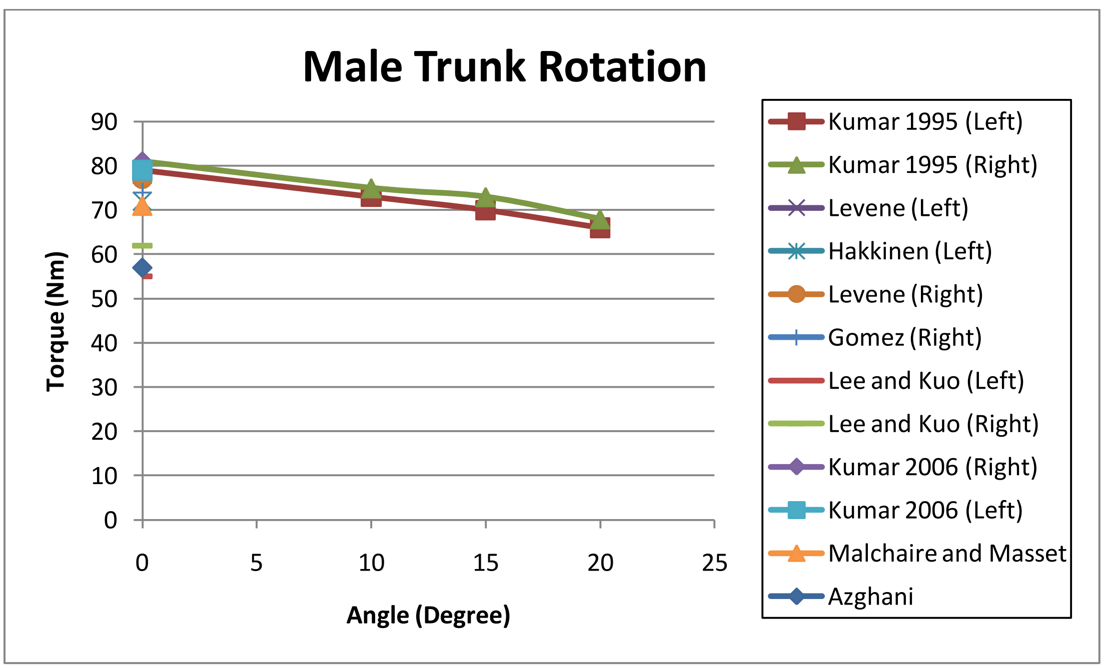

Figure 5.20. Male trunk rotation from 8 studies. Note that the side that was tested is indicated.

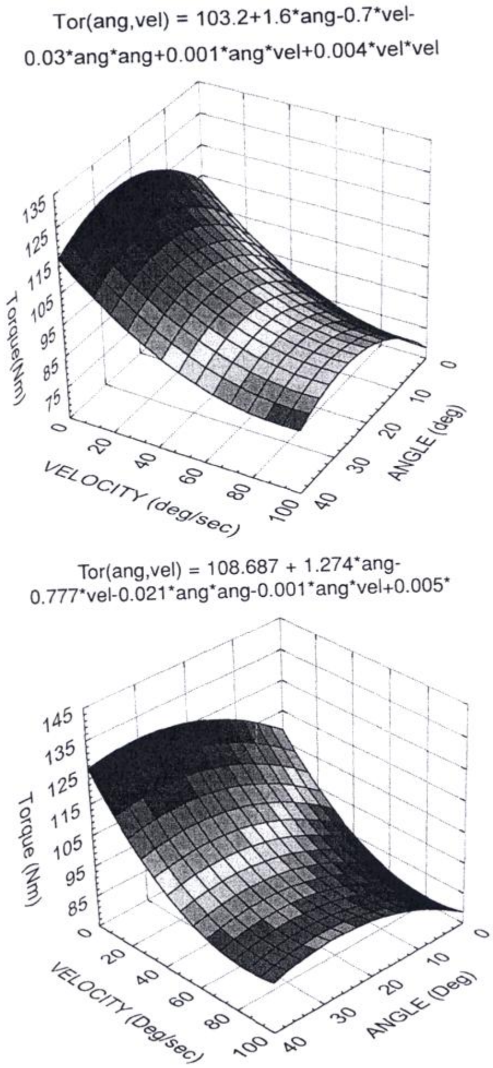

Figure 2.21. Three-dimensional trunk flexion for male and female.

Source: Khalaf, K, Parnianpour, M, Sparto, PJ "Model of functional trunk muscle performance: Interfacing ergonomics and spine rehabilitation in response to the ADA." Journal of Rehabilitation Research and Development **34**: 459-469

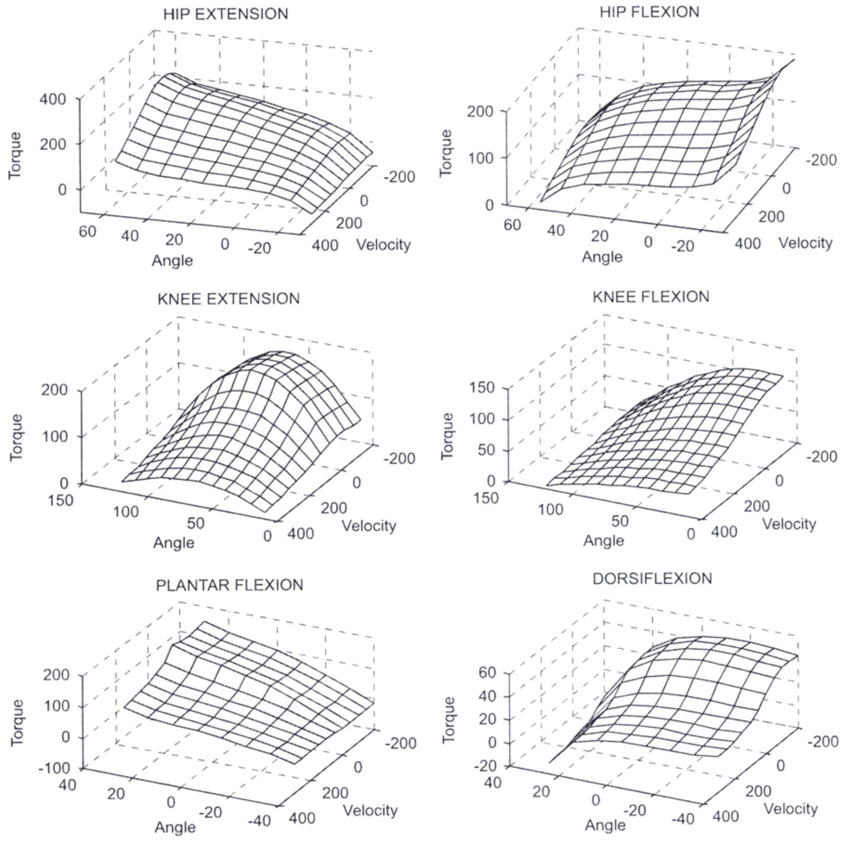

Figure 2.22. Modeled Three-dimensional strength surfaces for hip, knee, ankle joints. (Anderson et al., 2007)

Source: Anderson, DE, Madigan, ML, Nussbaum, MA (2007). "Maximum voluntary joint torque as a function of joint angle and angular velocity: Model development and application to the lower limb." Journal of Biomechanics **40**: 3105-3113.

CHAPTER 3

METHODS

Experimental Setup

Fifteen male subjects and twenty-one female subjects were recruited from the University of Iowa community to participate in the hip and trunk strength study. Male subjects had an average age of 24, weight of 81.64 kg, and height of 183.15 cm. Female subjects had an average age of 22, weight of 68.5 kg, and a height of 170.55 cm.

The study was approved by the University of Iowa Review Board number 200804750. Before starting each subject was asked to sign a written consent form to participate. Subjects were excluded if they had any history of neuromuscular disease, cardiac disease, diabetes, stroke, asthma, scoliosis, fainting, major injury or trauma the lower extremities, pelvis, hips, or trunk. Women who were pregnant were also excluded. Subjects were included if they were healthy and between the ages of 18 and 45.

The study required 2 visits for 2 hours each visit. One joint was tested per visit, and it was randomly selected which joint would be tested first. In visit 1, the subject's anthropometric data was collected. The participator's height (cm), weight (kg), neck (cm), waist (cm), and body fat (%) were all measured. The hips (cm) were also measured for women. To begin both visits, blood pressure was then taken and anyone with a blood pressure of (140/80) or greater was asked to reschedule. Finally, subjects were asked to warm up by riding on a stationary bike for 5 minutes at their self selected speed.

Three planes were measured for the hip testing, flexion/extension in the sagittal plane, abduction/adduction in the frontal plane, and internal/external rotation in the transverse plane. However, abduction/adduction and internal/external rotation are not considered in this study. It was randomly selected which order the planes would be tested. For all the positions, isometric testing was performed first followed by isokinetic testing. Isometric testing was performed at multiple angles and was randomize to which order the angles would be tested. At each angle, the subject would perform a maximum voluntary contraction in one direction for 5 seconds, rest for 30 seconds, and perform another maximum voluntary contraction in the opposite direction for 5 seconds. This totaling 6 maximum voluntary contractions, (3 in one direction, 3 in the opposite direction) Two minutes rest was given between each angle, and between isometric and isokinetic testing. Isokinetic testing had 4 velocities, and was also randomized to which order the velocities would be tested in. Two minutes rest was given between each velocity. All testing was completed on the System 3 Biodex (Biodex Medical Systems, Shirley, NY, USA) isokinetic dynamometer.

For hip flexion and extension testing, subjects stood in a custom made base that help stabilize upper body movement. The base was placed parallel to the Biodex dynamometer. The right lower leg was also stabilized to the base, and the left leg was placed into a knee brace and locked at 60° flexion. The left thigh was then attached to a custom made thigh attachment for the Biodex dynamometer. Subjects had the option of holding on to the Biodex, the back of the base, or leaving their arms at their side during testing. Figure 3.1. shows the experimental setup. The subjects' greater trocanher was aligned with the Biodex's dynamometer. When the greater trocanher was completely aligned with the dynamometer, this anatomical reference was considered zero. The range of motion was then set. Every subject had a range of motion of at least 70 degrees or greater. Isometric testing was completed at 15°, 30°, 45°, and 55° of flexion. Isokinetic testing was collected second at 60°/s, 90°/s, 120°/s, and 180°/s. Once both tests were finished, the subject was unstrapped from the base, and asked to take a 5 minute rest. The other two directions were tested with 5 minute rest between.

Three planes were measured for trunk testing, the flexion/extension in the sagittal plane, lateral flexion in the frontal plane, and rotation in the transverse plane. However, trunk lateral flexion was not considered in this study. It was randomly selected which plane would be tested first. Isometric testing was performed first followed by isokinetic testing. For isometric testing, subjects were asked to perform a maximum voluntary contraction for 5 seconds in one direction, rest for 30 seconds, and perform another maximum voluntary contraction in the opposite direction for 5 seconds. This was repeated 3 times with 6 maximum voluntary contractions total. A 2 minute rest was required between each angle. There was also a 2 minute rest between isometric and isokinetic testing. Isokinetic testing had 4 different velocities, with 2 minute rests between each velocity. Once isometric and isokinetic tests were finished, the subject was allowed to take a 5 minute rest.

The trunk flexion and extension motions were performed in a standing position and subjects were stabilized to the custom made base. Their legs were strapped to the lower part of the base, and the torso was secured to a custom made attachment for the Biodex. The subject's L5/S1 was aliened with the Biodex's dynamometer. The set up for this position is seen in Figure 3.2. Isometric testing was performed at 0°, 10°, 20°, 30°, and 40° angles for trunk flexion. After completing the isometric testing, the isokinetic tests were performed at 30°/sec, 60°/sec, 90°/sec, and 120°/sec. Subjects were asked to move as fast as they could, and apply as much force as possible through their defined range of motion. Each subject had a range of motion of at least 70°. Once the tests were complete, the subject was asked to take a 5 minute rest while the next position was arranged.

Finally, trunk rotational testing was performed in the standing position with the subject stabilized to the custom made base. Subjects were than strapped to a custom made attachment facing the Biodex. Figure 3.3. demonstrates the set up used. Isometric testing for trunk rotation had 4 angles, 0°, 10°, 20° and 30° to the left side. Isokinetic testing had 4 velocities at 30°/sec, 60°/sec, 90°/sec, and 120°/sec. Subjects were asked to move as fast as they could, and apply as much maximum force throughout their range of motion. Each subject had a range of motion of at least 90°. This concluded the testing for the trunk joint.

After each joint visit, subject's blood pressure was measured and recorded. At the end of the second visit, subjects were asked to fill out the international physical activity questionnaire.

Data Processing and Modeling

National Instruments Labview 8.0 was used to collect the raw analog torque values, velocities, and positions produced at 1000Hz. Custom made MatLab programs were used for data analyses. The data was first filtered with a fourth-order Butterworth filter for hip flexion/extension, trunk flexion/extension, and trunk rotation. Gravity was also corrected for by finding the passive joint torque at each isometric angle, and was subtracted from the subsequent angle-specific isometric torques. Once the signal processing was completed, the isometric and isokinetic peak torque was converted from foot-pound to Newton-meters by using calibrated torque conversion equations.

For trunk flexion and extension, 25 peak torque values were found: 5 isometric values and 5 angle-specific values each of the four isokinetic speeds. Trunk rotation found 15 peak torque values: 3 isometric values, 3 angle-specific values and 4 isokinetic velocities. For hip flexion and extension 20 peak torques were found: 4 isometric values and 4 angle-specific values at 4 isokinetic speeds. For subjects who were unable to reach isometric or isokinetic velocities, the data points were modeled using TableCurve3D (SYSTAT Software Inc, CA, USA). Modeled data points were based on the best fit equation and R^2 available in TableCurve3D. The mean, standard deviation, and coefficient of variation were calculated in Microsoft Excel separately for men and women. These mean data points were then plotted as a three-dimensional torque-angle-velocity surfaces using SigmaPlot version 9.0 (SYSTAT Software, Inc, CA, USA).

Statistical Analysis

T-tests and Pearson Correlations were performed using SPSS Statistics 19 (An IBM Company). Significance was set as an alpha=.05 for all statistics. Statistics were run for comparing men vs. women, trunk flexion vs. extension, hip flexion vs. extension, trunk flexion vs. hip flexion, trunk extension vs. hip extension, trunk flexion vs. hip extension, and trunk extension vs. hip flexion.

Figure3.1. Experimental setup for hip flexion and extension motion testing.

