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Biomechanical Risk Factors for Knee Osteoarthritis in Young Adults: The Influence of Obesity and Gait Instruction

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To the Graduate Council:

I am submitting herewith a dissertation written by Julia Ann Freedman entitled "Biomechanical Risk Factors for Knee Osteoarthritis in Young Adults: The Influence of Obesity and Gait Instruction." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Exercise and Sport Sciences.

Clare E. Milner, Major Professor

We have read this dissertation and recommend its acceptance:

Songning Zhang, Dixie Thompson, Xiopeng Zhao

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Dissertation Presented for

the Doctor of Philosophy

Degree

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Julia Ann Freedman

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ABSTRACT

With increasing rates of obesity, research has begun to focus of co-morbidities of obesity such as osteoarthritis. The majority of existing research has focused on older adults as the group most likely to suffer from osteoarthritis. The purpose of this study was to determine if overweight and obese young adults exhibit biomechanical risk factors for knee osteoarthritis, and to determine if young adults with biomechanical risk factors of osteoarthritis can modify these with instruction. This purpose was divided into two separate studies.

Study 1: Thirty adults between 18-35 years old were recruited into three groups according to body mass index: normal, overweight, and obese. Participants walked through the lab while we collected 3-d kinematic and kinetic data. Overweight and obese young adults walked with similar gait compared to normal weight young adults.

Study 2: Nine young adults between 18-35 years were recruited who walked with stiff-knee gait. Baseline measures of gait were collected in the form of 3-d kinematics and kinetics as participants walked through the laboratory. They then completed the gait instruction program which consisted of four blocks of training. Each block included ten single steps where the participant was provided feedback, followed by 100 practice steps around the laboratory. Participants were successful in increasing sagittal plane kinematics and kinetics of interest in the study.

Conclusion: Identifying individuals who had biomechanical risk factors of osteoarthritis according to body mass index was not possible. According to the results of our study, obese and overweight young adults are not at increased risk of osteoarthritis compared to

normal weight young adults. Individuals who may be at increased risk due to stiff-knee gait were able to improve their gait following instruction.

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CHAPTER I

Introduction

Osteoarthritis is a disease characterized by the progressive degeneration of cartilage and eventual damage to the underlying bone. Commonly, osteoarthritis severity is described by the Kellgren-Lawrence scale (Kellgren and Lawrence 1957), which utilizes radiographs to diagnose disease levels. Osteoarthritis is very common in older adults, with 10% of adults over the age of 65 suffering from knee osteoarthritis (Felson, Naimark et al. 1987). Women develop knee osteoarthritis at higher rates than men (Felson, Zhang et al. 1997). Obesity has also been highly correlated with development and progression of osteoarthritis (Cooper, Snow et al. 2000). As body weight increases, so does the load supported by the knee, putting more stress on the knee cartilage and increasing the rate of cartilage degeneration (Lementowski and Zelicof 2008). As expected with recent increases in rates of obesity, increases in rates of osteoarthritis have been observed (Lementowski and Zelicof 2008). It is, therefore, important to investigate the relationship between obesity and osteoarthritis and ways to decrease rates of osteoarthritis development and progression.

Osteoarthritis is more common in the medial compartment of the knee than the lateral compartment (Baliunas, Hurwitz et al. 2002). When osteoarthritis develops, there is cartilage damage in the medial compartment, altering the knee alignment and the distribution of loads both statically and dynamically. The major complication of knee osteoarthritis is increasing pain that limits an individual’s ability to complete everyday activities. Therefore, as the disease progresses, changes in function and in gait occur in an attempt to manage the pain.

An abundance of researchers have investigated knee osteoarthritis in older adults. This research has characterized the progression of knee osteoarthritis through changes seen in gait. Gait variables such as peak knee adduction angle, peak external knee adduction moment, knee flexion excursion and peak external knee flexion moment during stance differ between age-matched adults with and without knee osteoarthritis (Kaufman, Hughes et al. 2001; Baliunas, Hurwitz et al. 2002; McKean, Landry et al. 2007). Specifically, adults with knee osteoarthritis exhibit greater stance phase peak knee adduction angles (Astephen and Deluzio 2005), greater peak external knee adduction moments (Schipplein and Andriacchi 1991; Kaufman, Hughes et al. 2001; Baliunas, Hurwitz et al. 2002; Mündermann, Dyrby et al. 2005; Lynn, Reid et al. 2007; McKean, Landry et al. 2007), decreased knee flexion excursion (Kaufman, Hughes et al. 2001; Zeni and Higginson 2009; Zeni and Higginson 2009) and decreased peak external knee flexion moments (Kaufman, Hughes et al. 2001; Baliunas, Hurwitz et al. 2002).

With the increasing rate of obesity in the last 30 years (Flegal, Carroll et al. 2002), many health problems have become more prevalent, including osteoarthritis. There are biomechanical links between the consequences of obesity and the causes of osteoarthritis (Leach, Baumgard et al. 1973; Cooper, Snow et al. 2000; Niu, Zhang et al. 2009). For example, gait in obese individuals is different from healthy, normal weight adults. As seen with osteoarthritis, moments of the knee joint are greater in obese adults than in normal weight adults. This includes the peak knee adduction moment (Browning and Kram 2007; Lai, Leung et al. 2008), which has also been identified as a risk factor for knee osteoarthritis. An important first step in the prevention or delay of osteoarthritis development is identifying whether these risk factors for osteoarthritis also exist in young adults who are overweight or obese.

Since aspects of walking gait are associated with osteoarthritis, training programs to alter gait may reduce the risk of osteoarthritis development and progression. Initial research into retraining programs provides support for the ability of individuals to change the way they walk (Decker, Torry et al. 2004; Fregly, Reinbolt et al. 2007; Fregly, D'Lima et al. 2009). Gait retraining programs that utilize motor learning principles, may have a higher rate of success. Research has shown that feedback is an integral aspect of motor learning (Bilodeau and Bilodeau 1958; Bilodeau, Bilodeau et al. 1959). Therefore, it is important to further investigate whether a specific gait retraining program could reduce biomechanical risk factors for osteoarthritis development in young adults.

Purpose

The purpose of this study was: 1) to determine whether young adults who are overweight or obese exhibit biomechanical risk factors for osteoarthritis, and 2) to determine whether these risk factors can be reduced in young adults via gait retraining. This was accomplished through two separate studies. The aim of the first study was to determine whether biomechanical risk factors are observed more frequently in overweight and obese participants compared to normal weight young adults. Specifically, to investigate the kinematics and kinetics of gait and performance on functional activity tests typically used in investigating osteoarthritis across these groups.

The aim of the second study was to determine if adults, who exhibit a stiff knee gait, can reduce this and other biomechanical risk factors for osteoarthritis during a single session of gait retraining. The gait retraining focused on increasing knee flexion excursion during walking. Therefore, a secondary aim of the study was to determine whether improvements in knee flexion excursion lead to improvements in other biomechanical risk factors of osteoarthritis. These include peak knee adduction moment, peak knee flexion moment, and peak knee adduction angle.

Research Hypotheses:

1 Obese and overweight young adults will exhibit gait biomechanics similar to those reported previously for older adults with osteoarthritis.

   1.1 Knee flexion excursion during weight acceptance will progressively decrease from normal weight young adults to overweight young adults to obese young adults.

   1.2 Peak knee flexion angle during weight acceptance will progressively decrease from normal weight young adults to overweight young adults to obese young adults.

   1.3 External peak knee flexion moment will progressively decrease from normal weight young adults to overweight young adults to obese young adults.

   1.4 Peak knee adduction angle will progressively increase from normal weight young adults to overweight young adults to obese young adults.

1.5 External peak knee adduction moment will progressively increase from normal weight young adults to overweight young adults to obese young adults.

2 A single session of retraining will immediately improve stiff knee gait in adults who exhibit stiff knee gait at baseline.

2.1 Younger adults will increase knee flexion excursion post-training compared to baseline.

2.2 Younger adults will have an increased peak knee flexion angle post-training compared to baseline.

2.3 Younger adults will have an increase in the external peak knee flexion moment post-training compared to baseline.

2.4 Younger adults will have a decrease in peak knee adduction angle post-training compared to baseline.

2.5 Younger adults will have a decrease in peak external knee adduction moment post-training compared to baseline.

3 Stiff knee gait improvements will be retained short-term within a single session

3.1 Younger adults will retain increases in knee flexion excursion during retention testing compared to baseline.

3.2 Younger adults will retain increases in peak knee flexion angle during retention testing compared to baseline.

3.3 Younger adults will retain increases in external peak knee flexion moment during retention testing compared to baseline.

3.4 Younger adults will retain decreases in peak knee adduction angle during retention testing compared to baseline.

3.5 Younger adults will retain decreases in external peak knee adduction moment during retention testing compared to baseline.

Assumptions

1. Instructions for gait retraining were appropriate for participant learning.
2. Young adults without knee pain do not have osteoarthritis.

Delimitations

1. Participants in both study #1 and study #2 will be between the ages of 18 and 35.
2. Participants in study #1 will not have had a major lower extremity injury or surgery that will alter gait.

Limitations

1. Study #2 will be limited to individuals who exhibit stiff knee gait
2. All analyses will occur in a laboratory setting.

Independent Variable

Study #1

1. Body Mass Index category (Pi-Sunyer 1998)
    a. Normal Weight: BMI < 25
    b. Overweight: BMI 25-29.9
    c. Obese: BMI > 30

Study #2

2. Gait instruction protocol

Dependent Variables

Study #1 and Study #2

During the stance phase of gait:

1. Knee flexion excursion

2. Peak knee flexion angle during weight acceptance

3. External peak knee flexion moment

4. Peak knee adduction angle

5. External peak knee adduction moment

CHAPTER II

Literature Review

The purpose of this dissertation is to identify whether gait characteristics that have been linked to increased risk of knee osteoarthritis occur in young adults who are overweight and obese. Secondly, the purpose is to determine if younger adults are able to alter their gait to decrease this risk in a single session of retraining. This literature review will discuss: 1) what is known about the biomechanical causes of and associations with knee osteoarthritis, 2) the relationship between the dependent variables and osteoarthritis, 3) methods to measure body composition and obesity, 4) the relationship between obesity and osteoarthritis, and 5) gait retraining and motor learning.