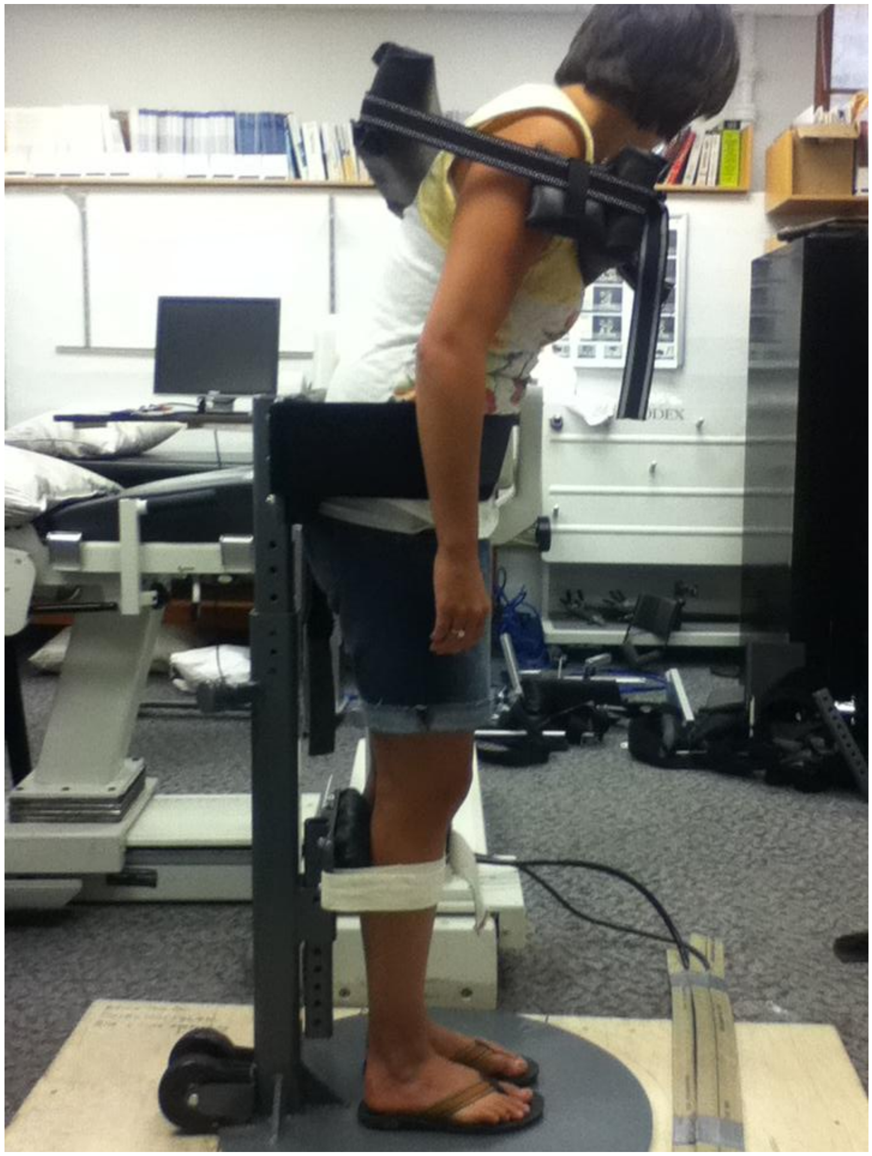

Figure 3.2. Experimental setup for trunk flexion and extension motion testing.

Figure 3 .3. Experimental setup for trunk rotational motion testing.

CHATPER 4

RESULTS

Experimental Results

Trunk Flexion/Extension

The trunk flexion and extension three-dimensional torque-angle-velocity strength surfaces are presented in figure 4.1. Men exhibited higher peak torques for flexion and extension than women. The maximum flexion peak torque for men was 182.1 Nm (40.3) and 111.8 Nm (32.2) for women at zero degrees. The maximum extension peak torque for men was 328.5 Nm (51.7) and 197.5 Nm (58.2) for women at 40 degrees trunk flexion.

Trunk flexion had the highest peak torques at zero and the torque decreased as the angle and the velocity increased. This torque-angle-velocity relationship created a smooth surface which can be observed in the Female Trunk Flexion graph in figure 4.1. (B). Unlike trunk flexion, the highest peak torque occurred at zero velocity and a 40 degree angle for trunk extension. It is observed that as joint angle and torque decrease the velocity increase. A representation of this can be seen in the Female Trunk Extension surface in figure 4.1. (D). Overall, trunk extension produced greater peak torques then trunk flexion regardless of sex.

The peak torques for trunk flexion and extension were significantly different for male and female, and all angles and velocities. The significant difference between male and female for trunk flexion was between .001 and .024, and for trunk extension between .000 and .024 from independent t-tests for equality of means. The males had a correlations coefficient of .858 and females had a coefficient of .687 for the 90 deg/sec velocity as seen in table 4.1-4.4. Like 90deg/sec, the remaining velocities have significant correlations between flexion and extension.

Trunk Rotation

The three-dimensional torque-angle -velocity strength surfaces for trunk left and right rotation are presented in figure 4.2. Once again, men exhibited higher peak torques for right and left rotation than women. Males had a maximum peak torque of 71.3 Nm (24.4) right rotation at a 30 degree angle and a zero velocity, and a maximum peak torque of 71.6Nm (20.7) left rotation at a 20 degree angle and a zero velocity for left rotation. Similar to males, females had a maximum peak torque of 42.6 Nm (16.9) right rotation at a 30 degree angle and zero velocity, and a maximum peak torque of 42.5 Nm (14.0) for left rotation at a 20 degree angle and zero velocity.

Trunk left rotations had the highest peak torques at a 20 degree angle and zero velocity. It is observed that as angle increases or decreases from 20 degrees the torque decreases, and the velocity increases. Female Left Rotation in figure 4.2. (D) shows a primary example of this relationship. Trunk right rotation has the highest peak torque at a 30 degree angle and a zero velocity. For right rotation, the peak torque decreases as the angle decreases, and the velocity increases. This relationship is observed in the Female Right Rotation strength surface in figure 4.2. (B).

In sex difference comparison, men were significantly stronger than women. For right rotation, they had significant values range from .000 to .001. For left rotation they had significant values of .000 for velocities.

Hip Flexion and Extension

The hip flexion and extension three-dimensional torque-angle-velocity strength surfaces are presented in figure 4.3. Men exhibited a higher peak torque for both hip flexion and extension than women did. The maximum peak torque for male flexion was 180.75 Nm (75.41) compared to the female maximum peak torque at 130.54 Nm (51.89). Males were also stronger in hip extension which was 183.23 Nm (57.24) than females 106.07 Nm (38.72).

Flexion and extension followed a trend that the highest peak torque occurred when the angle and the velocity were closest to zero. There were low peak torques at the angles zero and 55, creating a parabola shape across the angles. This is clearly observed in Female Hip Extension and Male Hip Flexion in figure 4.2. (A) & (D). It can also be seen that female flexion has greater peak torques then female extension were as male flexion and extension have similar peak torques.

The torque significantly varied between flexion and extension. Tables 4.1.-4.5. present the correlation coefficient for both men and women. Male flexion and extension had correlation coefficient of .886 at the 90 deg/sec velocity, and females had a coefficient of .703. There was a significant correlation coefficient for the remaining speeds for male and female, expect for females at the 60 deg/sec velocity. Men were also significantly stronger than in flexion and extension. For extension the significant difference fall between .000 and .018 for all velocities, and for flexion they fall between .000 and .005.

Hip and Trunk Comparison

In comparing the hip and trunk motions, a number of significant correlations were found. Males exhibited no significant correlations between trunk and hip motions. Figures 4.4.-4.7. present the isometric relationship between hip and trunk flexion and hip and trunk extension. However, females showed several different correlations between trunk and hip motions. In the isometric velocity, there were significant coefficients between trunk extension and hip extension, trunk extension and hip flexion, and trunk flexion and hip extension. Figure 4.4.-4.5. presents the significant correlations for trunk and hip extension, and figure 4.6.-4.7. shows the correlation between trunk and hip flexion. There was a female significant correlation between hip extension and trunk flexion for all velocities which can be seen in the tables 4.1-4.4.

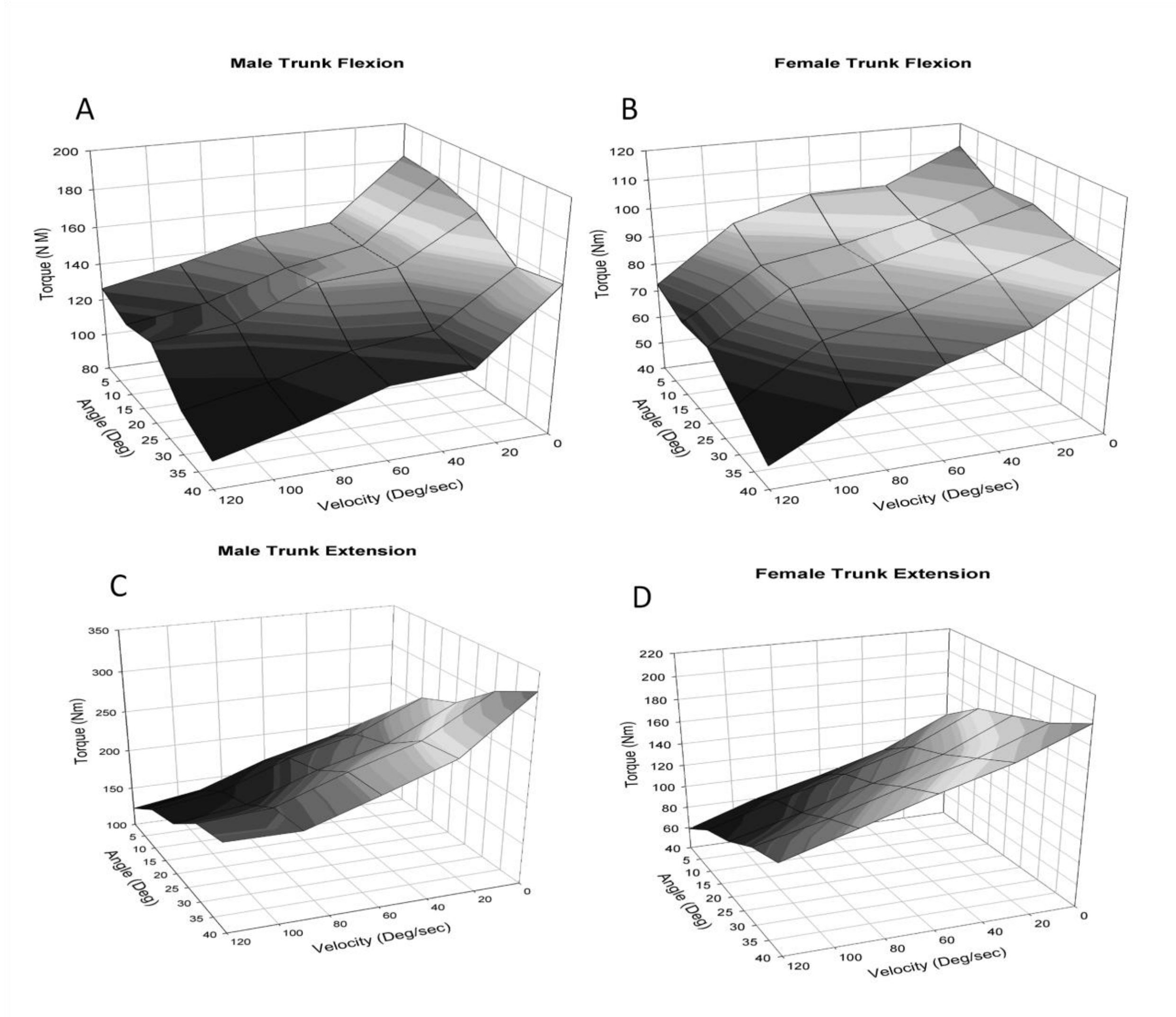

Figure 4.1. Mean male and female three-dimensional peak trunk strength surfaces for flexion/extension.
(A) Mean male trunk flexion.
(B) Mean female trunk flexion.
(C) Mean male trunk extension.
(D) Mean female trunk extension.

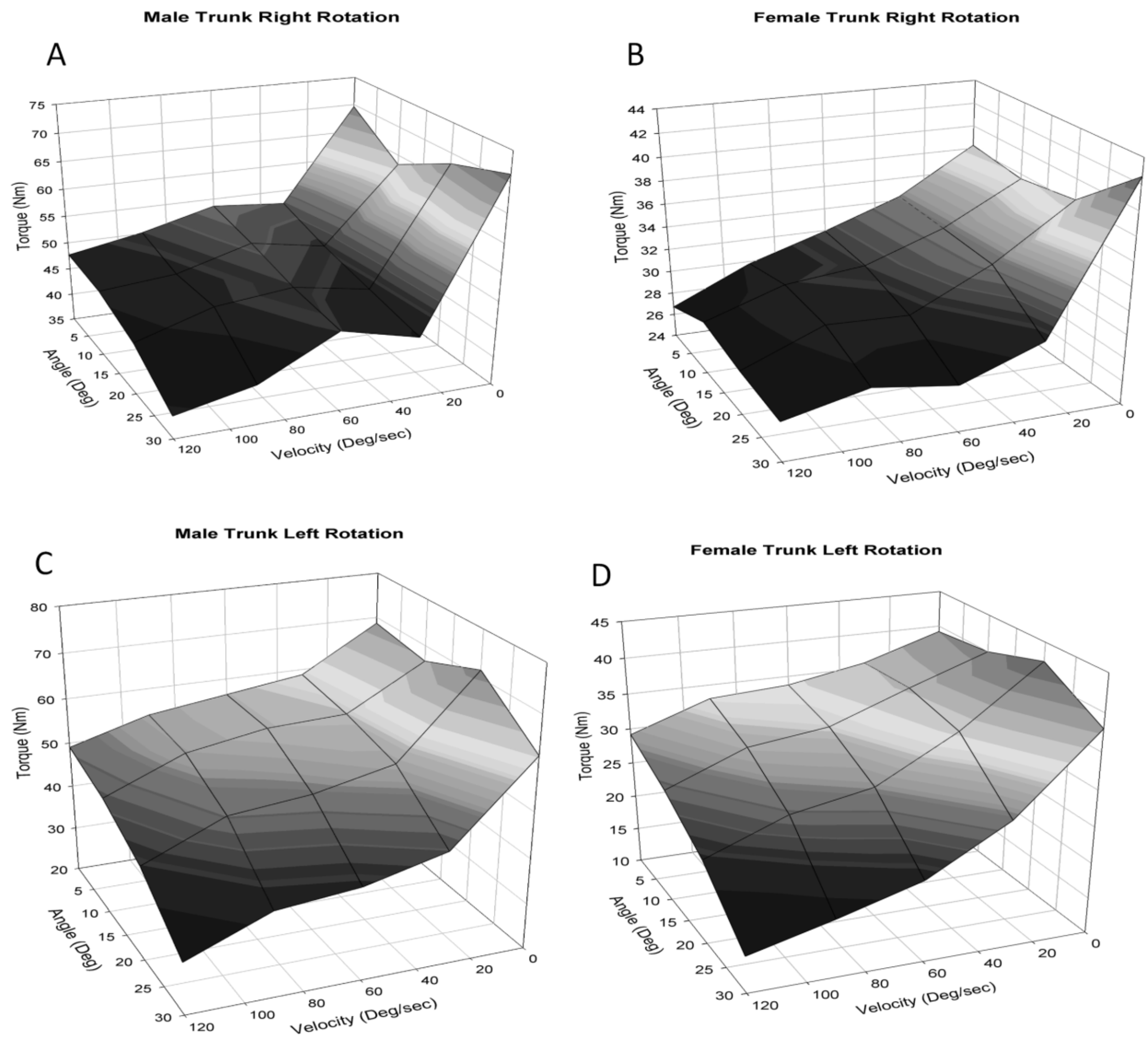

Figure 4.2. Mean male and female three-dimensional peak trunk strength surfaces for right and left rotation.
(A) Mean male trunk right rotation.
(B) Mean female trunk right rotation.
(C) Mean male trunk left rotation.
(D) Mean female trunk right rotation.

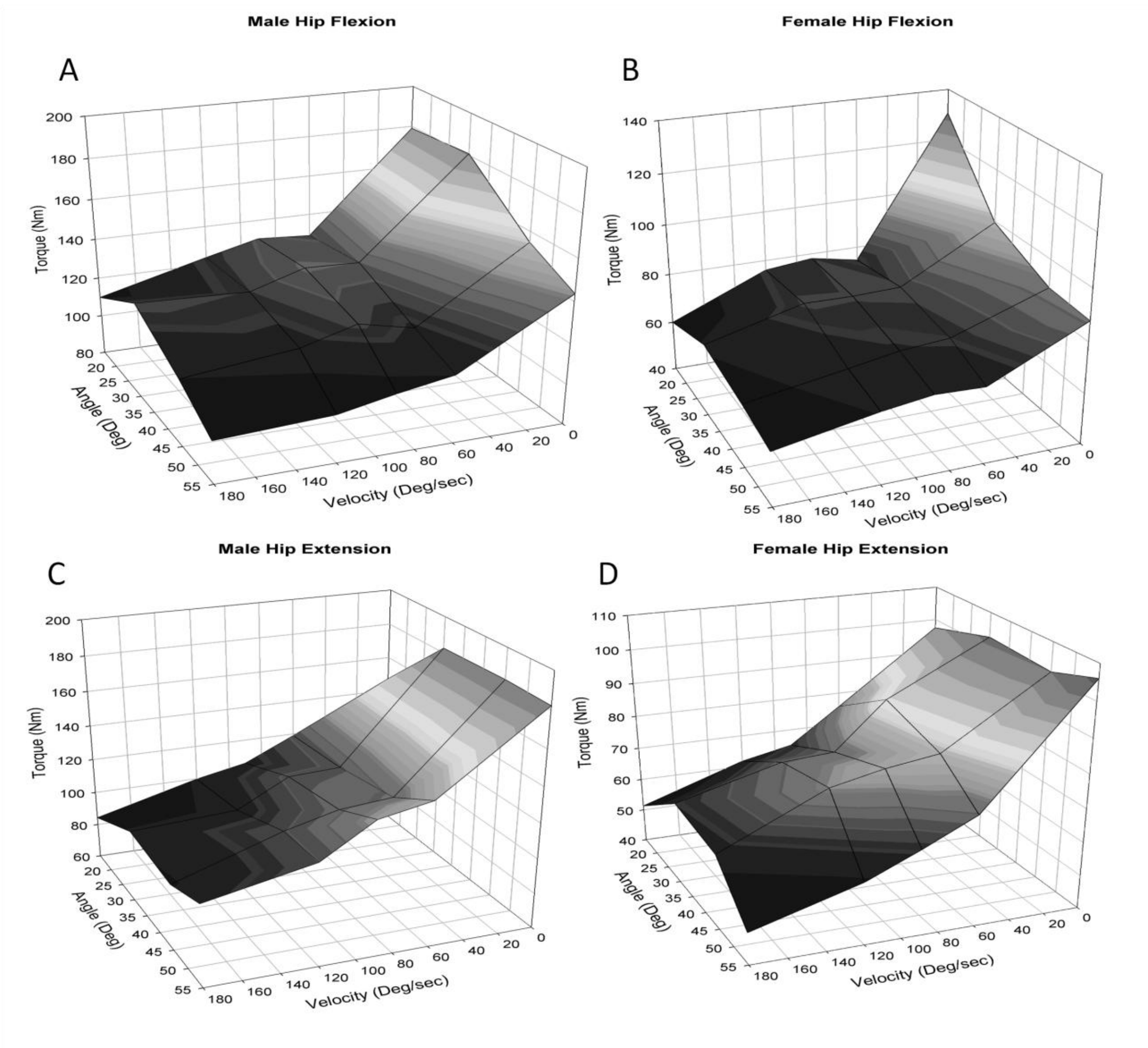

Figure 4.3. Mean male and female three-dimensional peak hip strength surfaces for flexion and extension.
(A) Mean male hip flexion.
(B) Mean female hip flexion.
(C) Mean male hip extension.
(D) Mean female hip extension.

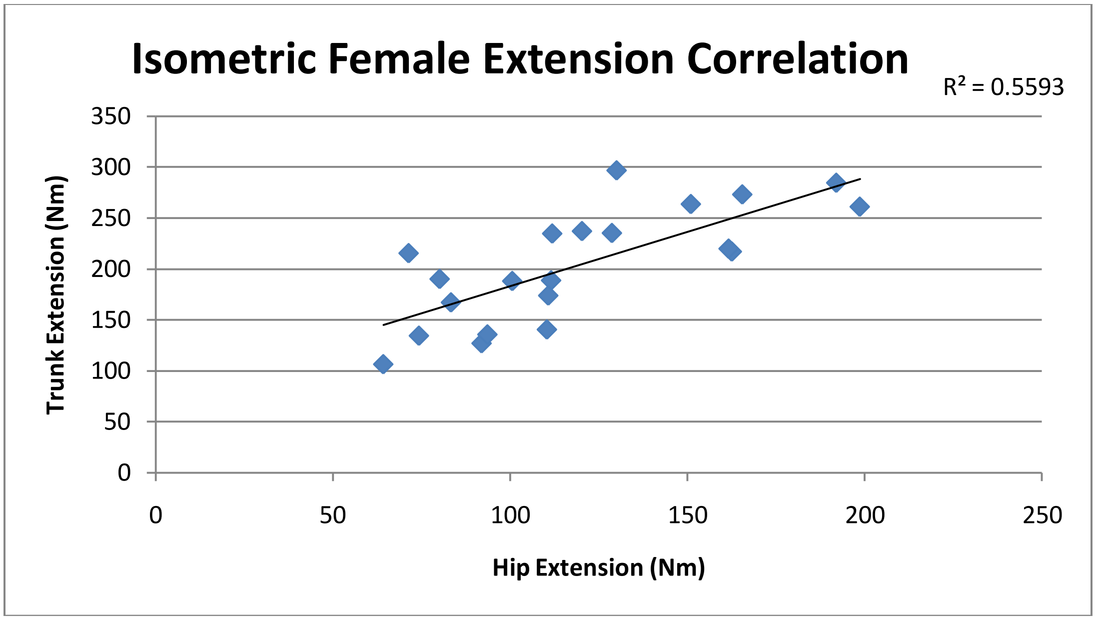

Figure 4.4. Isometric female correlation of maximum peak torques from hip extension and trunk extension.

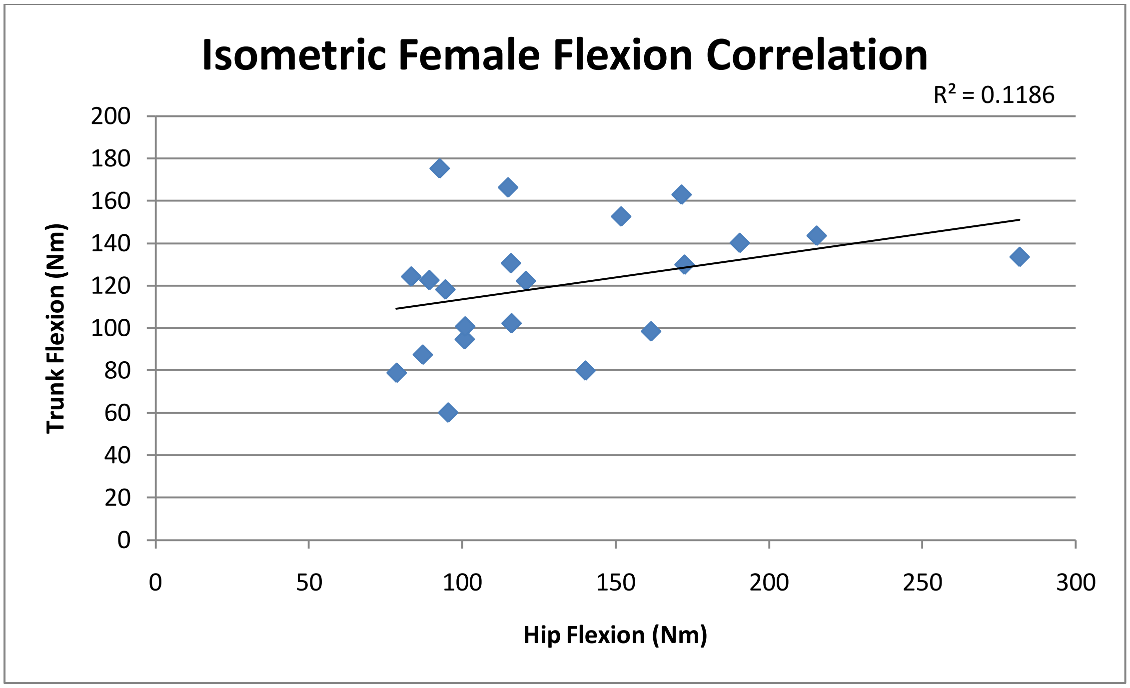

Figure 4.5. Isometric female correlation of maximum peak torques from hip flexion and trunk flexion.

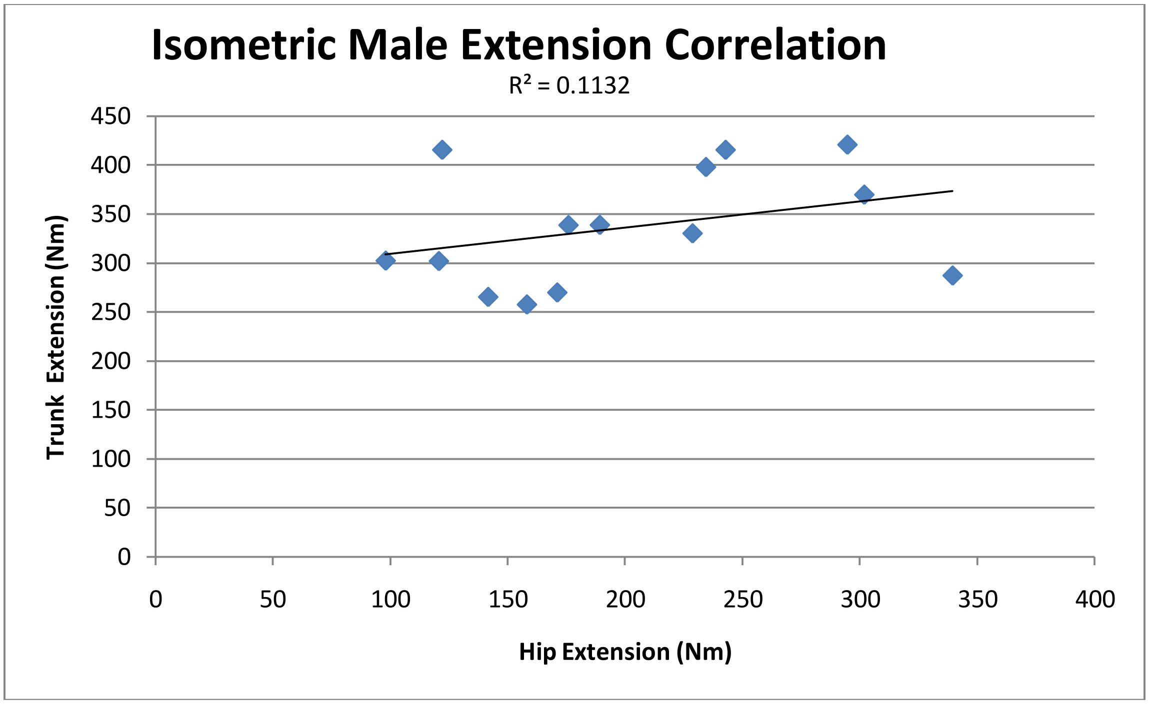

Figure 4.6. Isometric male correlation of maximum peak torques from hip extension and trunk extension.

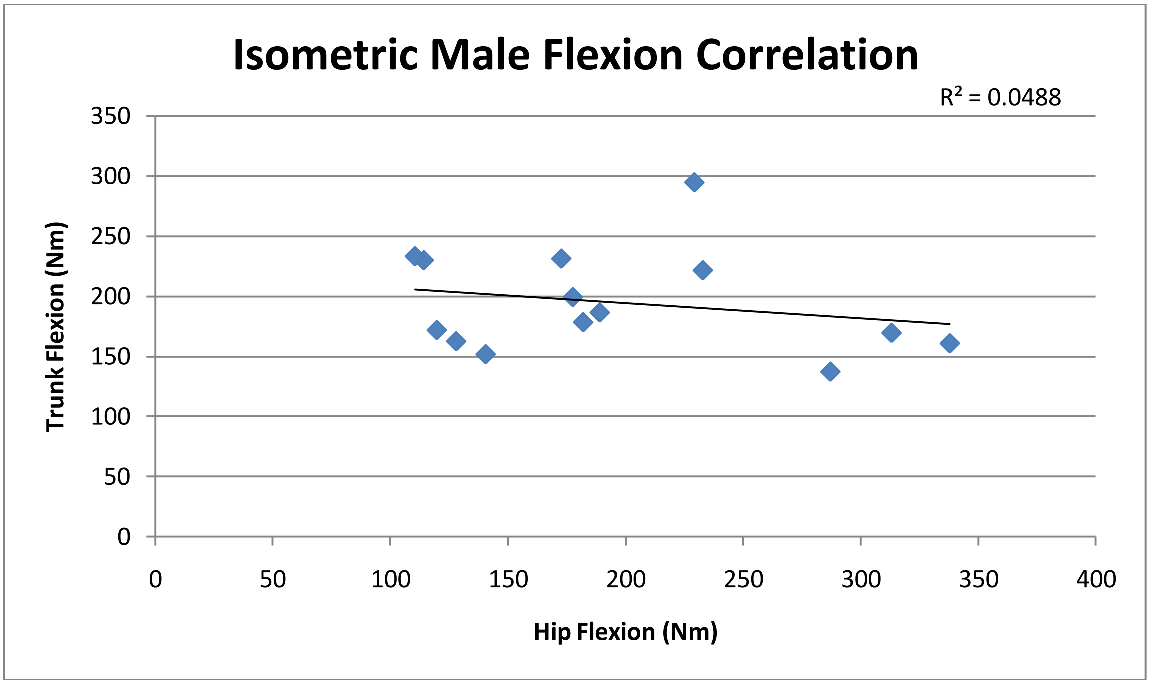

Figure 4.7. Isometric male correlation of maximum peak torques from hip flexion and trunk flexion.

Table 4.1. Correlation Coefficients for Isometric trunk flexion and extension and hip flexion and extension for men and women.

Isometric Correlations Females Top Diagonal Males Bottom Diagonal				
	Trunk Extension	Trunk Flexion	Hip Extension	Hip Flexion
Trunk Extension Correlation Coefficient	1	0.815**	0.748**	0.631**
Trunk Flexion Correlation Coefficient	0.829**	1	0.693	0.344
Hip Extension Correlation Coefficient	0.121	-0.073	1	0.757**
Hip Flexion Correlation Coefficient	0.248	-0.068	0.884**	1

** Correlation is significant at .01

*Correlation is significant at.05

Table 4.2. Correlation Coefficients for 60 deg/sec trunk flexion and extension and hip flexion and extension for men and women.