Risk Factors for Osteoarthritis

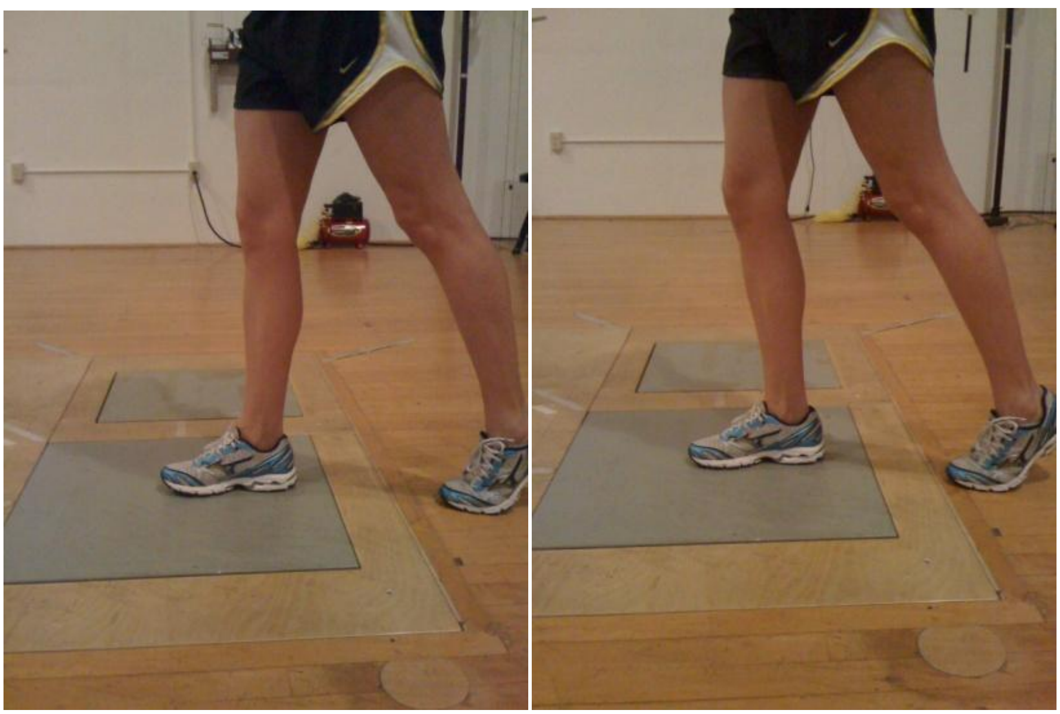
The risk of developing osteoarthritis is associated with certain demographic variables. Greater body mass index and increased body weight have been associated with greater risk of developing osteoarthritis (Felson, Zhang et al. 1997). Walking is a ubiquitous everyday activity. Therefore, there is a large body of research on the risk factors of osteoarthritis related to gait biomechanics. The changes in gait in individuals with osteoarthritis have also been extensively studied.

Gait Biomechanics

The relationship between osteoarthritis and the biomechanics of gait has been researched extensively in older adults. Individuals with knee osteoarthritis walk with decreased knee flexion excursion (Kaufman, Hughes et al. 2001; Zeni and Higginson 2009; Zeni and Higginson 2009), decreased peak knee flexion angle (Kaufman, Hughes et al. 2001; McKean, Landry et al. 2007), increased peak external knee flexion moments (Al-Zahrani and Bakheit 2002), greater stance phase peak knee adduction angles (Astephen and Deluzio 2005), and greater peak external knee adduction moments (Schipplein and Andriacchi 1991; Kaufman, Hughes et al. 2001; Baliunas, Hurwitz et al. 2002; Mündermann, Dyrby et al. 2005; Lynn, Reid et al. 2007; McKean, Landry et al. 2007), when compared to healthy individuals. The biomechanical consequences of changes in these variables, as well as the research establishing their relationship with osteoarthritis will be reviewed here.

Knee Flexion Excursion and Peak Knee Flexion

Knee flexion excursion is calculated by subtracting the knee flexion angle at heel contact from the peak knee flexion angle during the first half of stance. A decrease in knee flexion excursion has been associated with knee instability and pain (Perry 1992). When the knee is fully extended, it is the most stable because the tibia and femur have the most bony contact. This results in part, from the screw-home mechanism, which occurs as the knee extends. Due to the larger area of the medial contact, the knee extends but movement occurs longer in the medial compartment. As movement continues the tibia and femur rotate and the bones “lock” together (Nordin and Frankel 2001). As the knee flexes, the quadriceps force increases to maintain stability of the joint. This increases the compression force on the joint. In individuals with knee pain, compression forces will increase the pain. Thus, individuals with knee pain will want to avoid knee joint compression by decreasing the amount of flexion in the knee. This has been called “stiff knee gait" (Figure 2-1) and is common in adults with knee pain, including that caused by osteoarthritis. As osteoarthritis progresses, there is an increase in knee pain due to cartilage damage providing less cushion between the bones. In order to compensate, participants typically decrease knee flexion excursion. The knee is in a more extended position both at heel contact and at peak knee flexion, leading to a smaller knee flexion excursion. By maintaining a more extended knee position, individuals minimize contraction of the quadriceps.



(a) (b)

Figure 2-1: Sagittal view of the lower extremity during weight acceptance a) Stiff-knee gait and b) normal knee flexion.

The decreased knee flexion excursion may be associated with risk of further damage to the knee. The knee flexion during weight acceptance is largely responsible for the attenuation of the impact from the ground reaction force. With normal range of motion, contraction of the leg muscles attenuates the impact. Normally flexion of the knee extends the duration over which the ground reaction force is applied. Loading response extends through the occurrence of the peak knee angle in early stance. When this motion is limited, there is shorter duration of loading response. As the duration of loading response shortens, the force profile is altered. While the overall impulse value may remain the same, there will be a steeper curve, as the force is larger at any given moment through the shorter duration.

Cross sectional investigations have confirmed that there are differences in knee flexion excursion between participants with varying severities of osteoarthritis. Zeni and Higginson (Zeni and Higginson 2009) had groups of participants at different stages of osteoarthritis progression. In order to account for the difference in self-selected walking velocity, the researchers performed an analysis of co-variance using speed as a covariate. They found that at both the self-selected and fast walking velocities, the healthy control group had a greater knee flexion excursion than the severe osteoarthritis group, but similar to the moderate osteoarthritis group.

While not all investigators report values for knee flexion excursion, many will report values the related variables. As peak knee flexion is used in the computation of knee joint excursion, if the knee angle at footstrike is the same between groups, decreases in peak knee flexion will decrease knee flexion excursion. Kaufman et al. (Kaufman, Hughes et al. 2001) reported a 6° decrease in overall peak knee flexion in the osteoarthritis versus control groups. McKean et al. (McKean, Landry et al. 2007) also reported smaller peak knee flexion angle in adults with osteoarthritis compared to controls. There was an interaction effect between gender and osteoarthritis for peak knee flexion. Men with osteoarthritis had peak knee flexion values similar to healthy men and women. Decreases in peak knee flexion were only seen from healthy women to women with osteoarthritis. Contrary to previous studies, Mundermann et al. (Mündermann, Dyrby et al. 2005) reported that participants with both moderate and severe osteoarthritis had greater knee flexion excursion. Their participants had a more extended knee at heel contact and a similar peak knee flexion angle compared to healthy controls. It is important to note that the individuals in this investigation had bilateral knee osteoarthritis. Most investigations involve individuals with only unilateral osteoarthritis. Perhaps this change in knee flexion excursion is related to these individuals being unable to rely more on their healthy side.

Knee joint stiffness is calculated by dividing the change in knee joint moment by the knee flexion excursion. Therefore, if the knee joint moment is similar between groups, changes in knee joint stiffness indicate changes in knee joint excursion. Knee joint stiffness was assessed in participants with varying stages of osteoarthritis (Zeni and Higginson 2009). When participants had a fixed walking velocity of 1.0 m/s, the severe osteoarthritis group walked with a higher knee joint stiffness than either the moderate osteoarthritis or control group. Both the moderate osteoarthritis and control groups had similar knee joint stiffness. This suggests that knee joint stiffness may be employed to discern participants with moderate osteoarthritis from those with severe osteoarthritis. It also implies that greater knee stiffness is a risk factor for osteoarthritis.

Peak knee flexion angle and knee flexion excursion are important variables in determining abnormal gait. They can provide a good indication of the pain and dysfunction that and individual has. By incorporating these measures into the current study, we were able to determine whether or not being overweight or obese as a young adult is associated with decreased knee flexion. We were also able to determine whether or not young adults who had less flexion were able to increase it with training.

Peak External Knee Flexion Moment

During gait, the healthy knee is extended fully at heel contact and begins to flex until reaching a peak of approximately 15-20° during weight acceptance in the first half of stance. Following loading response the knee extends until reaching peak extension. After reaching peak extension, the knee flexes progressively more through the remainder of stance (Nordin and Frankel 2001). The initial flexion of the knee is the loading response. The limb is accepting the body weight. The amount of knee flexion is controlled eccentrically by the quadriceps so that the knee does not collapse or „give out'.

As discussed, walking with decreased knee flexion excursion occurs when individuals seek to avoid contraction of the quadriceps muscle. This can occur either as a result of quadriceps weakness, attempts to increase stability, or to avoid pain. Knee flexion excursion indicates the range of motion at the knee. Characteristic of stiff knee or "quadriceps avoidance" gait is a decrease in the external knee flexion moment. The external knee flexion moment represents the flexion torque. This moment is altered by the equal and opposite force of the ground reaction force vector. As the external flexion moment decreases, there is similar decrease in equal and opposite internal moment that is necessary to maintain the stability of the joint. The smaller internal moment results in less muscle force required from eccentric quadriceps contraction. Therefore, a decrease in the quadriceps contraction will appear as a decrease in the external knee flexion moment. When the knee maintains a more extended position during gait, the ground reaction force vector stays more in line with the knee joint itself (Figure 2-2). This decreases the flexor moment on the knee.

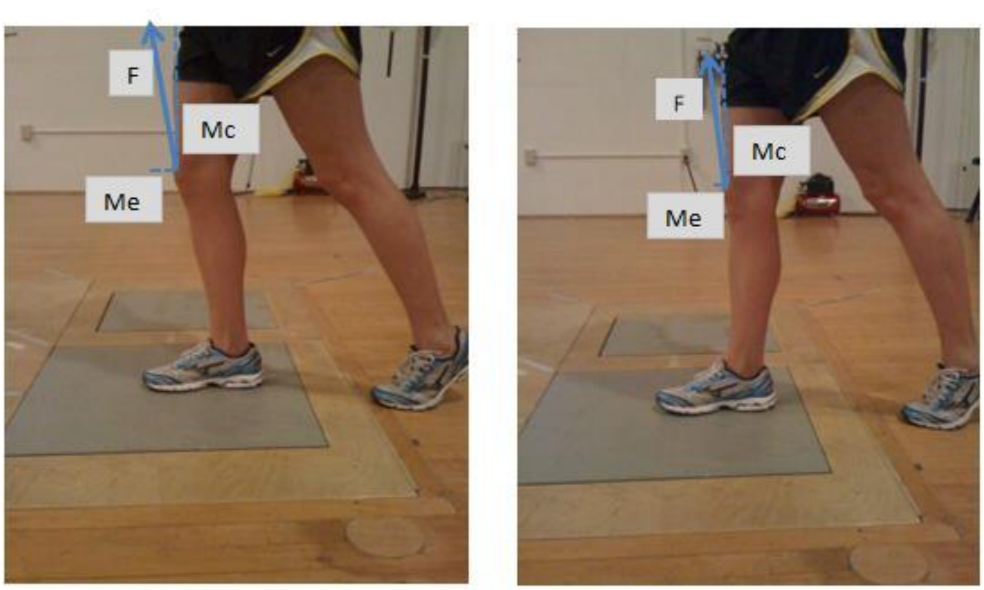


Figure 2-2: Sagittal plane view of the knee during weight acceptance: a) normal gait and b) stiff knee gait. F: Resultant force vector, Me: Extensor moment at the knee, Mc: Compressive moment at the knee

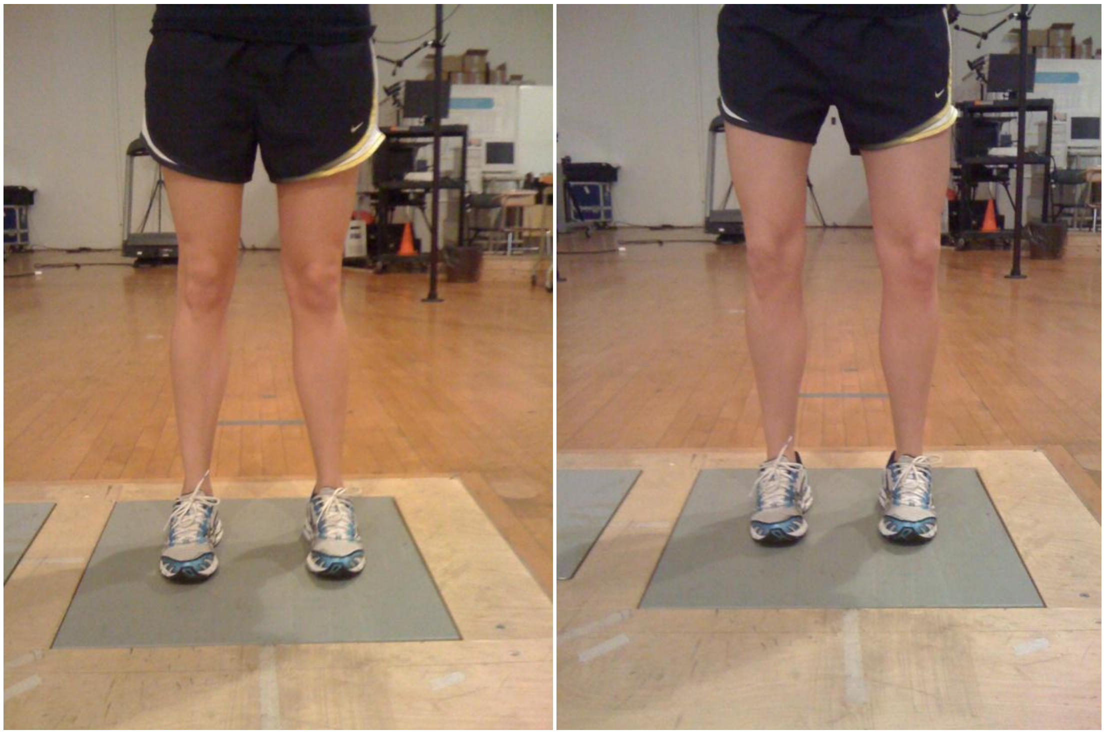
Kaufman et al. (Kaufman, Hughes et al. 2001) reported that adults with osteoarthritis walked with a significantly smaller peak external flexion moment than healthy adults. However, the age of their healthy participants (30 years) was younger than their adults with osteoarthritis (57 years).

Al-Zahrani and Bakheit (Al-Zahrani and Bakheit 2002) investigated the walking gait of patients who had been to an orthopedic clinic to discuss total knee replacement. Contrary to other investigations they reported that the osteoarthritis group had an increased midstance external knee flexion moment compared to healthy participants. However, they did not report the peak value, but just the value at midstance. The midstance value gives a false impression of what is occurring. It is more applicable to report peak values.

Measuring the peak external knee flexion moment allows researchers to determine whether individuals are minimizing quadriceps contraction. Therefore, for the purpose of this investigation, it is important to determine whether overweight and obese young adults are already avoiding a larger peak external knee flexion torque. It is also important to monitor how successful gait retraining will be at increasing peak external knee flexion torque in young adults with stiff knee gait.

Peak Knee Adduction Angle

The peak knee adduction angle during gait indicates frontal plane dynamic alignment. It can provide an indication of the load distribution going across the knee. An individual with increased knee adduction will likely have an increase in load bearing on



(a) (b)

Figure 2-3: Frontal plane knee alignment. a) Normal, b) Excessive knee adduction.

the medial compartment compared to a normally aligned individual (Figure 2-3). When increased knee adduction is observed there is an increase in load and pressure on the areas of contact in the medial compartment. The majority of individuals with knee osteoarthritis exhibit increased adduction of the knee during gait (Astephen and Deluzio 2005).

There is a paucity of research investigating the relationship between the dynamic knee adduction angle and knee osteoarthritis. One investigation (Astephen and Deluzio 2005) developed a multidimensional model to account for differences in gait in those with osteoarthritis compared to healthy individuals. They found that one of the most discriminatory factors in gait was a larger dynamic knee adduction angle in those with osteoarthritis. Lynn et al. (Lynn, Reid et al. 2007) found a positive relationship between the frontal plane knee angle and the development of osteoarthritis. They completed a longitudinal investigation including the collection of gait analysis, completion of the WOMAC questionnaire, and radiographic evaluation on healthy adults. Follow up data collection occurred a mean of 7.5 years later. Two of the 28 participants had radiographic and symptomatic evidence of osteoarthritis one in the medial compartment, the other in the lateral compartment. The knee adduction angle changed over time in the participant with medial compartment osteoarthritis. They had a neutral alignment at the first visit, but at the second visit a marked knee adduction alignment. The remaining participants had an increase in radiographic evidence of osteoarthritis, measured using the Scott scoring system. Since they were asymptomatic, and therefore considered healthy, they were used as a control group. The control participants had an overall slight knee abduction alignment at both visits. The results of this study are important in that it was a longitudinal investigation of osteoarthritis development and progression. It was, however, limited by the fact that there was only one individual who developed medial compartment osteoarthritis and could be studied. However, the relationship between peak knee adduction angle during gait is important to monitor. In the current study it will provide an indication of how individuals may alter their gait in response to excess weight.

External Peak Knee Adduction Moment

The external peak knee adduction moment is dependent on the location of the ground reaction force in relation to the knee (Figure 2-4). The increase in knee adduction

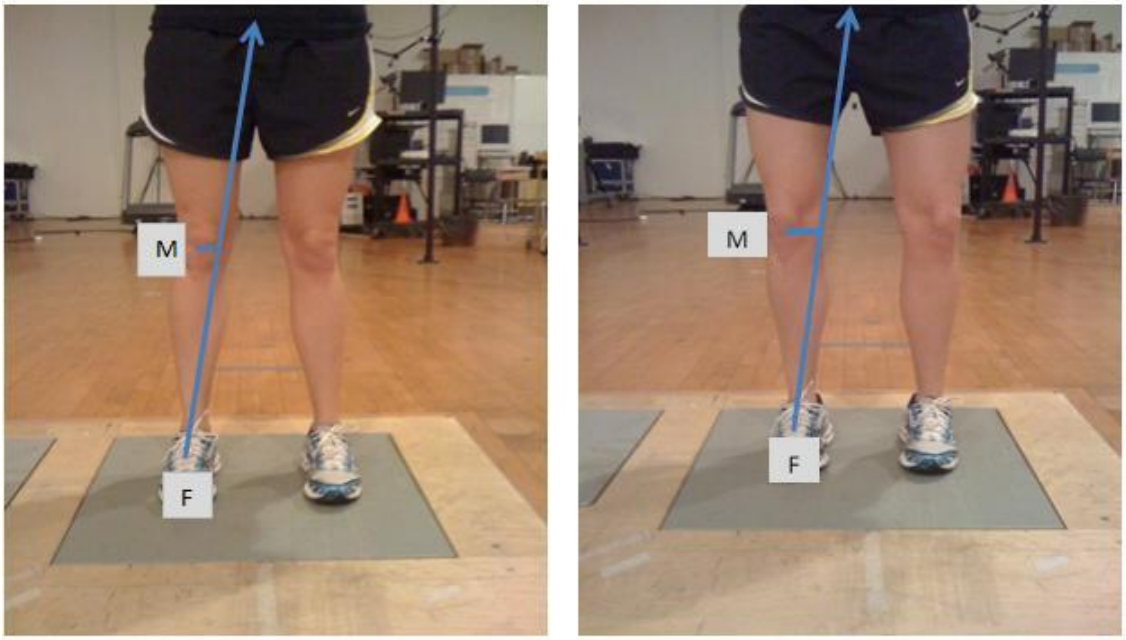


Figure 2-4: Representation of external knee adduction moment (M) and ground reaction force vector (F) in: a) normally aligned knee, b) alignment with greater knee adduction, creating a larger external knee adduction moment.

angle, typically seen in participants with medial compartment knee osteoarthritis, may move the location of this vector more medially, thus increasing the knee adduction moment.