60 Deg/sec Correlations Females Top Diagonal Males Bottom Diagonal				
	Trunk Extension	Trunk Flexion	Hip Extension	Hip Flexion
Trunk Extension Correlation Coefficient	1	0.62**	0.274	0.542
Trunk Flexion Correlation Coefficient	0.846**	1	0.521*	0.444**
Hip Extension Correlation Coefficient	0.277	0.052	1	0.387
Hip Flexion Correlation Coefficient	0.371	-0.021	0.841**	1

** Correlation is significant at .01

*Correlation is significant at.05

Table 4.3. Correlation Coefficients for 90 deg/sec trunk flexion and extension and hip flexion and extension for men and women.

90 Deg/sec Correlations Females Top Diagonal Males Bottom Diagonal				
	Trunk Extension	Trunk Flexion	Hip Extension	Hip Flexion
Trunk Extension Correlation Coefficient	1	0.687**	0.233	0.414
Trunk Flexion Correlation Coefficient	0.858**	1	0.559**	0.365
Hip Extension Correlation Coefficient	0.223	0.012	1	.703**
Hip Flexion Correlation Coefficient	0.309	-0.032	0.886**	1

** Correlation is significant at .01

*Correlation is significant at.05

Table 4.4 Correlation Coefficients for 120 deg/sec trunk flexion and extension and hip flexion and extension for men and women.

120 Deg/sec Correlations Females Top Diagonal Males Bottom Diagonal				
	Trunk Extension	Trunk Flexion	Hip Extension	Hip Flexion
Trunk Extension Correlation Coefficient	1	0.698**	0.337	0.341
Trunk Flexion Correlation Coefficient	0.876**	1	0.654**	0.415
Hip Extension Correlation Coefficient	0.176	0.026	1	0.653**
Hip Flexion Correlation Coefficient	0.222	-0.019	0.917**	1

** Correlation is significant at .01

*Correlation is significant at.05

CHATER 5

DISCUSSION

3D Hip and Trunk Strength Surfaces Findings

The three-dimensional normative strength surfaces were generated for hip flexion, hip extension, trunk flexion, trunk extension, trunk right rotation, and trunk left rotation. It was also determined that correlations existed between the hip motion directions, and trunk motion directions for males and females. However, there were correlations for women between the hip and trunk joints. Men produced higher maximum peak torques than women for these joints.

Flexion/Extension

The three-dimensional strength surfaces for trunk and hip flexion and extension generated relationships similar to those seen in a two-dimensional torque-angle relationships and torque-velocity relationships. Trunk flexion surfaces had a peak point at zero velocity and a zero degree angle, and it was seen that as both the angle and velocity increased the torque decreased. Trunk extension had a maximum peak torque at zero velocity and a 40 degree angle, and saw that as the torque decreased, the angle decreased, but the velocity increased. Like trunk, hip presented similar relationships. Hip flexion had a maximum peak torque at zero velocity and a zero degree angle, while hip extension had a maximum peak torque at zero velocity and a 55 degree angle. In case of flexion, both the trunk and hip had peak torques at zero velocities and zero degree angles as expected. This occurs because the muscle is at the longest length at zero, and can produce the highest amount of torque. The same principle applies for trunk and hip extension, the muscle length is greatest at the highest angle and can generate the largest torque.

In the correlation comparisons for flexion and extension, it was observed that males and females had correlations between motions for the same joint. This indicates that strong hip flexors are associated with strong hip extensors, and strong trunk flexors are coupled with strong trunk extensors.

The uniqueness of this study is the comparison of hip flexion and extension strength to trunk flexion and extension strength. As it was presented in the results, females had a strong correlation between hip extension and trunk extension at the isometric and 60 deg/sec velocity. This indicates that for extension movements the hip extensor muscles are linked with the trunk extensor muscles and vice verse. Similar to the hip extension assisting trunk extension, there was a significant correlation between hip extension and trunk flexion at isometric and 60 deg/sec, 90 deg/sec, and 120 deg/sec velocities. This indicates to a relationship between the hip extensors and trunk flexors, however, this relationship needs to be further explored. Unlike the females, the males had no significant correlations between trunk and hip motions. However, the number of subjects for males were less than females, if the more males were tested these correlations could change and correlations maybe seen. Since there is a large inconsistency between men and women, further comparisons and testing of the hip and trunk flexion/extension motion is needed.

Rotation

The three-dimensional strength surfaces for left and right trunk rotation were the most controversial. For right rotation the peak torque occurred at a 30 degree angle and zero velocity for both men and women. The torque-angle-velocity surface for right rotation followed the same trend as trunk extension that as torque and angle decreased while the velocity increased. This could indicate a strength relationship between trunk extension and rotation. Trunk left rotation had similar relationship to trunk right rotation, however, the maximum peak torque occurred at the 20 degree angle and zero velocity for both men and women. An explanation for the peak being at 20 degrees for left rotation could be the test set up. Since the isometric angles were all tested to the left, it can be assumed the muscle length was longest when rotated at 20 degrees. An opposite relationship might appear if the isometric angles were tested to the right. Meaning that maximum peak torques for right rotation may occur at a 20 degree angle, and left rotation maximum peak torques could happen at a 30 degree angle. In order to prove this further testing must be performed.

Literature Comparison

The data presented in this study can be rearranged into torque-angle and torque-velocity relationships. The current study follows the same pattern as the previous published studies for the torque-angle and torque-velocity relationships.

Trunk Flexion/Extension

The trunk torque-angle relationship from the current study had a similar relationship for the flexion and extension directions as the studies presented in literature. Keller 2002 was one of the only studies to have a torque-angle relationship. It had peak torques about twice the value as the data compare to this study. Although there is large range of maximum peak torque values, Keller's peak torque values are twice as high as this study which may indicate a scaling difference during analysis. Figures 5.1.-5.4. compare the current study to the Keller's study and other literature studies.

The current study was expected to have a similar torque-velocity relationship compare to other studies because of the extensive research already available for isokinetic testing. Figures 5.5-5.8. show a comparison of the current study's torque-velocity relationship to previous studies. It is observed that some of studies produce higher peak torques then the current study. This can be attributed to the population, experimental equipment differences, or gravity correction errors. Overall, the torque-velocity relationship of this study is within an acceptable range with previous published studies.

The only known published trunk torque-angle-velocity relationship was completed by Khalaf (1997). Comparing the current study to Khalaf, the peak torques for the torque-angle-velocity relationship were similar. Khalaf had a 92.1 Nm (31.8) for a 20 degree angle, and 60 velocity female flexion were as this study had 89.2 Nm (31.2) for the same angle and velocity. This consistency continues over many angles and velocities. In general, the three-dimensional surfaces are comparable to one another.

Hip Flexion/Extension

The torque-angle relationship for hip flexion and extension follows a similar pattern compare to the previous studies. Figures 5.9.-5.12. present the comparisons of isometric hip flexion and extension for males and females. From the figures, Nemeth 1983 appears to have a higher peak torque than the current study for hip extension. This can be attributed to the impact the different testing positions have on maximum peak torques. Although the standing position mimics the natural position of the hip, it may not be the optimal position to use for maximum peak torques.

Like the testing position influencing the peak torques seen in the torque-angle relationship, the range of motion affects the maximum peak torques in the torque-velocity relationship. The hip flexion and extension torque-velocity relationships comparison can be seen in figures 5.13-5.16. Comparing the current study to Calahan's study for hip flexion and extension, it is observed that the current study's extension was lower than Calahan's, but the current studies flexion was greater than Calahan's. One reason for the differences could be that the current study had a much larger range of motion available then Calahan's in the standing position. This influencing the peak torques values seen in the torque-velocity relationships.

Trunk Rotation

The torque-angle relationship for trunk rotation shows a consistency between the previous studies and the current study. The overlapping relationships are seen in figures 5.17.-5.18. Kumar 1995 had a maximum peak torque of 79 Nm (26) at a zero degree angle compare to the current study that had a maximum peak torque 71.6 Nm (20) at a 20 degree angle. The maximum peak torques occurring at different angles could be a result of the position the motion was tested in, since Kumar tested in a seated position and the current study tested in the standing position.

Like the torque-angle relationship, the torque-velocity relationship had similar results to the previous studies. The comparison can be seen in figures 5.19-5.20. As presented the current study's maximum peak torques were lower than the previous study. This again could be attributed to a scaling error since the peak torque for the current study is half of the previous studies like in the trunk isometric flexion and extension studies.

Benefits for Digital Human Modeling

The implementation of this normative three-dimensional strength surfaces into the University of Iowa's Santos, gives this digital human model the capabilities of predicting hip and trunk static positions and dynamic motions. This enhancement to digital human modeling will allow ergonomists to predict and receive feedback on certain functional tasks. For instance, ergonomists will be able to model a certain amount of strength required by the trunk to lift an object and move it. This data set would provide a Santos user with realistic human trunk and hip strength limits, and provides an output of strength values used. In addition, the user will be able to set what percent strength they want Santos to have. They can choose from 25%, 50%, 75%, and 95% strength. With this tool, ergonomists and clinicians can make proper adjustments to people's environments that could ultimately reduce back pain in the American population and reduce healthcare costs.

Limitations

A number of limitations are associated with the three-dimensional strength surfaces in this study. In normal human motion, the trunk and hips are capable of many combinations of motion in multiple anatomical planes. However during clinical testing of these joints, the motions are limited to one anatomical plane, which in turn limits the peak torque available to that plane. In addition, the position which the test was performed can change the maximum peak torque. For example, the current study had the hip tested in the standing position, but different peak torques may have been produced if the test was conducted in a sitting, prone, or supine position.

Besides the testing type limiting digital human modeling, two-joint interaction limits the strength a digital human model has. The hip and trunk strength are influenced by a number of different joints. For instance, the position and available strength the knee has impacts the strength at the hip. In future implantation for digital human models, two-joint interactions need to be included.

Conclusions

The raw peak torque data from isometric and isokinetic testing in this study has provided enough data to create three-dimensional strength surfaces for The University of Iowa's Santos. Surfaces were made for males and females for the following motions: hip flexion, hip extension, trunk flexion, trunk extension, trunk left rotation, and trunk rotation. In comparison of the same joint plane motions, it was found that correlations between motions were found at all velocities for both men and women. However, the comparison the joints, correlations were only found in women at different velocities. These correlations prove that hip and trunk strength can be dependent on each other, and one joint influences the other.

Further investigation between the hip and trunk is needed to expand the understanding how these joints impact one another. A detailed comparison of the trunk and hip planes could continue to prove the correlations between the two joints. In addition to more correlations, further testing for trunk rotation is also needed. More isometric testing in trunk rotation can lead to a better understand of dangerous angles, and prove where maximum peak torques occur. Finally, two-interactions the hip and trunk with other joints, especially the hip and the knee must be researched for further enhancements in digital human modeling.

The three-dimensional strength surfaces for the hip and trunk joints will enhance digital human models, like Santos. All the surfaces had similar relationships to those found in literature. In addition, males had higher peak torques in all joints and directions. Correlations were found between trunk flexion and extension, hip flexion and extension, hip and trunk extension, and trunk and hip flexion. The implementation of the hip and trunk strength into digital human models will enhance their abilities to predict and output strength parameters for functional tasks. The proper use of digital human models can lead to the reduction of back pain experienced by the American people which has the potential to drastically reduce healthcare costs at large.

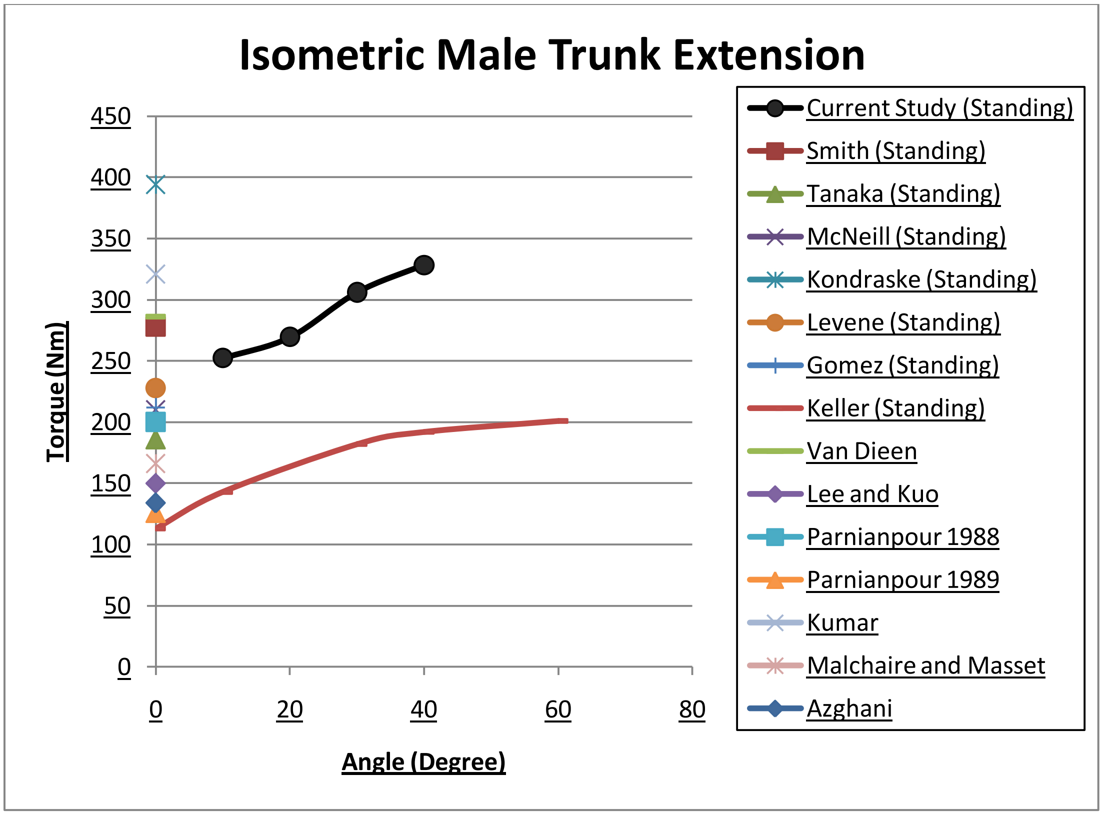

Figure 5.1. Male trunk extension from 14 studies with the current study in bold.