Previous research supports the hypothesis that increased risk of development and progression of osteoarthritis is related to increased peak knee adduction moment (Schipplein and Andriacchi 1991; Kaufman, Hughes et al. 2001; Baliunas, Hurwitz et al. 2002; Mündermann, Dyrby et al. 2005; Lynn, Reid et al. 2007; McKean, Landry et al. 2007). Additional insights have been provided by several studies. Mundermann et al.

(Mündermann, Dyrby et al. 2005) also observed greater peak knee adduction moments yet also investigated the impact of osteoarthritis severity. They observed that participants with more severe osteoarthritis had greater peak knee adduction moments than those with less severe osteoarthritis. This suggests that peak knee adduction moment can be used to discriminate both the existence and severity of osteoarthritis. McKean et al. (McKean, Landry et al. 2007) compared walking gait in males and females both with and without osteoarthritis. They found that there was a significant interaction effect between gender and disease in the peak knee adduction moment. Further analysis revealed that men with osteoarthritis walked with knee moments similar to that of healthy participants. Conversely, women had greater peak knee adduction moment when osteoarthritis was present. This gender effect was limited to participants with osteoarthritis, as healthy men and women exhibited similar walking gait. Lastly, Baliunas et al. (Baliunas, Hurwitz et al. 2002) investigated the impact of walking velocity on peak external knee adduction moment. Investigators analyzed trials for each subject that were near the same walking velocity. Yet they still observed a higher peak external knee adduction moment in adults with osteoarthritis compared to healthy controls.

Astephen and Deluzio (Astephen and Deluzio 2005) compared gait between healthy control participants and participants with osteoarthritis using a multidimensional model. They determined that these groups could be discriminated with an error less than 6% using 12 features of gait. These features included the knee adduction moment, the lateral-medial knee joint force, the stance time and velocity. The most discriminating factor was described as a "stance phase, frontal plane loading and alignment factor", which included lateral-medial knee joint force, knee adduction moment, stance time, internal rotation moment of the knee, static frontal plane alignment, velocity and the standing knee flexion angle. This investigation provided support for the hypothesis that peak knee adduction moment is related to osteoarthritis.

Similarly, Schipplein and Andriacchi (Schipplein and Andriacchi 1991) reported that participants who had a static alignment with greater knee adduction walked with a greater knee adduction moment than healthy controls. They confirmed radiographically that none of the participants had more than moderately severe medial compartment osteoarthritis and no indication of lateral compartment osteoarthritis. As participants did not have osteoarthritis, it is implied that the greater knee adduction moment is perhaps related to the static knee adduction angle. Although, since the inclusion criterion was to have no more than moderate osteoarthritis, it is possible that some of the participants had mild or moderate osteoarthritis that could have led to the change in knee adduction moment. Therefore, caution must be used in interpreting these results.

One longitudinal study (Lynn, Reid et al. 2007) has supported the hypothesis of a causal relationship between knee adduction moment and the development of osteoarthritis. This study observed that when following up with participants, one individual developed medial compartment osteoarthritis. In baseline testing this individual had a larger adduction moment than control participants. The differences in the loading variables prior to the development of osteoarthritis suggest that changes in the adduction moment may initiate osteoarthritis and are not just a symptom of the disease.

Evidence that increased peak adduction moment indicates greater loading on the medial compartment of the knee was provided by Hurwitz et al. (Hurwitz, Sumner et al. 1998). They completed a gait analysis and measure of bone mineral content with dual energy x-ray absorptiometry on 26 healthy participants. Linear regression indicated that a greater peak external knee adduction moment was the best predictor of increased medial compartment bone mineral density compared to lateral compartment bone mineral density. According to Wolff's law, bone remodels based on the stresses applied. Therefore, an increase in the bone mineral density in a region indicates a greater load on that bone. Thus the greater peak external knee adduction moment increases the stress on the medial compartment of the knee.

As one of the most commonly cited predictors of osteoarthritis development and progression, the peak external knee adduction moment is important to measure. When investigating risk of disease development in certain populations, such as overweight and obese young adults, the peak external knee adduction moment provides valuable information. Similarly, tracking peak external knee adduction moment over a training period can provide feedback on the success of a gait retraining program.

Gait Velocity and Osteoarthritis

Adults with osteoarthritis of the knee walk at a slower velocity than healthy individuals (Kaufman, Hughes et al. 2001; Al-Zahrani and Bakheit 2002; McKean, Landry et al. 2007). There was no difference seen between moderate and severe osteoarthritis groups in their self-selected walking velocity (1.03 m/s, 1.13 m/s) (Zeni and Higginson 2009). However, the control group had a faster velocity (1.22 m/s) than either group. This suggests that walking speed cannot be used to discern severity of osteoarthritis, but only its existence. Al-Zahrani and Bakheit (Al-Zahrani and Bakheit 2002) reported the self-selected walking velocity in their control group as 1.17 m/s and 0.55 m/s in the osteoarthritis group. Lynn and colleagues (Lynn, Reid et al. 2007) found that participants who develop osteoarthritis decreased their self-selected walking velocity by an average of 36% over a period of between five and eleven years. Individuals who did not develop osteoarthritis were able to maintain their walking velocity over the same follow up period. This supported the hypothesis that a decrease in preferred walking velocity was a response to the osteoarthritis.

This issue of changes in walking velocity has led some researchers to question whether differences observed in gait, in individuals with osteoarthritis versus control participants, are simply a function of this change. The outcome of the following investigations provided conflicting results. Baliunas et al. (Baliunas, Hurwitz et al. 2002) accounted for this change by having participants walk at a variety of speeds. They selected trials from each participant to analyze so that the mean velocity of both groups was the same. They still found that peak external knee adduction moment was greater in the osteoarthritis group. However, they found no differences in midstance knee flexion angle or peak knee flexion moment between control and osteoarthritis groups. Bejek et al. (Bejek, Paróczai et al. 2006) had participants walk at four different velocities, and found differences in gait between controls and participants with osteoarthritis at each velocity. They observed a decrease in the maximum knee flexion angle as well as an increased minimum knee flexion angle in individuals with osteoarthritis. They also reported that participants with knee osteoarthritis walked with a faster cadence, decreased step length, wider base of support and a decrease in the percentage of stride spent in double support, especially at faster walking velocities.

More recently, results were published which conflict with those reported previously. Zeni and Higginson (Zeni and Higginson 2009) investigated the impact of walking velocity on gait in participants with knee osteoarthritis. They observed similar gait in participants with and without osteoarthritis when walking at a given speed. All participants, with varying severities of osteoarthritis, walked on the treadmill at their preferred walking speed, at 1.0 m/s, and at their fastest possible walking speed. They found that participants with severe osteoarthritis walked at a preferred velocity that was slower than the control participants. They also observed that all groups differed in their fastest walking velocity, with those with severe osteoarthritis walking the slowest and the controls walking the fastest. Differences between groups were seen in the peak knee flexion moment, loading rate, and knee flexion excursion at both preferred and fastest velocities. Yet at 1.0 m/s, only loading rate, which was lower in individuals with moderate osteoarthritis compared to the control group, was different between groups. This suggests that changes in gait are less a result of disease progression and more a result of the associated decrease in walking velocity. Contrary to that found in previous research (Kaufman, Hughes et al. 2001; Al-Zahrani and Bakheit 2002; Baliunas, Hurwitz et al. 2002; Bejek, Paróczai et al. 2006; McKean, Landry et al. 2007), peak knee adduction moment was not different between groups at any speed (Zeni and Higginson 2009). This investigation was completed with individuals walking on a treadmill. Therefore, it is possible that the effect of the treadmill altered loading as compared to overground walking.

To account for differences in preferred walking velocity, many studies choose to have participants walk at either their self-selected velocity or a given velocity. While walking at self-selected velocity allows for a more natural movement to be collected, differences in both kinetic and kinematic factors may be related to velocity. If walking velocity is constrained to a given velocity for both groups, gait may be altered in individuals who may be walking at a velocity that is either faster or slower than their preferred velocity. Therefore, comparisons of the biomechanics in healthy individuals and individuals with osteoarthritis must be made with caution. In order to account for this, the present study incorporated both preferred and constrained walking velocity (1.0 m/s) conditions.

Obesity and Osteoarthritis

Obesity prevalence in the United States has been increasing at alarming rates. Data from the National Health and Nutrition Examination Survey (Flegal, Carroll et al. 2002) showed that rates of obesity in adults doubled from 15% to 30% between 1980 and 2002. In 2004, 32% of adults in the United States were obese (Ogden, Carroll et al. 2006).

Obesity and Osteoarthritis

Leach and colleagues (Leach, Baumgard et al. 1973) first established the relationship between obesity and osteoarthritis by interviewing adults with osteoarthritis about their weight in past years. In obese women with osteoarthritis, 75% reported that by the age of 25 to 30 years they were heavy or fat. Nearly all of these women said that by the age of 30 they were overweight. There was a greater tendency for men to report more recent weight gain compared to women. When comparing the general population of women seen in an orthopedic clinic to women with osteoarthritis that were seen in the clinic, they observed 83% of women with osteoarthritis were obese whereas only 42% of the women seen in the clinic overall were obese.

More recently longitudinal and cross sectional studies have established that obesity is a risk factor for the development and progression of knee osteoarthritis (Felson, Zhang et al. 1997; Cooper, Snow et al. 2000; Niu, Zhang et al. 2009). This risk has been attributed to many factors. Some researchers suggest that it is related to gait biomechanics with increased loading of the knee due to increased body weight (Griffin and Guilak 2005; Browning and Kram 2007). Others suggest that it is related to metabolic changes in obese individuals that lead to the break-down of cartilage (Griffin and Guilak 2008; Sowers, Karvonen-Gutierrez et al. 2009). The current study focuses on biomechanical aspects of the risk of osteoarthritis, as they have the potential to be modified.