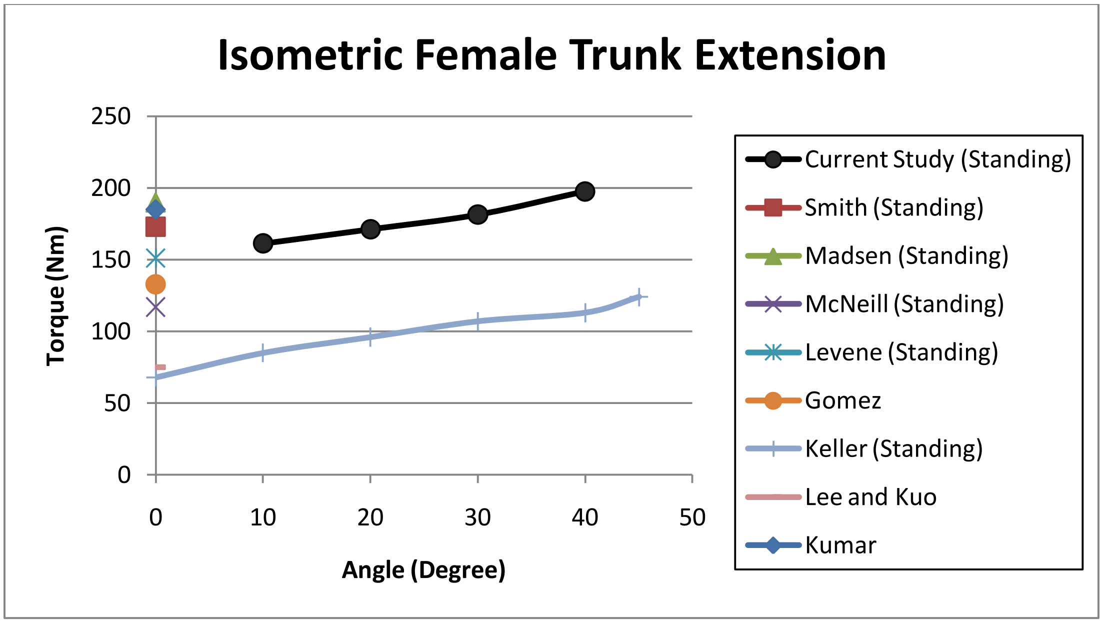

Figure 5.2. Female trunk extension from 8 studies with the current study in bold.

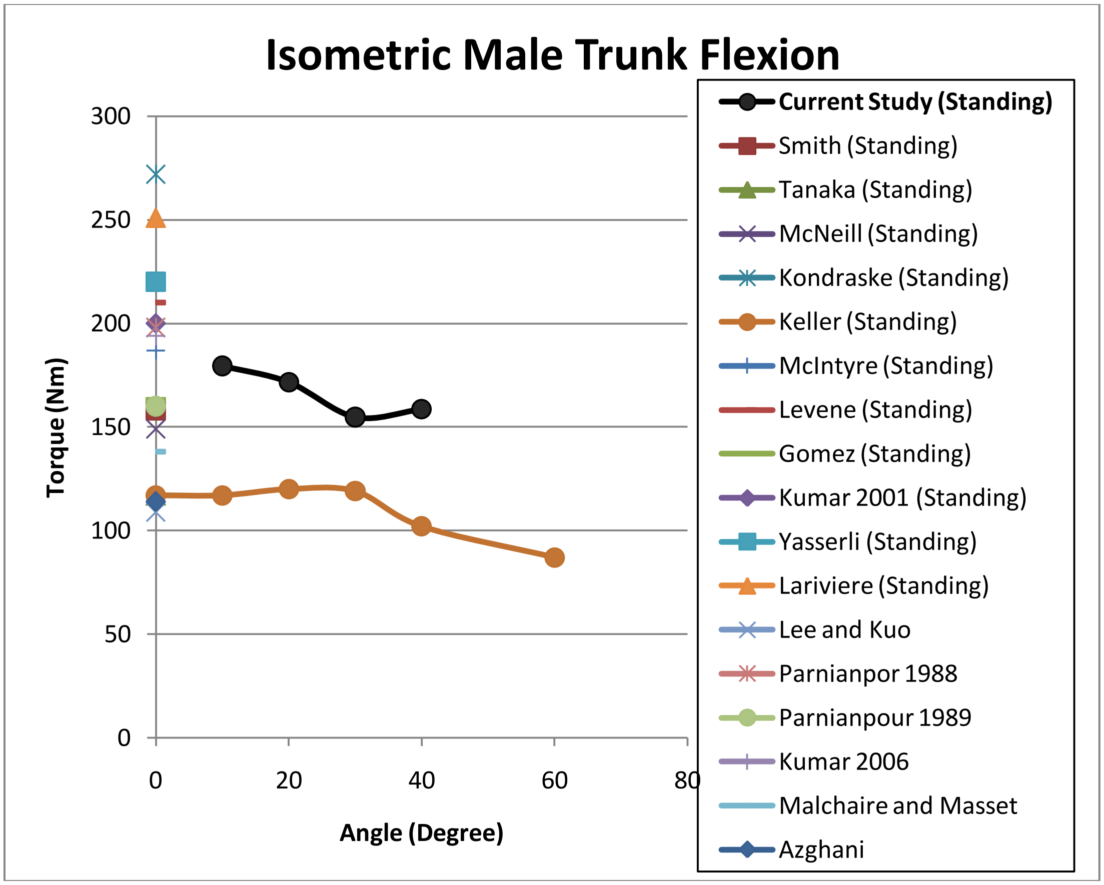

Figure 5.3. Male trunk flexion from 17 studies with the current study in bold.

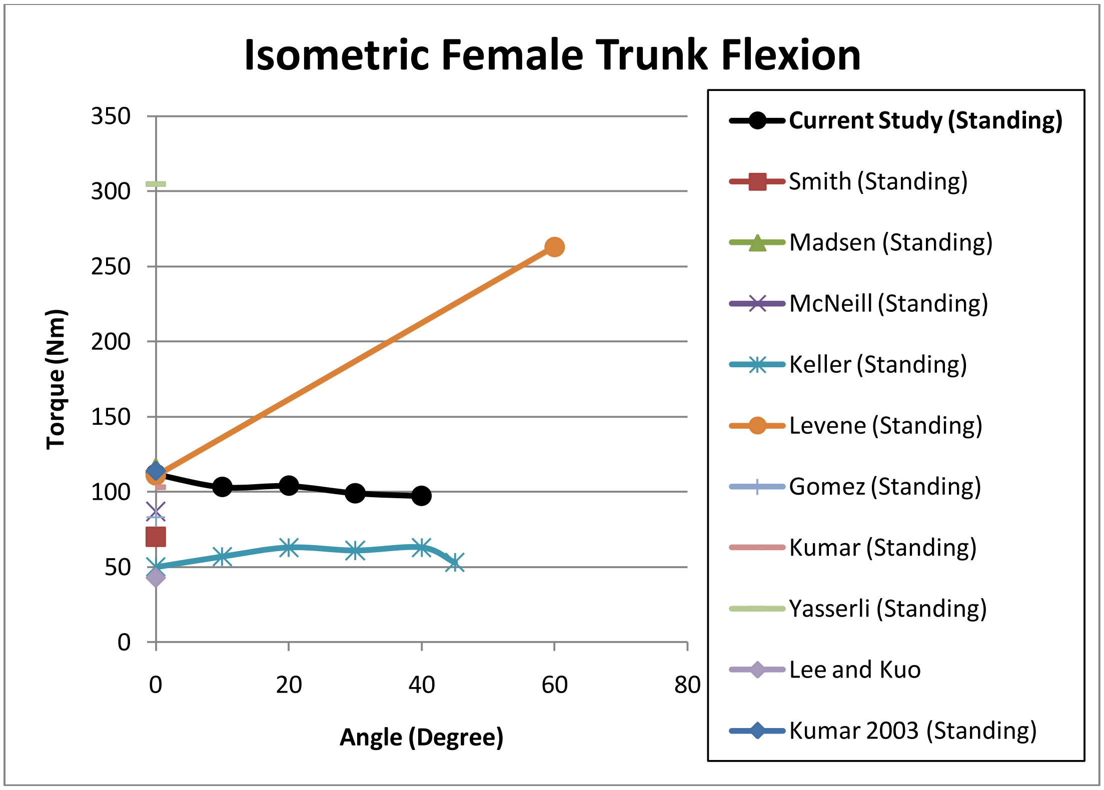

Figure 5.4. Female trunk flexion from 10 studies with the current study in bold.

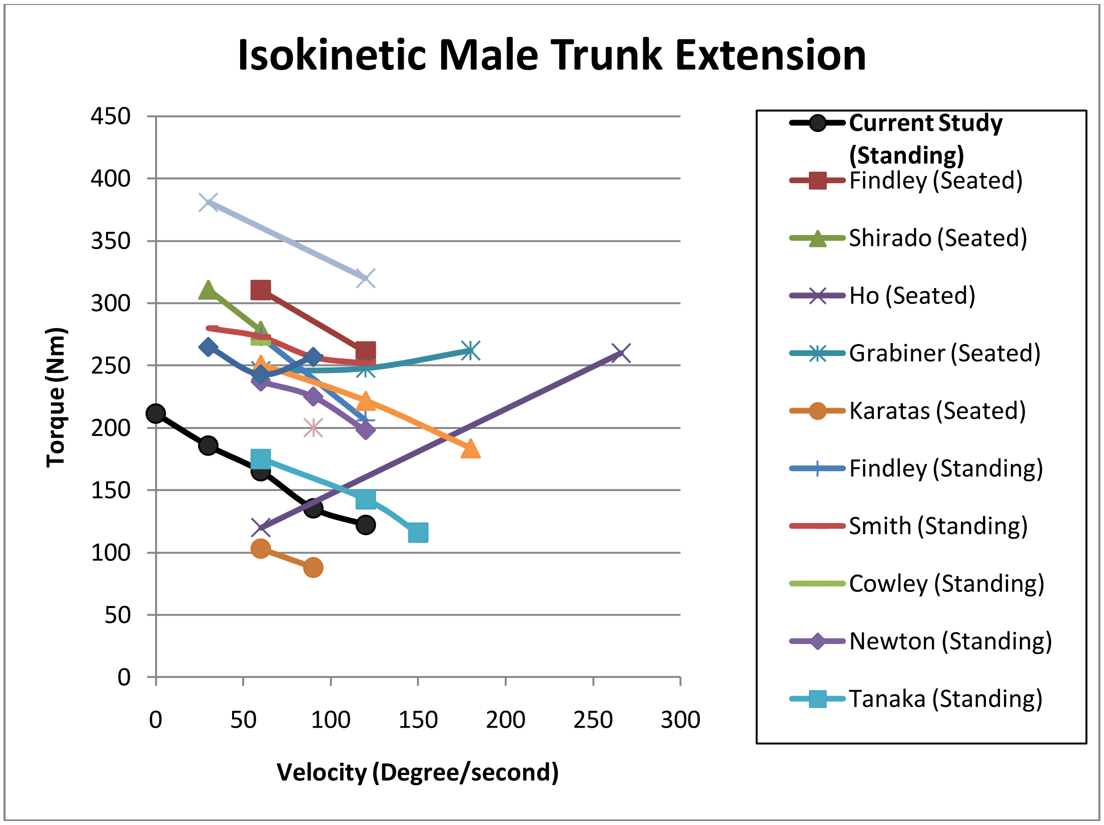

Figure 5.5. Male trunk extension from 14 studies with the current study in bold.

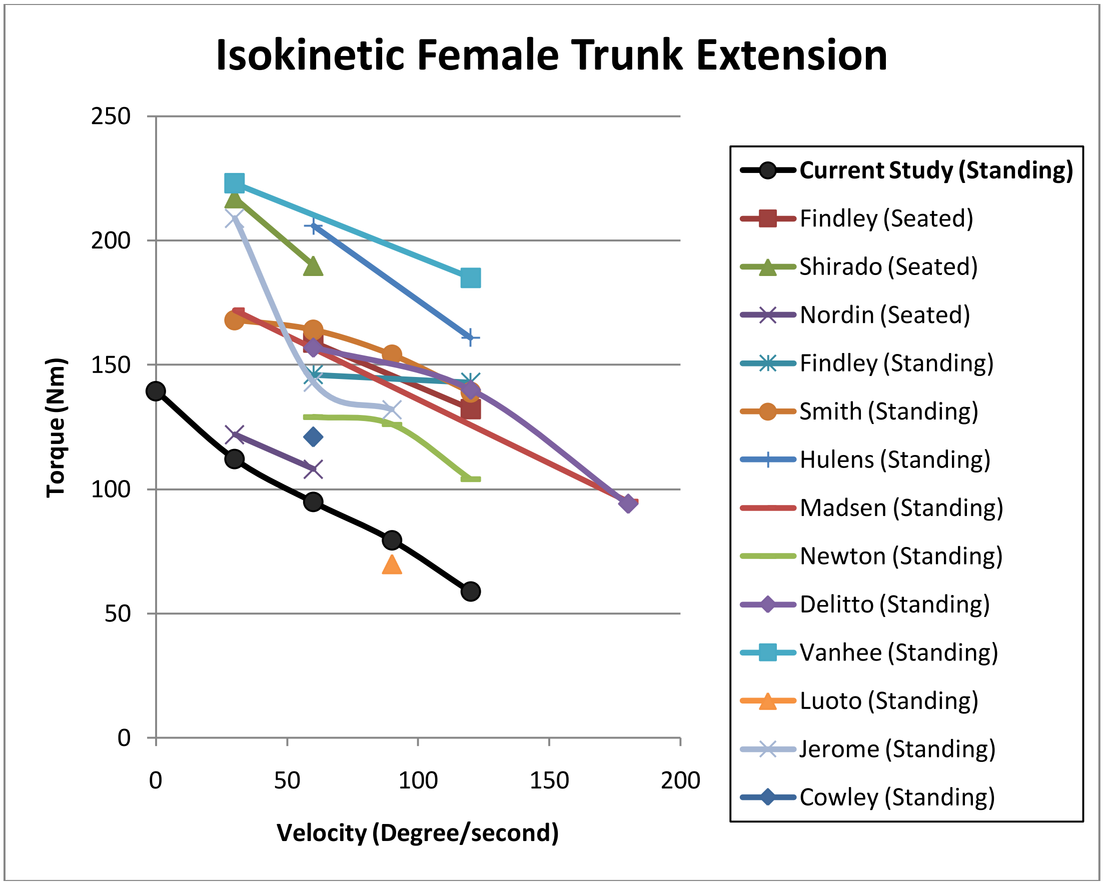

Figure 5.6. Female trunk extension from 13 studies with the current study in bold.