The Framingham study has followed cohorts of individuals over many years. They established that obesity was a significant risk factor for osteoarthritis. They found that body mass index was correlated with the development of osteoarthritis (Felson, Zhang et al. 1997). They found that for every 10-pound weight gain there was a 40% increase in the risk of developing osteoarthritis. However, when investigated by gender, the change in the risk of developing osteoarthritis as weight increases was only seen in females.

Cooper et al. (Cooper, Snow et al. 2000) conducted a five-year study of osteoarthritis progression in those with and without knee pain among 354 participants. In baseline measurements, there was a strong positive relationship between knee pain and radiographic Kellgren-Lawrence score. Progression of osteoarthritis over the five-year period could be predicted strongly based on obesity. There was a nine times greater risk of developing osteoarthritis in the top third of participants by BMI. Progression of existing osteoarthritis was also best predicted by increasing BMI (Cooper, Snow et al. 2000).

Niu et al. (Niu, Zhang et al. 2009) investigated development and progression of osteoarthritis in a 30-month investigation. Obese participants had a 3.2 times greater risk of developing osteoarthritis than normal weight participants. Greater than 50% of the participants who had knee osteoarthritis at baseline had progression of the disease over the 30 months. There was not, however, an overall effect of BMI on this progression. In participants with static valgus and neutral alignments, there was an increased risk of osteoarthritis progression with increasing BMI. This relationship did not exist in participants with varus alignment of the knee. While this investigation showed limited impact of obesity on osteoarthritis progression, it provided additional support for the relationship between the development of osteoarthritis and obesity.

The link between obesity and osteoarthritis becomes more important as rates of obesity continue to rise in the United States. Addressing osteoarthritis in young adults also becomes relevant in terms of prevention. Gait retraining and other prevention programs may be key to the prevention and delay of osteoarthritis.

Impact of Weight Loss on Osteoarthritis

Research has provided evidence that weight loss is associated with a decrease in the risk of osteoarthritis (Felson, Zhang et al. 1992). This further supports the link between obesity and osteoarthritis. As a part of the Framingham Study, weight was tracked over time and correlated with the development of osteoarthritis. Felson et al. (Felson, Zhang et al. 1992) reported BMI as a predictor of the development of osteoarthritis. Additionally, individuals who lost weight over the study period significantly decreased their risk of osteoarthritis development. Every two units of BMI lost led to over a 50% decrease in the odds of developing osteoarthritis. For example, an overweight woman, with a mass of 71 kg, height of 1.65 m and BMI of 26, would have to lose 5.5 kg for a two unit BMI loss. An obese man, with a mass of 103.7 kg, height of 1.82 m and BMI of 31, would have to lose 6.7 kg for the same two unit loss in BMI.

Messier et al. (Messier, Gutekunst et al. 2005) investigated the impact of weight loss on gait biomechanics in individuals with osteoarthritis. Participants performed baseline and post weight loss gait analyses. Gait analysis consisted of walking overground at self-selected velocity in laboratory shoes. Participants achieved a 2.6% loss in body mass compared to baseline. Messier et al. found that a 1 kg loss in body mass was associated with a 40.6 N decrease in knee compressive force. The same loss in body mass was also associated with a 0.496 Nm reduction in peak internal knee abduction moment. This supports the hypothesis that weight loss reduces biomechanical risk factors for osteoarthritis development and progression.

Obesity and Gait Biomechanics

Increased loading of the knee in obese individuals with normal activity has been hypothesized to increase the risk of osteoarthritis (Griffin and Guilak 2005). Messier (Messier 2009) suggested that alterations in priorities during walking may also alter loading. He suggested that obese individuals alter their main goal from forward progression to stability. The consequence of changing the goal of movement is that it may alter joint loading patterns, especially in the knee. There is some support for this in the literature (Browning and Kram 2007; Lai, Leung et al. 2008).

Browning and Kram (Browning and Kram 2007) investigated sagittal plane kinetics in obese and normal weight participants. Participants walked on a treadmill at a variety of walking velocities. Greater ground reaction forces were found in obese participants compared to normal weight participants at all walking velocities. Net muscle moments in the hip, knee and ankle joints were greater in obese participants compared to normal weight participants. This included the risk factors of osteoarthritis, peak external knee adduction moment and peak external knee flexion moment. The researchers did not normalize kinetics in this study. They suggested that normalizing disguises the significance of the loads that the joints actually received. Therefore, they reported that greater absolute loads are placed on the knee in obese people, which may increase joint loading and therefore, their risk of developing osteoarthritis. In normal weight adults normalization techniques account for the greater mass that contributes to shock attenuation. In obese individuals there is a greater proportion of fat mass, which does not contribute to shock attenuation. Therefore, in obese, normalizing disguises the actual loads that are being placed on the knee joint.

Lai et al. (Lai, Leung et al. 2008) also investigated gait in obese individuals. They observed greater peak knee adduction angles in obese individuals compared to normal weight individuals during both stance and swing phases. However, risk factors for osteoarthritis, knee joint moments were similar in the obese and normal weight groups. However, it is important to note that these moments were normalized to both body mass and height. As suggested by Browning and Kram (Browning and Kram 2007), this may disguise greater loading. The altered biomechanics observed in obese individuals are similar to changes known to be associated with the risk of osteoarthritis development and progression.

Artificially Added Mass and Risk of Osteoarthritis

Obese individuals have greater body mass than normal weight individuals of equivalent height. Therefore, attempts have been made to determine the influence of added mass on gait by artificially adding mass to normal weight individuals. By adding weights to the waist, thigh and foot, Browning et al. (Browning, Modica et al. 2007) investigated the impact of added mass and its distribution on gait. However, the addition of weight did not alter kinematics at the knee. There were also similar joint moments in the knee across all conditions. Joint moments appeared to be normalized to body mass. Therefore, changes seen in walking gait in obese individuals may not only be a consequence of added weight, but likely a combination of many factors including comfort and muscular strength. In particular, increases in metabolic rate were observed with increasing amounts of added weight. The more distally the weight was placed also led to greater metabolic costs.

Body Composition Measures

Body mass index is used by the Center of Disease Control to classify obesity. Body mass index is a ratio of an individual's weight in kilograms to their height in meters squared. While a larger body mass index has been associated with poorer quality of life and increased risk of disease (Sach, Barton et al. 2006), it provides no information on the composition of the body. Two individuals can have the same body mass index yet have very different body types. At the same height, an athlete and an overweight individual may weigh the same amount. Yet the athlete will have a greater percentage of lean mass compared to the overweight individual who will have a greater percentage of fat mass. According to body mass index, these individuals are similar, yet their health is likely to be quite different. Determining body composition can provide more information on an individual's health and fitness level.

Bioelectric Impedance Analysis

Bioelectrical impedance analysis (BIA) is a commonly used body composition method among clinicians and researchers. All commercial systems measure body composition through the impedance of a small current sent through the body. Some systems measure from the foot to the hand on one side of the body. Other systems measure foot to foot, providing impedance of the lower body from which the body composition of the entire body is predicted (Lazzer, Boirie et al. 2003). Lastly, there are systems that consist of hand and foot electrodes on both sides of the body allowing regional measurements to be made as well (Jebb, Cole et al. 2000). BIA allows for extremely fast measurements with little impact on the individual being measured. BIA allows for measurement to be done on larger individuals than dual energy x-ray absorptiometry (DEXA). Many BIA systems can measure individuals up to 440 pounds.

The theory behind BIA is that lean tissue contains greater amounts of water and therefore has lower impedance than fat mass. Therefore, it is extremely reliant on adequate hydration levels to provide accurate results. Individuals should prepare by abstaining from exercise 12 hours prior to testing, as well as abstaining from food and drink four hours prior to testing. In order to compensate for some differences in hydration levels of different groups, there are equations for body fat calculations that are specific to gender and physical activity level. In normal weight adults, body fat percentage in BIA is associated with a standard error of the estimate (SEE) between 3.5% and 5% (Ratamess 2010). SEE is a useful measure of test validity. SEE indicates the range that 68% of tests would provide for a given individual. When used to determine a method's validity it displays the range of error. A smaller SEE is indicative of a more reliable measure. Therefore, an SEE of 3.5% suggests a good measure according to Lohman (Lohman 1992). Further analyses have been completed to investigate variations in weight on the ability of BIA to accurately predict percent body fat and have found differing results. The key to valid measures using BIA is to maintain proper hydration when testing. Due to errors observed, BIA must be used with caution. Careful instruction must be provided to individuals prior to testing, so that results may provide accurate measures.

DEXA is an alternative method to measure body composition using low-levels of radiation. While hydrostatic weighing is still considered the gold standard in body composition measures, DEXA is often used as a criterion measure to compare BIA to. The accuracy of DEXA is limited in lean and obese populations (van der Ploeg, Withers et al. 2003; LaForgia, Dollman et al. 2009). While it has been considered a valid measure of body composition, slight variations in DEXA may lead to greater apparent errors in comparisons with BIA. Therefore, caution must be used in making comparisons between DEXA and BIA.

Nevertheless, research has supported the hypothesis that caution must be exercised when using BIA to determine body fat percentage. Shafer and colleagues (Shafer, Siders et al. 2009) compared percent body fat in normal weight, overweight and obese participants determined by a segmental BIA system and DEXA. Body fat percentage, predicted by segmental BIA, was overestimated among obese individuals compared to DEXA. They also observed that segmental BIA underestimated body fat percentage in normal weight individuals. Pateyjohns and colleagues (Pateyjohns, Brinkworth et al. 2006) also compared BIA and DEXA. They investigated the accuracy of three different types of BIA in overweight and obese men. Similar values were observed comparing DEXA measures to two different BIA instruments. Although statistically similar values were observed between DEXA and all methods, there was poor agreement between methods observed. This suggests that these methods do not have good agreement with DEXA and may not be very accurate measures in overweight and obese populations.

Further support for the observation that BIA underestimated body fat percentage compared to DEXA was provided by Neovius et al. (Neovius, Hemmingsson et al. 2006) and Boneva-Asiova and Boyanov. (Boneva-Asiova and Boyanov 2008). Neovius and colleagues (Neovius, Hemmingsson et al. 2006) found that as body fat percentage increased, so did the difference between BIA and DEXA measures. Boneva-Asiova and Boyanov (Boneva-Asiova and Boyanov 2008) looked at body composition in overweight, obese and severely obese individuals. They found that correlations revealed a non-significant trend for BIA to underestimate body fat percentage in overweight and obese individuals. In severely obese individuals this was reversed, with a tendency of BIA to overestimate body fat percentage. A considerable limitation of all of these investigations was the use of DEXA as a criterion measure.

Therefore, for the purpose of this study, segmental BIA provided the best body composition measure. With the inclusion of both overweight and obese individuals, it was important to consider the comfort of participants. Both DEXA and BIA have limitations in the accuracy of measures in overweight individuals (Neovius, Hemmingsson et al. 2006; Pateyjohns, Brinkworth et al. 2006; Boneva-Asiova and Boyanov 2008; LaForgia, Dollman et al. 2009). DEXA requires individuals to lie on a table within a given small area for tests that last approximately 12-15 minutes. For larger individuals, maintaining a crowded position on the table can be uncomfortable. DEXA also exposes participants to radiation, albeit at very low levels. Using BIA avoids both of these issues while also providing additional benefits of ease and comfort. BIA measures are completed in minutes and require only that participants wear lightweight shorts and shirt. In order to avoid unnecessary errors, all participants were instructed to maintain normal hydration prior to measurement and to abstain from exercise and food before testing. As with DEXA, segmental BIA provides body composition measures separately for the upper and lower body and right and left sides. This can provide additional information on the relationship between obesity and osteoarthritis that has not been reported previously.

Gait Retraining to Reduce Biomechanical Risk Factors for Osteoarthritis

Methods can be developed to alter biomechanical variables that can lead to osteoarthritis development and progression when these variables are identified. These methods can be used to reduce osteoarthritis risk. Rehabilitation following an injury or surgery often contains elements of relearning movement patterns, including gait. Further evolution of retraining extends to injury prevention rather than just rehabilitation. If people at risk of osteoarthritis development and progression can be taught to move with less damaging movement patterns, perhaps osteoarthritis can be avoided or delayed. Gait retraining may attempt to address sagittal or frontal plane changes.

A few research studies have investigated gait retraining for either injury rehabilitation or injury prevention (Decker, Torry et al. 2004; Fregly, Reinbolt et al. 2007; Fregly, D'Lima et al. 2009). These studies have investigated the capability of various retraining protocols to alter movement patterns and have observed positive results. Decker and colleagues (Decker, Torry et al. 2004) used two retraining protocols to alter gait in adults following anterior cruciate ligament reconstructive surgery. They focused on improving walking velocity, stride length and stride frequency as well as knee range of motion. By 12 weeks after surgery, all of their participants had regained a walking velocity equal to healthy participants. However, there were differences depending on the retraining protocol the subject followed. All participants were asked to walk at least three days per week for at least 20 to 30 minutes each day. One group was given a metronome and was asked to match their heel-strikes to the metronome. The metronome was set for an individually calculated stride frequency for each subject. The stride frequency was based on inputs including body weight, and thigh, shank and foot lengths. The other group was not given additional instructions for walking. The group of participants given the metronome had a more positive outcome than those who were not. While both groups achieved normal walking velocity, this was achieved in different ways. The group with the metronome increased both their stride frequency and stride length to increase walking velocity. The other group increased walking velocity through increases in stride frequency only, with their stride length remaining the same. The group with the metronome also regained a greater stance phase knee flexion angle range of motion. This suggests that the walking by itself was not enough to regain normal gait providing support for gait retraining.

Fregly and colleagues (Fregly, Reinbolt et al. 2007; Fregly, D'Lima et al. 2009) have conducted gait retraining specific to participants with osteoarthritis. The first investigation (Fregly, Reinbolt et al. 2007) was a case study of one individual whose gait retraining program was individualized. Initial gait analysis was performed and optimization predictions were calculated to determine target walking gait. The optimizations were intended to decrease peak knee adduction moment and promote a decreased hip adduction moment and increased knee extension moment. The subject attempted to train himself through qualitative analyses over a nine-month training period according to these individualized gait patterns. This was done by showing the individual graphs of the kinematic, kinetic center of pressure and ground reaction force curves both of his normal walking pattern and of the optimized walking pattern. The individual focused on increasing knee extension torque, decreasing hip adduction torque and increasing ankle inversion torque. Following the training period, the subject was successful in decreasing the peak knee adduction moment through improvements in the targeted kinetic changes.

Following this investigation, Fregly et al. (Fregly, D'Lima et al. 2009) conducted another case study analysis of an individual with an instrumented knee replacement, that measured contact force in the joint. In this study, two short-term, same day training sessions were conducted in an attempt to alter medial compartment knee loading. They trained the subject in two different conditions to 1) walk with a "medial thrust" pattern and 2) walk using a walking pole to disperse some of the ground reaction force. Training for the "medial thrust" gait included instructions to "bring his stance leg knee toward the midline of his body by increasing knee flexion slightly and internally rotating his hip slightly." They observed decreases in the force on the medial compartment of the knee in both new walking conditions. Greater decreases in force on the medial compartment were seen throughout gait when walking with the walking pole (15-45%) compared to the medial thrust gait (7-28%). This investigation indicated that in the short-term individuals are capable of altering their gait according to instructions. While walking with a pole may help offload the knee, it will not help restore a more normal gait. Therefore, focusing on gait rather than additional walking aids may benefit a patient's long-term outcome. If retraining programs are shown to be successful, individuals may be able to decrease risk of osteoarthritis development and progression.

These initial investigations provide optimistic outlooks for gait retraining. By establishing that individuals are capable of altering their gait patterns upon instruction, the importance of research to the utilization of gait retraining is increased. The factors that contribute to the success of gait retraining are not yet known. Further research is necessary to determine the ability of gait retraining to succeed in other populations such as older adults and those with mobility limitations due to osteoarthritis or obesity.

Motor Learning and Gait Retraining

In order to develop a successful gait retraining protocol, motor learning concepts must be considered carefully. Early studies in motor learning determined feedback is necessary for learning a new motor skill (Bilodeau and Bilodeau 1958; Bilodeau, Bilodeau et al. 1959). Further investigations showed that the frequency and type of feedback were also important aspects of learning (Nicholson and Schmidt 1991; Schmidt 1991; Vander Linden, Cauraugh et al. 1993; Weeks and Kordus 1998). Feedback can be categorized as intrinsic, or inherent, and extrinsic, or augmented. Frequent extrinsic feedback is important in the early stages of learning, but harmful as learning progresses because the learner begins to rely on receiving feedback (Nicholson and Schmidt 1991; Schmidt 1991). Therefore, it is important that as individuals learn a new task, they develop methods of receiving intrinsic feedback. Developing intrinsic feedback mechanisms allow them to monitor their own movements once extrinsic feedback is no longer provided.

Extrinsic and intrinsic feedback are both vital to motor learning. Extrinsic feedback is often provided in sports settings by coaches and may not be provided with motor learning principles in mind. In the research environment, extrinsic feedback may be provided as instructions from the researcher, information on the performance of the task, information on results of the task or even as visual feedback where the individual can see their performance during the task. Intrinsic feedback is something that the performer must have an opportunity to develop themselves. Intrinsic feedback is often related to proprioception, and may be developed by having the individual concentrate on what a correct performance feels like. Providing extrinsic feedback early in learning is important to enable this development.

The frequency at which feedback is given is also an important motor learning principle. Investigations of both sequential key pressing tasks and of sports skills, have shown that learning is inhibited when feedback is provided too often (Nicholson and Schmidt 1991; Vander Linden, Cauraugh et al. 1993; Weeks and Kordus 1998). Each of these investigations provided feedback to different groups at varying frequencies. Nicholson and Schmidt (Nicholson and Schmidt 1991) compared constant feedback with feedback on 50% of the trials. The groups who received 50% feedback either received more feedback early in practice and less later in practice, or received feedback on five trials and then no feedback for the next five trials. In retention tests of the task, both groups who received 50% feedback did significantly better than those who received constant feedback. A fourth group received feedback that was reverse-tapered, where they received more feedback late in practice. This was also detrimental to learning. This study suggests that the frequency and distribution of feedback is important in learning. Similar results were found by Weeks and Kordus (Weeks and Kordus 1998) who investigated a soccer throw-in task. Feedback was provided to one group 100% of the time and to another 33% of the time. The group with less frequent feedback was more successful in learning and retention of the task.

When developing a motor learning protocol, it is important to keep the principles of feedback in mind. It is important to provide enough feedback for the learner to develop a feel of the activity but not so much feedback that they begin to rely on it. This can be accomplished by developing a tapered feedback schedule that begins with frequent, but not continuous feedback which becomes less and less frequent through the program. It is important to incorporate these principles to assist the learner in developing intrinsic feedback. By intermittently asking the learner whether they think they were successful, you encourage them to think about how the movement feels and develop their own feedback system. The development of protocols that incorporate these principles increase the potential for successful learning of motor tasks.

Conclusion

The current treatment for end stage osteoarthritis is total knee arthroplasty. While this treatment has proven successful in treating pain, subjects do not return to a normal gait (Milner and O'Bryan 2008). A nonrandom pattern of progression of osteoarthritis following joint replacement has been documented with a higher likelihood of development of osteoarthritis in the contralateral limb (Shakoor, Block et al. 2002). Rates of total knee arthroplasty have risen recently in synchronization with rates of obesity (Mehrotra, Remington et al. 2005). The relationship between obesity and osteoarthritis has been established (Cooper, Snow et al. 2000). It has been suggested that the increased incidence of osteoarthritis among obese populations is simply a result of the increased loading on the joint from excess body weight. However, it may be that changes in the biomechanics of gait secondary to obesity are the factors that lead to increased risk of osteoarthritis. Research on gait kinetics and kinematics in subjects who are overweight or obese, but do not have osteoarthritis is sparse. Determining whether these individuals exhibit gait patterns that may increase the risk of development and progression of osteoarthritis, is imperative. Surgery and other treatments aim to treat pain associated with osteoarthritis, yet still result in future osteoarthritis progression. Therefore, it is important to determine who may be at greater risk of developing osteoarthritis at a stage where it can still be prevented. If these individuals can be identified and gait retraining programs are successful, osteoarthritis prevention programs can be implemented on a wide scale.