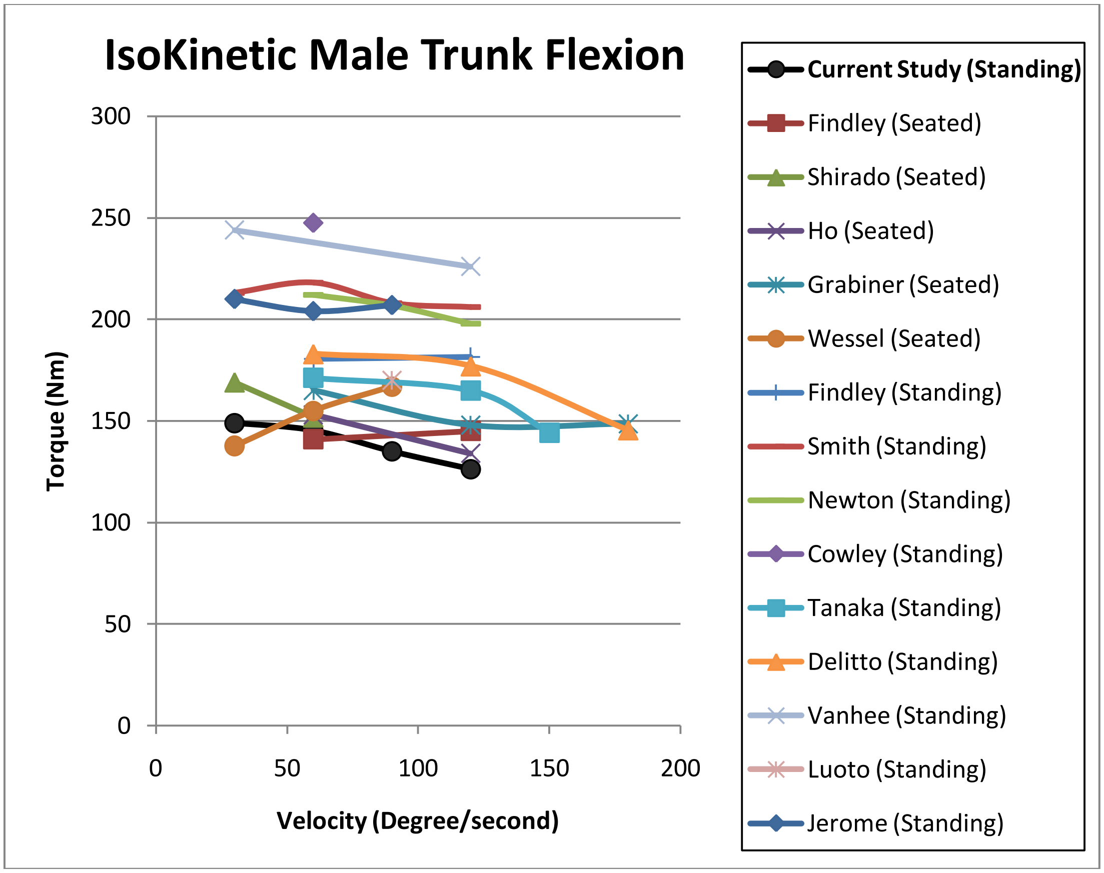

Figure 5.7. Male trunk flexion from 14 studies with the current study in bold.

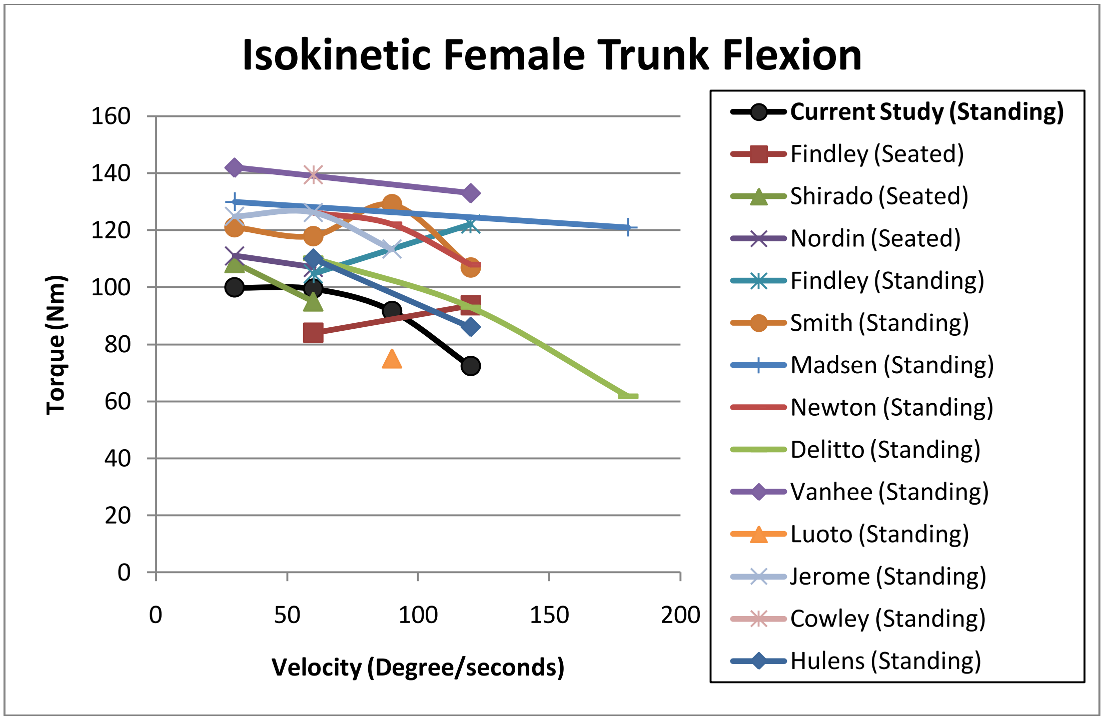

Figure 5.8. Female trunk flexion from 13 studies with the current study in bold.

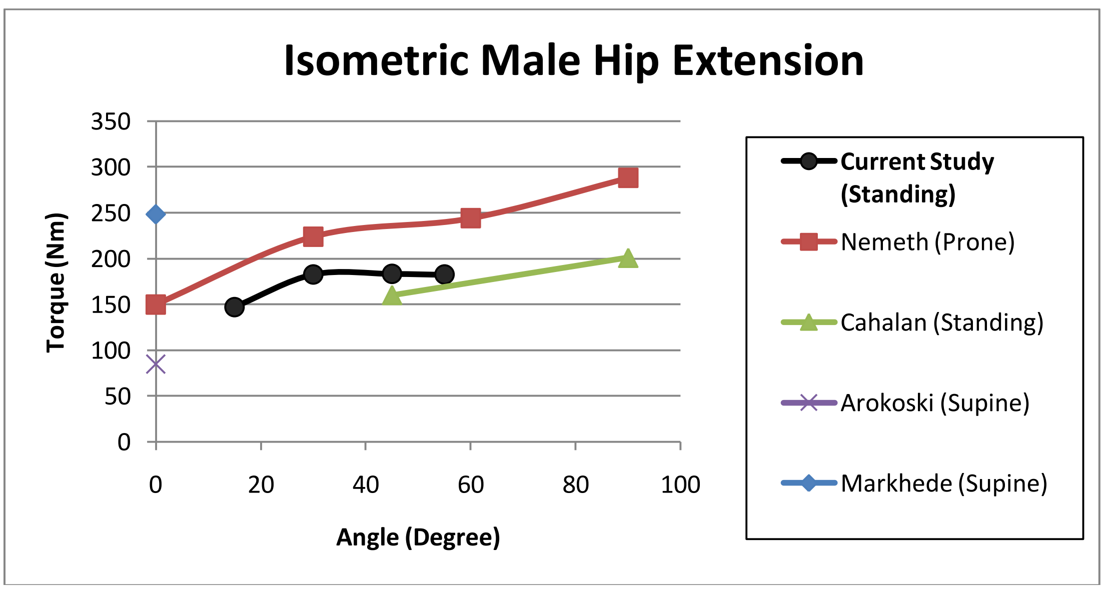

Figure 5.9. Male hip extension from 4 studies with the current study in bold.

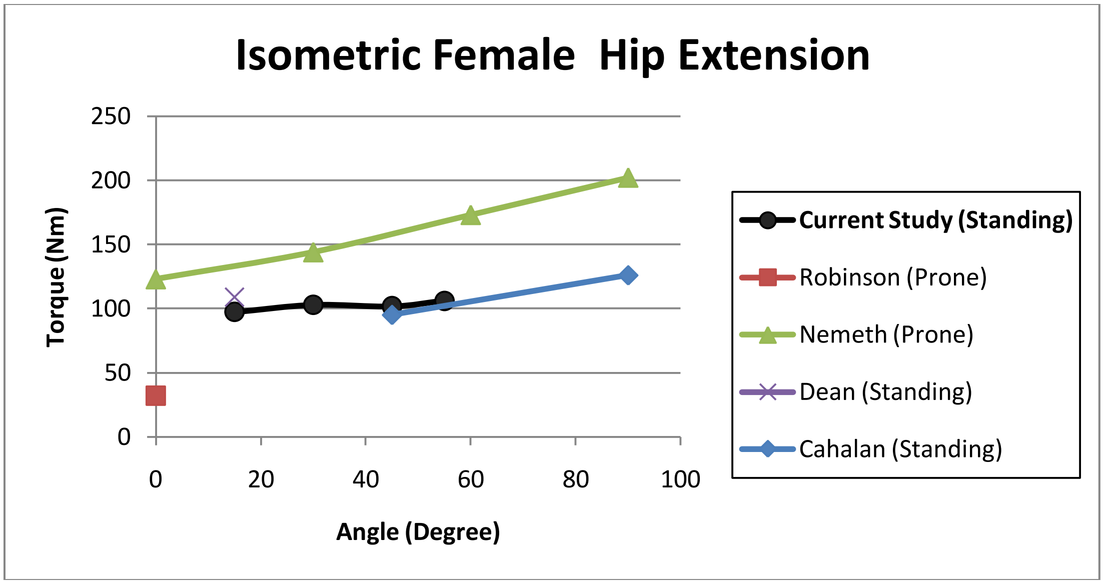

Figure 5.10. Female hip extension from 4 studies with the current study in bold.

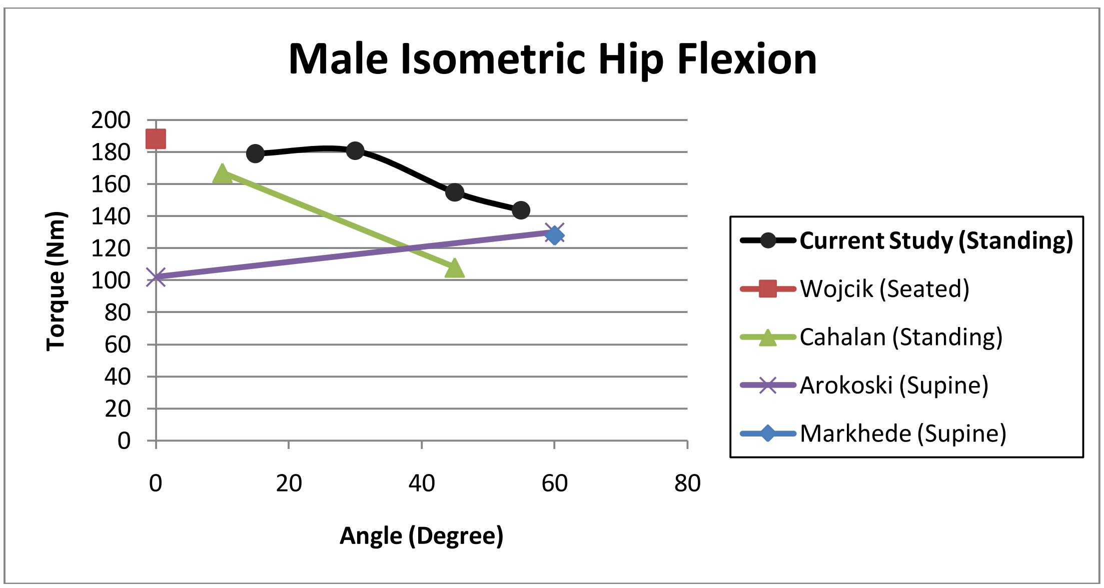

Figure 5.11. Male hip flexion from 4 studies with the current study in bold.

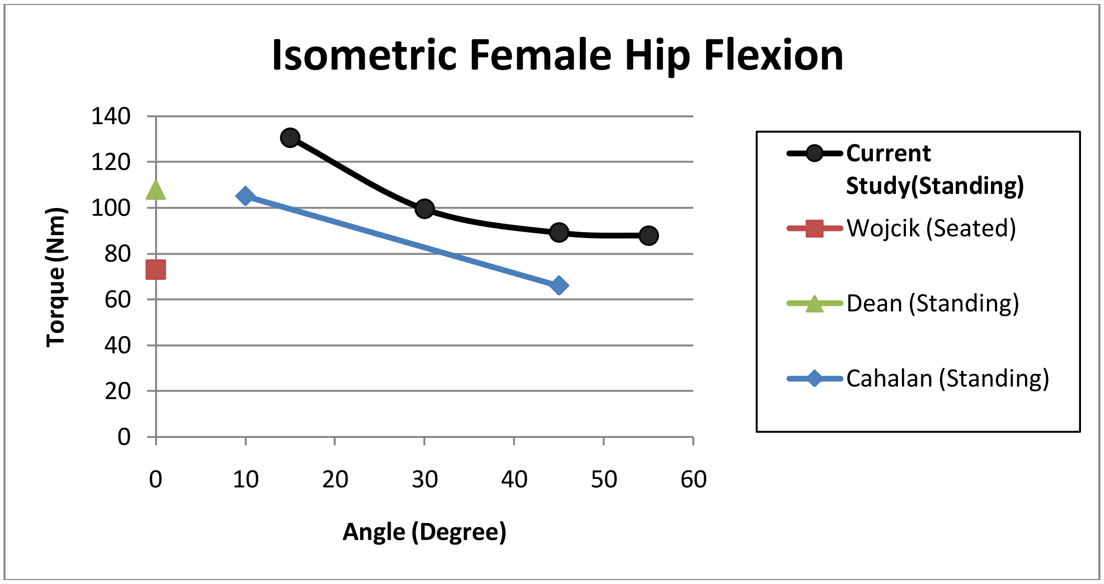

Figure 5.12. Female hip flexion from 3 studies with the current study in bold.

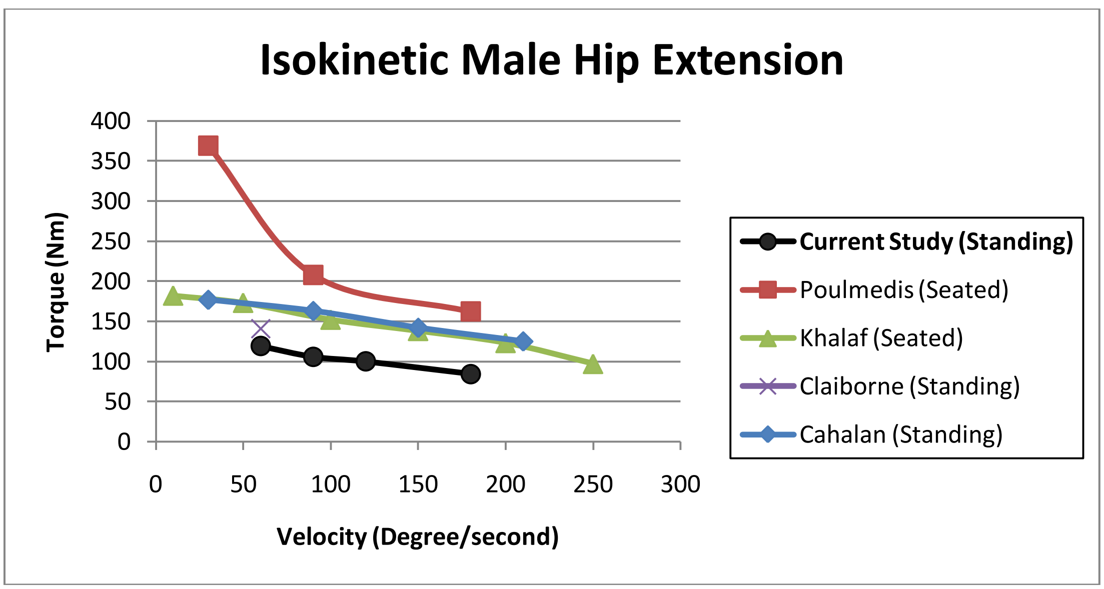

Figure 5.13. Male hip extension from 4 studies with the current study in bold.