CHAPTER III

Materials and Methods

Study #1: Impact of Overweight and Obesity on Walking Gait in Young Adults

Participants

Thirty participants between the ages of 18 and 35 years were recruited from the University and surrounding community to participate in this study. Participants were excluded if they had a previous injury or surgery that may affect gait. They were also excluded if they were currently injured, or if they required the use of a walking aid or if they had a diagnosis of existing lower extremity osteoarthritis. They were also excluded if they answered "yes" to any questions on the physical activity readiness questionnaire (Appendix A) (Shepard, Thomas et al. 1991). Participants were recruited according to BMI to have ten participants in each of three groups: normal weight with a BMI < 25, overweight BMI from 25-30, and obese BMI >30 (Pi-Sunyer 1998). Participants were matched for gender, age, and height.

Power Analysis

Sample size was estimated using G*Power3 software (Faul, Erdfelder et al. 2007). Sample size was calculated for an alpha level of 0.05 and a beta of 0.80 based on data reported by Zeni et al. and Baliunas et al. (Baliunas, Hurwitz et al. 2002; Zeni and Higginson 2009). The sample size to detect differences between healthy individuals and individuals with osteoarthritis previously seen in the literature was calculated. Sample size was calculated for knee flexion excursion, peak external flexion moment, and peak external knee adduction moment. Sample size was not able to be calculated for peak knee adduction angle or peak knee flexion angle. Calculations for these variables were not possible due to a lack of reporting of mean and standard deviation values for these variables in the literature. A minimum of 6 participants per group was indicated. Therefore, inclusion of 10 participants per group should be adequate to detect significant differences between conditions.

Procedures

Participants provided written informed consent as approved by the University's Institutional Review Board (Appendix B). Height and weight were measured to confirm BMI and participants completed the physical activity readiness questionnaire. Prior to arrival for data collection, participants were instructed to maintain normal hydration, and to abstain from exercising 12 hours prior to coming to the lab and eating four hours prior to coming to the lab. Body composition was measured using segmental BIA (Tanita BC-418, Tanita Corporation of America, Inc., Arlington Heights, Ill). Waist, hip and thigh circumference were measured to provide additional body composition measures. To determine the subject's current knee pain and function they completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire (Roos, Roos et al. 1998) (Appendix C) which incorporates the Western Ontario and McMaster Universities Index of Osteoarthritis (WOMAC) (Bellamy, Buchnan et al. 1988).

Functional Tests

The six-minute walk and timed up and go tests were completed next. For the six-minute walk test participants walked around a 100 meter loop as many times as possible during the six-minute test, while the investigator counted the number of loops the participant finished. Upon completing the six minutes, the participant's ending location was marked and the investigator measured to the nearest end of the loop, to determine total distance travelled. Participants then returned to the lab where they were prepared for the timed up and go test. A chair with arm rests was set up three meters from a clear marking on the floor. Participants were asked to sit comfortably in the chair with their back resting against the back of the chair. They were told on cue, to get up from the chair and walk at a regular pace to the mark on the floor, turn around and walk back to the chair and sit back down. They were allowed a practice trial before actual testing. During the measured test, the investigator began timing on the cue to the participant, and stopped timing when the participant's back returned to resting on the back of the chair.

Gait Analysis

Participants changed into laboratory shorts, socks and footwear (BITE Footwear, Redmond, WA) and were instrumented with retro-reflective anatomical and tracking markers while standing in a standard position (McIlroy and Maki 1997). Anatomical markers were placed bilaterally on the iliac crest, greater trochanter, medial and lateral epicondyles, medial and lateral malleoli, and the first and fifth metatarsal heads. Four non-collinear tracking markers were attached to molded thermoplastic shells on the posterior pelvis, proximal posterior-lateral thighs and distal posterior shanks (Manal, McClay et al. 2000) and as three separate non-collinear markers on the heels (Figure 3-1).

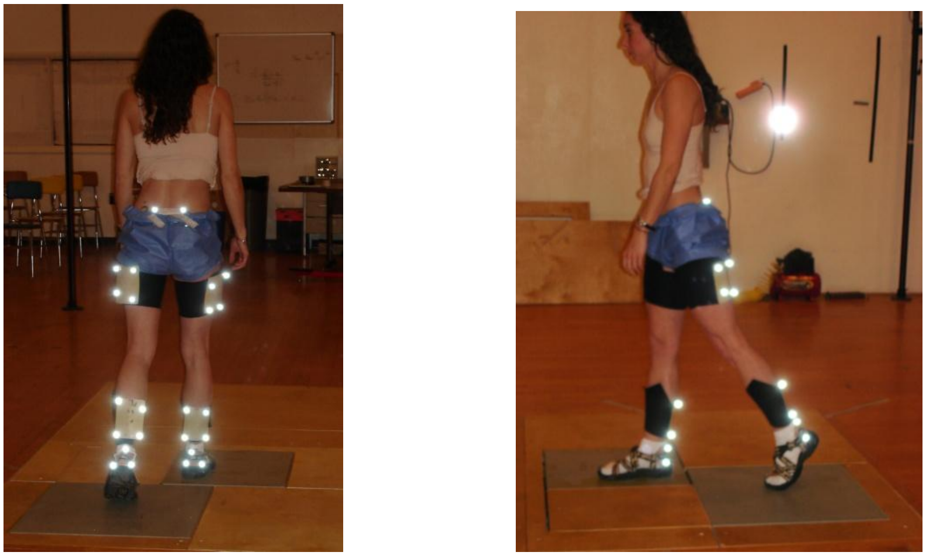
(a)

(b)

(c)

Figure 3-5: Static marker set for gait analysis: a) anterior view, b) sagittal view and c) posterior view

Kinematic data (120 Hz) and kinetic data (1200 Hz) were collected using a seven camera three-dimensional motion capture system (Vicon Inc., Centennial, CO) and two force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA). Initially, a standing trial was collected in the standard position. The anatomical markers were then removed and subjects wore only tracking markers (Figure 3-2). Participants walked overground across a ten meter walkway contacting a force platform with each foot in the center of the walkway. They walked at their self-selected velocity followed by walking at 1.0 m/s. Walking velocity was monitored using two photo-cells which were placed three meters apart on either side of the force platforms. Prior to data collection at each walking velocity, participants were given the opportunity to complete practice walking trials as needed. They were instructed to walk while looking straight ahead. The researcher than told the participants to adjust their starting position so that they would contact the force platforms without targeting. Five trials were collected at each walking velocity.



(a) (b)

Figure 3-6: Tracking marker set: a) posterior view and b) sagittal view.

Data Processing

Data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). Marker coordinate data were filtered using a 6 Hz low-pass recursive Butterworth filter. Force platform data were filtered using a 50 Hz low-pass recursive Butterworth filter. Heel contact and toe-off were identified during each trial using a threshold of 20 N for the vertical ground reaction force. Customized laboratory software (Matlab, The Mathworks Inc., Natick, MA) extracted the dependent variables from the stance phase data for each of the five trials in each condition. Peak knee flexion was the maximum flexion angle in the first half of the stance phase, during weight acceptance. Knee flexion excursion was the difference between the peak knee flexion angle and the knee flexion angle at footstrike. Peak external knee flexion moment was the maximum value within the stance phase. Peak knee adduction angle was the maximum value during stance phase. Peak external adduction moment was the first maximum value within the stance phase. Joint moments were normalized to subject's height and fat free body weight determined from BIA. For all participants, the mean of five steps was calculated for each variable in each condition. The group mean value for each variable in each condition was then determined.

Statistical Analysis

Two-way analysis of variance was used to compare each of the five dependent variables across the three groups and across the two walking velocities (SPSS Inc., Chicago, Ill). When a significant omnibus F-ratio was observed ($p < 0.05$), post-hoc pairwise comparisons were made to determine where the differences occurred. Descriptive statistics were also calculated for each of the five dependent variables.

Study #2: Gait Retraining in Younger Adults with Stiff-Knee Gait

Participants

Ten individuals between 18 and 35 years old were recruited to participate in this study. All participants were recruited from the university and the surrounding community. To be included in this study, participants had to walk with a stiff knee gait during a screening session. This was defined as having a knee flexion excursion that was at least one standard deviation less than the mean of the normal weight participants in the first study. To recruit participants who were eligible, advertisement focused on individuals who had „stiff or achy knees'. Participants were excluded if they had neurological impairments or were not able to follow instructions, if they were currently injured, or if they required the use of a walking aid. They were also excluded if they answered "yes" to any questions on the physical activity readiness questionnaire (Shepard, Thomas et al. 1991).

Power Analysis

Sample size was estimated using regression equations developed by Park and Schutz (Park and Schutz 1999). Sample size was calculated for an alpha level of 0.05 and a beta of 0.80 based on data reported by Zeni et al. and Kaufman et al. (Kaufman, Hughes et al. 2001; Zeni and Higginson 2009). The sample size to detect differences between healthy individuals and individuals with osteoarthritis previously seen in the literature was calculated. Sample size was calculated for knee flexion excursion, peak external flexion moment, and peak external knee adduction moment. Sample size was not calculated for peak knee adduction angle or peak knee flexion angle. Calculations for these variables were not possible due to a lack of reporting of mean and standard deviation values for these variables in the literature. A minimum of 6 participants was indicated. Therefore, inclusion of 10 participants should be adequate to detect significant differences between conditions.

Procedures

Participants provided written informed consent as approved by the university's institutional review board (Appendix D). Participants completed the physical activity readiness questionnaire. As long as they did not answer "yes" to any of the questions, they were given laboratory shorts, socks and footwear (BITE Footwear, Redmond, WA) to wear for the gait analysis. Upon enrollment, participants were taken for body composition measurement. Prior to arrival for data collection, participants were instructed to maintain normal hydration, and to abstain from exercising 12 hours prior to coming to the lab and eating four hours prior to coming to the lab. This was confirmed verbally prior to body composition measurement. Body composition was measured using segmental BIA (Tanita BC-418, Tanita Corporation of America, Inc., Arlington Heights, Ill).