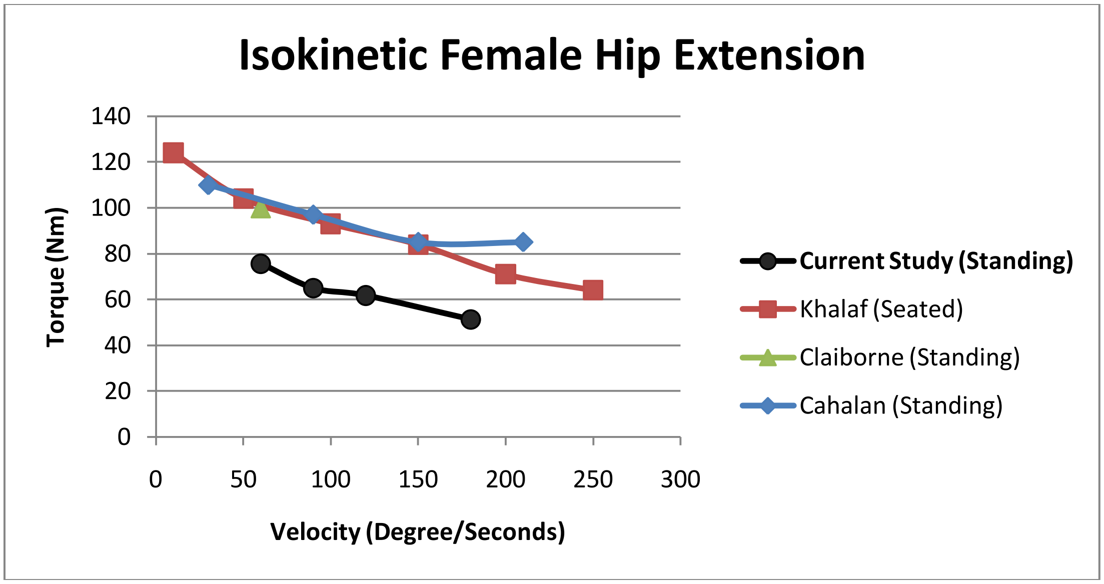

Figure 5.14. Female hip extension from 3 studies with the current study in bold.

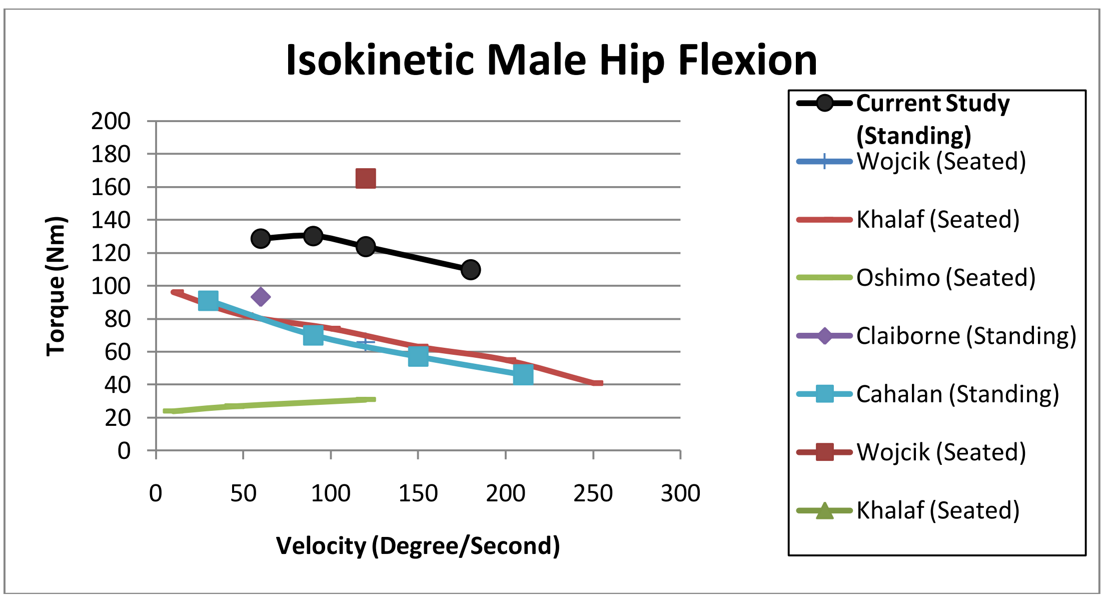

Figure 5.15. Male hip flexion from 7 studies with the current study in bold.

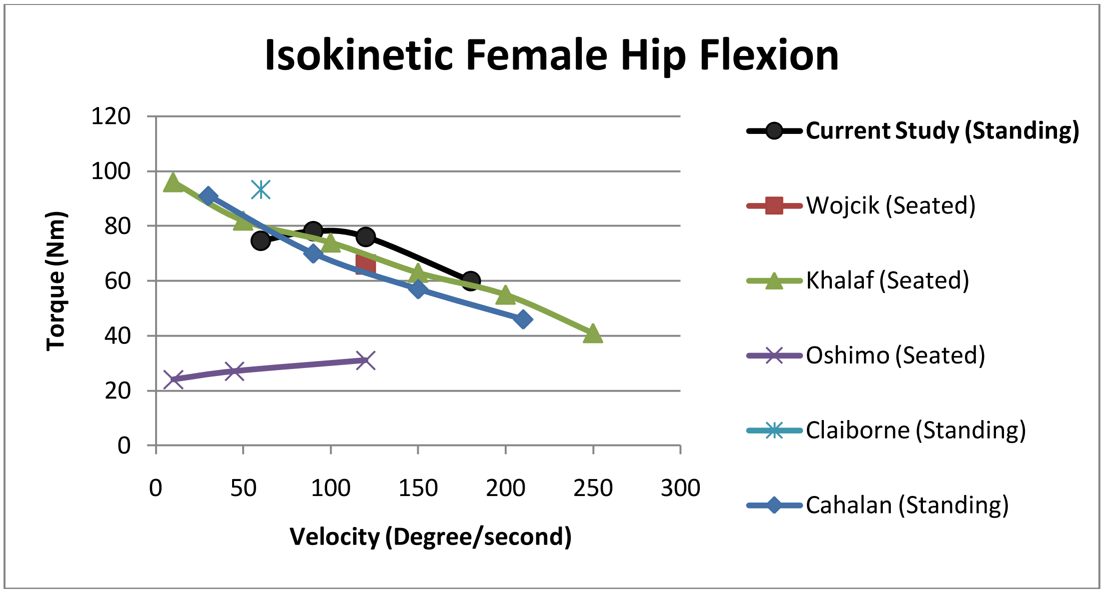

Figure 5.16. Female hip flexion from 5 studies with the current study in bold.

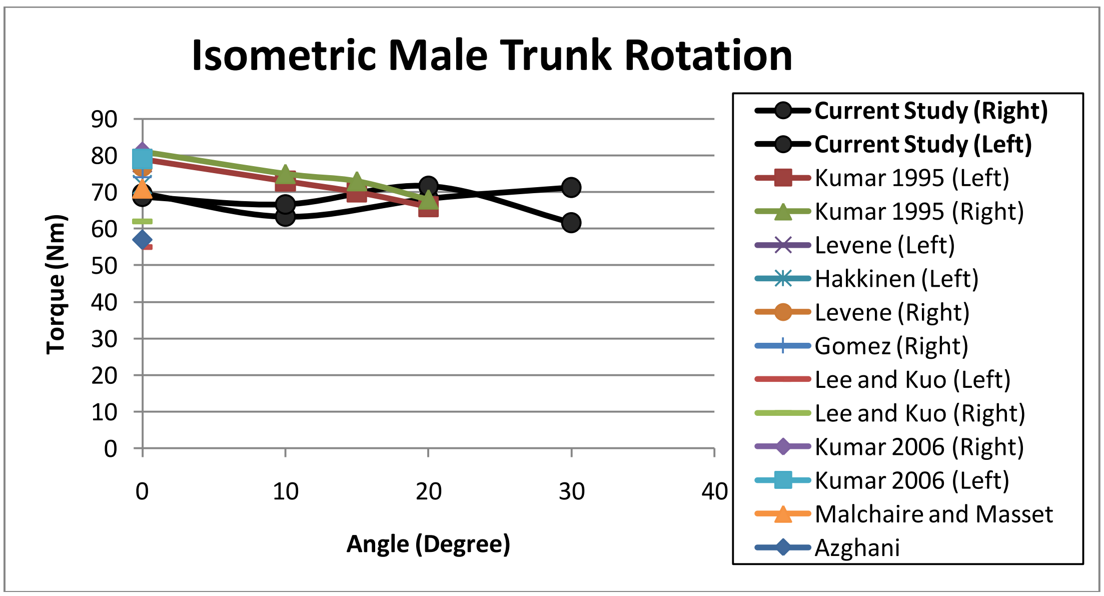

Figure 5.17. Male rotation from 12 studies with the current study in bold.

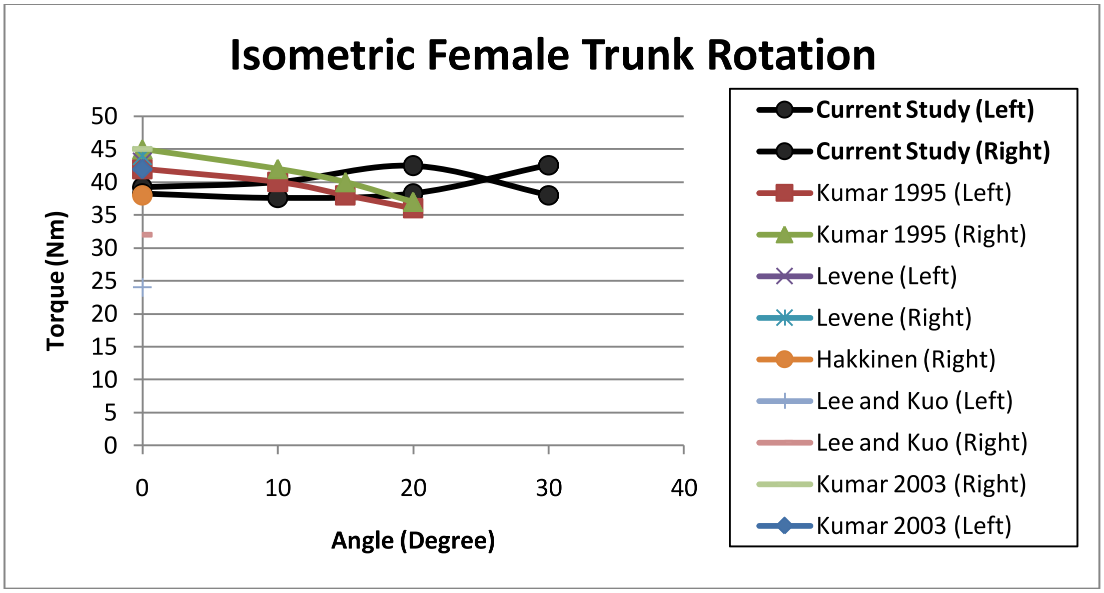

Figure 5.18. Female trunk rotation from 9 studies with the current study in bold.

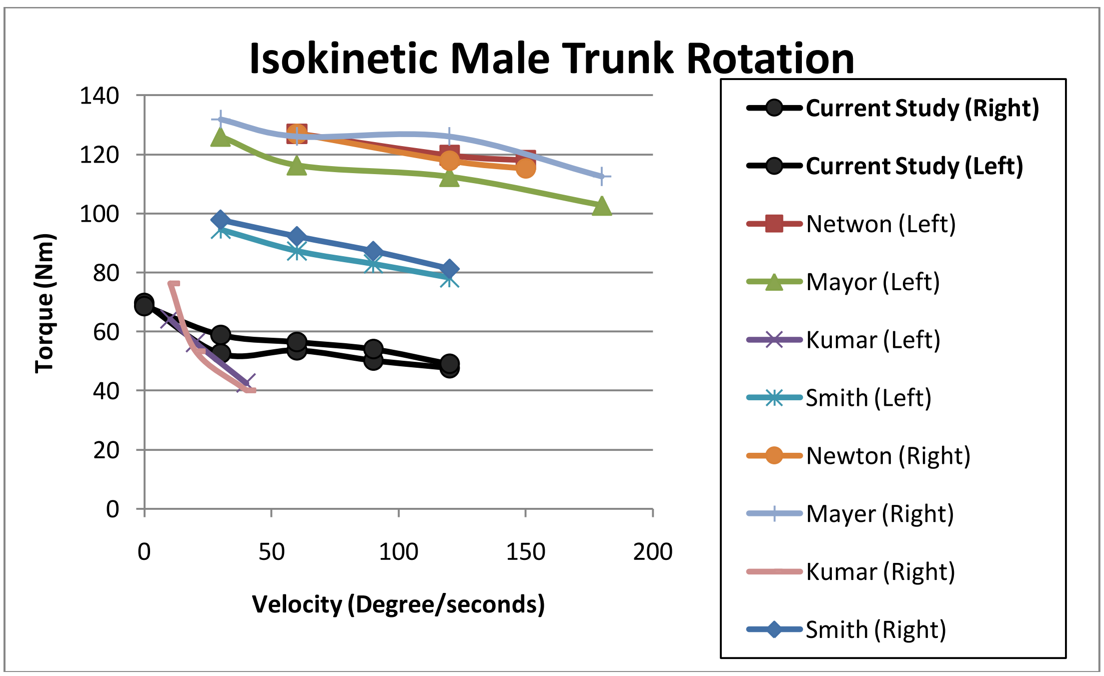

Figure 5.19. Male trunk rotation from 8 studies with the current study in bold.

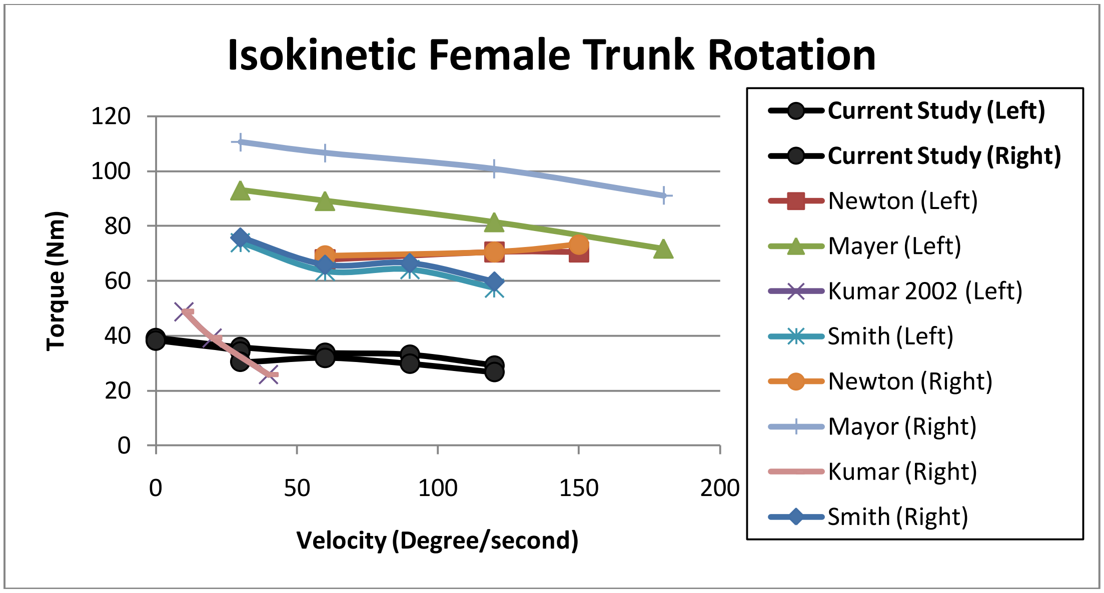

Figure 5.20. Female from 8 studies with the current study in bold.

REFERENCES

Agency for Health Care Policy and Research (1994). "This total represents only the more readily identifiable costs for medical care, workers compensation payments and time lost from work.." Back Pain Patient Outcomes Assessment Team MEDTEP **1** (1)

Alexander, MJL (1990). "Peak Torque Values for Antagonist Muscle Groups and Concentric and Eccentric Contraction Types for Elite Sprinters." Archives of Physical Medicine and Rehabilitation **71**(5): 334-339.

Anderson DE, Madigan, ML, Nussbaum, MA (2007). "Maximum Voluntary Joint Torque as a Function of Joint Angle and Angular Velocity: Model Development and Application to the Lower Limb." Journal of Biomechanics **40**:3105-3113.

Arokoski, MH, Arokoski, JPA, Haara, M, Kankaanpaa, M, Vesterinen, M, Niemitukia, LH, Helminen, HJ (2002): "Hip Muscle Strength and Muscle Cross Sectional Area in Men with and without Hip Osteoarthritis." The Journal of Rheumatology **29** (10): 2185-2195

Azghani, MR, Farahmand, F, Meghdari, A, Vossoughi, G, Parnianpour, M (2009). "Design and Evaluation of a Novel Triaxial Isometric Trunk Muscle Strength Measurement System." J. Engineering in Medicine **223**:755-765

Cahalan, TD, Johnson, ME, Liu, S, Chao, EYS (1989). "Quantitative Measurements of Hip Strength in Different Age Groups." Clinical Orthopaedics and Related Research (246): 136-145

Chaffin, DB, Andersson, GBJ, Martin, BJ (2006). Occupational Biomechanics Fourth Edition. New Jersey, John Wiley &Sons, Inc.

Claiborne, TL, Timmons, MK, Pincivero, DM (2008). "Test-Retest Reliability of Cardinal Plane Isokinetic Hip Torque and EMG. " Journal of Electromyography and Kinesiology **10**

Claiborne, TL, Armstrong, CW, Gandhi, V, Pincivero, DM (2006). "Relationship Between Hip and Knee Strength and Knee Valgus During a Single Leg Squat." Journal of Applied Biomechanics **22**: 41-51

Corin, G, Strutton, PH, McGregor, AH (2005). "Establishment of a Protocol to Test Fatigue of the Trunk Muscles." Br J Sports Med **39**: 731-735

Cowley, PM, Fitzgerald, S, Sottung, K, Swensen T (2009). "Age, Weight, and the Front Abdominal Power Test as Predictors of Isokinetic Trunk and Work in Young Men and Women." Journal of Strength and Conditioning Research **23** (3): 915-925

Davis, KG, Marras, WS, Waters, TR (1998). "Evaluation of Spinal Loading During lowering and Lifting." Clinical Biomechanics **13** (3):141-152

Dean, JC, Kuo, AD, Alexander, NB (2004). "Age-Related Changes in Maximal Hip Strength and Movement Speed." Journal of Gerontology: Medical Science **59A** (3): 286-292

Delitto, A, Rose, SJ, Crandell, CE, Strube, MJ (1991). "Reliability of Isokinetic Measurements of Trunk Muscle Performance." Spine **16** (7): 800-803

Deyo, RA, Mirza, SK, Martin, BI, (2006) "Back Pain Prevalence and Visit Rates: Estimates from U.S. National Surveys 2002" Spine **31**: 2724-2727

Findley, BW, Brown, LE, Whitehurst, M, Gilbert, R, Groo, DR, O'Neal, J (2000). "Sitting vs. Standing Isokinetic Trunk Extension and Flexion Performance Differences." Journal of Strength and Conditioning Research **14** (13): 310-315

Gomez, T, Beach, T, Cooke, C, Hrudey, Goyert, P (1991). "Normative Database for Trunk Range of Motion, Strength, Velocity, and Endurance with the Isostation B-200 Lumbar Dynamometer." Spine **16** (1): 15-21

Gupta, A, Fernihough, B, Bailey, G, Bombeck, P, Clarke, A, Hopper, D (2004). "An Evaluation of Differences in Hip External Rotation Strength and Range of Motion between Female Dancers and Non-Dancers." Br J Sports Med **38**: 778-783

Ho, CW, Chen, LC, Hsu, HH, Chiang, SL, Li, MH, Jiang, SH, Tsai, KC (2005). "Isokinetic Muscle Strength of the Trunk and Bilateral Knees in Young Subjects With Lumbar Disc Herniation." Spine **30** (18): 528-533

Hulens, M, Vansant, G, Lysens, R, Claessens, A, Muls, E (2002). "Assessment of Isokinetic Muscle Strength in Women Who are Obese." Journal of Orthopaedic &Sports Physical Therapy **32** (7): 347-357

Hunt, GC, Fromherz, WA, Danoff, J, Waggoner, T (1986). "Femoral Transverse Torque: An Assessment Method." The Journal of Orthopaedic and Sports Physical Therapy **7** (6): 319-324

Hupli, M, Hurri, H, Luoto,S, Sainio, P, Alaranta, H (1996). "Isokinetic Performance Capacity of Trunk Muscles. Part I: The Effect of Repetition on Measurement of Isokinetic Performance Capacity of Trunk Muscles Among Healthy Controls and Two Different Groups of Low-Back Pain Patients." Scand J Rehab Med **28**: 201-206

Jerome, J, Hunter, K, Gordon, P, McKay, N (1990). "A new Robust Index for Measuring Isokinetic Trunk Flexion and Extension." Spine **16** (7): 804-808

Karatas, GK, Gogus, F, Meray, J (2002). "Reliability of Isokinetic Trunk Muscle Strength Measurement." Am J Phys Med Rehabil **81**: 79-85

Keller, TS, Roy, AL (2002). "Posture-Dependent Isometric Trunk Extension and Flexion Strength in Normal Male and Female Subjects." Journal of Spinal Disorders & Techniques **15** (4): 312-318

Khalaf, KA, Parnianpour, M, Karakostas, T (2001). "Three Dimensional Surface Representation of Knee and Hip Joint Torque Capability." Biomedical Engineering-Applications, Basis, &Communications **13** (2): 53-65

Khalaf, KA, Parnianpour, M (2001). "A Normative Database of Isokinetic Upper-Extremity Joint Strengths: Towards the Evaluation of Dynamic Human Performance." Biomedical Engineering-Applications, Basis, &Communications **13** (2): 79-92

Khalaf, KA, Parniampour, M, Sparto, P, Simon, S (1997). "Modeling of Functional Trunk Muscle Performance: Interfacing Ergonomics and Spine Rehabilitation in Response to the ADA." Journal of Rehabilitation Research and Development **34** (4): 459-469

Kondraske, GV, Deivanayagam, S, Carmichael, T, Mayer, TG, Mooney, V (1987). "Myoelectric Spectral Analysis and Strategies for Quantifying Trunk Muscular Fatigue." Archives of Physical Medicine & Rehabilitation **68**: 103-110

Kumar, S, Narayan, Y, Garand, D (2003). "An Electromyographic Study of Isokinetic Axial Rotation in Young Adults." The Spine Journal **3**:46-54

Kumar, S, Narayan, Y, Amell, T, Ferrari, R (2002). "Electromyography of Superficial Cervical Muscles with Exertion in the Sagittal, Coronal, and Oblique Planes." Eur Spine **11**: 27-37

Kumar, S, Narayan, Y, Garand, D (2002). "Electromyography of Trunk Muscles in Isometric Graded Axial Rotation." Journal of Electromyography and Kinesiology **12**: 317-328

Kumar, S, Dufresne, RM, Schoort, TV (1995). "Human Trunk Strength Profile in Lateral Flexion and Axial Rotation." Spine **20** (2) : 169-177

Laake, AN (2008). Modeling three-dimensional knee and elbow joint strength as a function of velocity and position, University of Iowa, 2008.:ix, 85 leaves, bound.

Langrana, NA, Lee, CK (1984). "Isokinetic Evaluation of Trunk Muscles." Spine **9** (2):171-175

Lee, YH, Kuo, CL (2000). "Factor Structure of Trunk Performance Data for Healthy Subjects." Clinical Biomechanics **15** : 221-227

Levene, JA, Seeds, RH, Goldberg, HM, Frazier, M, Fuhrman, GA (1989). "Trends in Isodynamic and Isometric Trunk Testing on the Isostation B200." Journal of Spinal Disorders **2** (1) : 20-35

Lieber, RL (2002). Skeletal muscle structure, function & plasticity : the physiological basis of rehabilitation. Philadelphia, Lippincott Williams & Wilkins.

Lindsay, DM, Maitland, ME, Lowe, RC, Kane, TJ (1992). "Comparison of Isokinetic Internal and External Hip Rotation Torques Using Different Testing Positions." The Journal of Orthopaedic and Sports Physical Therapy **16** (1) : 43-50

Luoto, S, Hupli, M, Alaranta, H, Hurri, H (1996). " Isokinetic Performance Capacity of Trunk Muscles. Part II: Coefficient of Variation in Isokinetic Measurement in Maximal Effort and in Submaximal Effort." Scand J Rehab Med **28** : 207-210

Madsen, Or (1996). "Trunk Extensor and Flexor Strength Measured by the Cybex 6000 Dynamometer: Assessment of Short-Term and Long-Term Reproducibility of Several Strength Variables." Spine **21** (23) : 2770-2776

Malchaire, JB, Masset, DF (1995). "Isometric and Dynamic Performances of the Trunk and Associated Factors." Spine **20** (15): 1649-1656

Markhede, G, Grimby, G (1980). "Measurement of Strength of Hip Joint Muscles." Scandinavian Journal of Rehabilitation Medicine **12** (4): 169-174

Masuda, K, Kikuhara, N, Takahashi, H, Yamanaka, K (2003). "The Relationship Between Muscle Cross-Sectional Area and Strength in Various Isokinetic Movements Among Soccer Players." Journal of Sports Science **21**: 851-858

Mayer, TG, Smith, SS, Kondraske, G, Gatchel, RJ, Carmichael, TW, Mooney, V (1985). "Quantification of Lumbar Function Part 3: Preliminary Data on Isokinetic Torso Rotation Testing with Myoelectric Spectral Analysis in Normal and Low-Back Pain Subjects." Spine **10** (10): 912-920

McIntyre, DR (1989). "The Stability of Isometric Trunk Flexion Measurements." Spine **2** (2): 80-86

McNeill, T, Warwick, D, Andersson, G, Schultz, A (1980). "Trunk Strengths in Attempted Flexion, Extension, and Lateral Bending in Healthy Subjects and Patients with Low-Back Disorders." Spine **5** (6): 529-538

Newton, M, Somerville, D, Henderson, I, Waddell, G (1993). "Trunk Strength Testing with Iso-Machines Part 2: Experimental Evaluation of the Cybex II Back Testing System in Normal Subjects and Patients with Chronic Low Back Pain." Spine **18** (7): 812-824

Nemeth, G, Ekholm, J, Arborelinus, UP, Harms-Ringdahl, K, Schuldt, K (1983). "Influence of Knee Flexion on Isometric Hip Extensor Strength." Scandinavian Journal of Rehabilitation Medicine **15** (2): 97-101

Nordin, M, Kahanovitz, N, Verderame, R, Parnianpour, M, Yabut, S, Viola, K, Greenidge, N, Mulvihill, M (1987). "Normal Trunk Muscle Strength and Endurance in Women and the Effect of Exercises and Electrical Stimulation Part 1: Normal Endurance and Trunk Muscle Strength in 101 Women." Spine **12** (2): 105-111

Oshimo, TA, Greene, TA, Jensen, GM, Lopopolo, RB (1983). "The Effect of Varied Hip Angles on the Generation of Internal Tibial Rotary Torque." Medicine and Science in Sports and Exercise **15** (6): 529-534

Parnianpour, M, Nordin, M, Kahanovitz, N, Frankel, V (1988). " The Triaxial Coupling of Torque Generation of Trunk Muscles During Isometric Exertions and the Effect of Fatiguing Isoinertial Movements on the Motor Output and Movement Patterns." Spine **13** (9): 982-992

Payne, JW (2009) "Finding the Effective Treatment for Chronic Pain" USNews

Pierce, GM (2009). Modeling Three-Dimensional Shoulder Peak Torque as a Function of Joint Angle and Velocity, University of Iowa, 2009.: ix, 77 leaves, bound.

Poulmedis, P (1985). "Isokinetic Maximal Torque Power of Greek Elite Soccer Players." Journal of Orthopaedic and Sports Physical Therapy **6** (5): 293-295

Robinson, RL, Nee, RJ (2007). "Analysis of Hip Strength in Females Seeking Physical Therapy Treatment for Unilateral Patellofemoral Pain Syndrome." Journal of Orthopaedic Sports Physical Therapy **37** (5): 232-238

Shirado, O, Kaneda, K, Ito, T (1992). "Trunk-Muscle Strength During Concentric and Eccentric Contraction: A Comparison Between Healthy Subjects and Patients with Chronic Low-Back Pain." Journal of Spinal Disorders **5** (2): 175-182

Smith, DJ (1987). "The Relationship Between Anaerobic Power and Isokinetic Torque Outputs." Canadian Journal of Sport Sciences **12** (1): 3-5

Smith, S, Mayer, TG, Gatchel, RJ, Becker, TJ (1985). "Quantification of Lumbar Function Part 1: Isometric and Multispeed Isokinetic Trunk Strength Measures in Sagittal and Axial Planes in Normal Subjects." Spine **10** (8): 757-764

Tanaka, S, Hachisuka, K, Ogata, H (1998). "Muscle Strength of Trunk Flexion-Extension in Post-Stroke Hemiplegic Patients." American Journal of Physical Medicine **77** (4): 288-290

Vallfors B. Acute, (1998). "Subacute and Chronic Low Back Pain: Clinical Symptoms, Absenteeism and Working Environment." Scan J Rehab Med Suppl **11**: 1- 98

Vanhee, JL, Voisin, Ph, Vezirian, Th, Vanvelcenaher, J (1996). "Isokinetic Trunk Flexors and Extensors Performance with and without Gravity Correction." Isokinetics and Exercises Science **6**: 89-94

Wessel, J, Ford, D, van Driesum, D (1992). "Measurement of Torque of Trunk Flexors at Different Velocities." Scand J Rehab Med **24**: 175-180

Wojcik, LA, Thelen, DG, Schultz, AB, Ashton-Miller, JA, Alexander, NB (2001). " Age and Gender Differences in Lower Peak Extremity Joint Torques and Ranges of Motion Used During Single-Step Balance Recovery from a Forward Fall." Journal of Biomechanics **34**: 67-73

Yassierli, Nussbaum, MA, Iridiastadi, H, Wojcik (2007). "The Influence of Age on Isometric Endurance and Fatigue is Muscle Dependent: A Study of Shoulder Abduction and Torso Extension." Ergonomics **50** (1): 26-45