Participants were then instrumented with retro-reflective anatomical and tracking markers while standing in a standard position (McIlroy and Maki 1997). Anatomical markers were placed bilaterally on the iliac crest, greater trochanter, medial and lateral epicondyles, medial and lateral malleoli, and the first and fifth metatarsal heads. Four non-collinear tracking markers were attached to molded thermoplastic shells on the posterior pelvis, proximal posterior-lateral thighs and distal posterior shanks (Manal, McClay et al. 2000) and as three separate non-collinear markers on the heels (Figure 3-1).

Initially, a standing trial was collected in the standard position. The anatomical markers were then removed and only tracker markers were left on the participant (Figure 3-2).

A baseline gait analysis was then conducted. Kinematic data (120 Hz) and kinetic data (1200 Hz) were collected using a seven camera three-dimensional motion capture system (Vicon Inc, Centennial, CO) and two force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA). Participants walked overground across a ten meter walkway contacting a force platform with each foot in the center of the walkway at their self-selected velocity. Walking velocity was monitored using two photo-cells which were placed three meters apart on either side of the force platforms. Five walking trials were completed after participants were allowed practice. During practice trials, investigators adjusted the participants starting position, so that they contacted the force platforms without targeting to do so. While participants rested, data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). The knee flexion excursion was determined for each trial by identifying the knee flexion angle at footstrike and the peak knee flexion in the first half of stance. The mean flexion excursion was calculated for the five walking trials. If the mean knee flexion excursion fell greater 10.3°, the subject's participation concluded. The range of knee flexion excursion came from data previously collected on normal subjects. The value that was one standard deviation less than the mean normal participants' knee flexion excursion was 10.3° and therefore used as the maximum value to classify stiff-knee gait. If participant's knee flexion excursion fell below this value, the participant was considered to have a stiff knee gait, and continued with the study protocol. If the participant exhibited stiff-knee gait in both knees, the knee that had the least knee flexion excursion was selected for retraining.

Prior to gait retraining, qualified participants completed the six-minute walk test. For the six-minute walk test participants walked around a 100 meter loop as many times as possible during the six-minute test, while the investigator counted the number of loops the participant finished. Upon completing the six minutes, the participant's ending location was marked and the investigator measured to the nearest end of the loop, to determine total distance travelled. Following the six-minute walk test participants were prepared for gait retraining.

Gait Retraining

For gait retraining a dual inclinometer was attached to the thigh and leg surrounding the knee joint using neoprene wraps and velcro. Using the digital display, the investigator gave verbal instructions based on the knee angle from the inclinometer. Retraining consisted of four blocks of ten single step practice trials followed by 100 walking steps. After each step participant were allowed to rest until they were ready for the next step. Feedback was tapered over the four blocks for single steps, while no feedback was provided during walking (Weeks and Kordus 1998). During the first practice block feedback was provided after every other trial. During the second block, feedback was provided after every third trial. During the third block, feedback was provided after the fifth and tenth steps. During the fourth block, feedback was only provided halfway through the steps. Feedback was provided during the single steps by informing the participants to increase or decrease knee flexion so that they were within range or to tell them that they were within the correct range. Participants were also asked to rate their own performance on one trial, which they were not given feedback for, in each practice block. This was done to encourage participants to think about how the movement felt, to assist in development of intrinsic feedback. Following each retraining block participants were reminded to think about their knee flexion as they walked the 100 steps around the lab.

Immediate and Short-Term Retention Tests

Immediately after the practice blocks were completed, three-dimensional gait analysis was completed, for five trials. Participants then completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire (Roos, Roos et al. 1998) (B), during a twenty minutes resting period. Following this break they completed a final gait analysis of five trials to assess retention of the modified gait pattern.

Data Processing

Data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). Marker coordinate data were filtered using a 6 Hz low-pass recursive Butterworth filter. Force platform data were filtered using a 50 Hz low-pass recursive Butterworth filter. Heel contact and toe-off were identified during each trial using a threshold of 20 N in the vertical ground reaction force. Customized laboratory software (Matlab, The Mathworks Inc., Natick, MA) extracted the dependent variables from the stance phase data for each of the five trials in each condition. Peak knee flexion was the maximum flexion angle in the first half of the stance phase, during weight acceptance. Knee flexion excursion was the difference between the peak knee flexion angle and the knee flexion angle at footstrike. Peak external knee flexion moment was the first maximum value within the stance phase. Peak knee adduction angle was the maximum value during stance phase. Peak external adduction moment was the maximum value within the stance phase. Joint moments were normalized to subject's height and fat free body weight. For all participants, the mean of five steps was calculated for each variable in each condition. The group mean value for each variable in each condition was then determined.

Statistical Analysis

Repeated measures ANOVA tests were completed for each dependent variable comparing within participants over time (SPSS Inc., Chicago, Ill). When a significant omnibus F-ratio was observed ($p < 0.05$), post-hoc pairwise comparisons were made as needed to determine where the differences occurred. Descriptive statistics were also calculated for each of the five dependent variables.

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PART 2

CHAPTER IV

The Influence of Body Mass Index on Biomechanical Risk Factors for Osteoarthritis during Walking

ABSTRACT

Obesity has been associated with both development and progression of knee osteoarthritis. Research on osteoarthritis has thus far focused on older adults. However, being overweight or obese from a young age is likely to decrease the age of onset for co-morbidities of obesity such as osteoarthritis. Therefore, the purpose of this study was to determine whether young adults who are overweight or obese exhibit biomechanical risk factors for osteoarthritis at either their preferred walking velocity or at 1 m/s. Thirty healthy adults between 18 and 35 years old were grouped according to body mass index: normal, overweight and obese. Three dimensional kinetics and kinematics were collected while participants walked overground at both velocities. Preferred walking velocity was slower in obese compared to normal weight individuals. Knee flexion excursion, peak knee flexion angle, peak external knee flexion moment, peak knee adduction angle and peak external knee adduction moment were determined. There were no differences in knee flexion excursion, peak knee flexion angle or peak knee flexion moment among groups. Obese participants walked with a significantly lower peak knee adduction angle than both overweight and normal participants and many obese individuals shifted towards knee abduction. Peak external knee adduction moment was similar among groups. All groups walked with smaller knee flexion excursion, peak knee flexion angle, peak knee flexion moment and peak knee adduction moment at 1 m/s compared to preferred walking velocity. Overweight and obese participants do not show differences from normal that would suggest an increased risk of osteoarthritis development due to gait biomechanics. Obese individuals may be walking slower and shifting towards knee abduction to maintain lower knee joint moments.

1. Introduction

Osteoarthritis is common in older adults, with 10% of adults over the age of 65 suffering from knee osteoarthritis [1]. Obesity has been highly correlated with development and progression of osteoarthritis [2]. Larger than normal body weight puts more stress on the knee cartilage and increases the rate of cartilage degeneration [3]. From 1960 to 1999 the rate of obesity in adults in the United States jumped from 13.4% to a staggering 30.9% [4]. A 2001 [5] investigation of disabled adults reported that the leading cause of disability was arthritis and rheumatism. The consequences of obesity are becoming ever more important as the obesity epidemic spreads among youth. Between 1999 and 2003 the percentage of overweight children under the age of 19 rose from 28.2% to 36.6%. The percentage of obese children rose from 13.9% to 17.1% [6]. Being overweight or obese from a young age is likely to decrease the age of onset for co-morbidities of obesity such as osteoarthritis. Therefore, it is important to understand the influence of overweight and obesity on risk factors for osteoarthritis in young adults.

The relationship between osteoarthritis and the biomechanics of gait has been researched extensively in older adults. Individuals with knee osteoarthritis walk with decreased knee flexion excursion [7-9], decreased peak knee flexion angle [8, 10], decreased peak external knee flexion moments [8], greater stance phase peak knee adduction angles [11], and greater peak external knee adduction moments [8, 10, 12-15], when compared to healthy individuals. Individuals with more severe osteoarthritis exhibit greater peak knee adduction moments than those with less severe osteoarthritis [14]. Longitudinal research has also suggested that healthy individuals with higher peak knee adduction moments are more likely to develop osteoarthritis [15]. There appears to be some overlap between the consequences of obesity on gait biomechanics and biomechanical risk factors for osteoarthritis [2, 15-17]. Greater peak knee adduction angles [18] have been observed in obese individuals compared to normal weight individuals. It has also been observed that obese individuals walk with less knee flexion in early stance than normal weight individuals [19]. The literature is inconclusive in regards to peak knee flexion moment and obesity. It has been reported that obese individuals have higher peak knee flexion moments than normal weight individuals [19]. However, there have also been investigations reporting that normal weight and obese participants had similar knee flexion moments [20].

Individuals with osteoarthritis walk at a slower preferred walking velocity than healthy individuals [8]. Changes in walking velocity have been associated with changes in gait in both normal weight and obese individuals [20]. Having participants walk at their preferred velocity provides a good indication of the individual's daily gait pattern. However, in order to observe the effect of body mass index alone on gait, a standardized walking velocity for all groups may provide additional insight.

Therefore, the purpose of this study was to determine whether young adults who are overweight or obese exhibit biomechanical risk factors for osteoarthritis during walking. Comparisons were made at both participants' preferred walking velocity and a standardized walking velocity. We hypothesized that, at both walking velocities, peak knee flexion angle, knee flexion excursion and external peak knee flexion moment during weight acceptance will decrease as body mass index increases from normal to overweight to obese in young adults. We also hypothesized that, at both walking velocities, peak knee adduction angle and external peak knee adduction moment will increase as body mass index increases from normal weight to overweight to obese in young adults.

2. Methods

2.1 Participant Details

Thirty participants (Table 4-1) between the ages of 18 and 35 years were recruited from the University and surrounding community to participate in this study. Participants were excluded if they had a previous injury or surgery that may affect gait. They were also excluded if they were currently injured, if they required the use of a walking aid or if they reported an existing diagnosis of lower extremity osteoarthritis. They were also excluded if they answered "yes" to any questions on the physical activity readiness questionnaire [21]. Participants were recruited according to body mass index (BMI) to have ten participants in each of three groups: normal weight (BMI less than 25), overweight (BMI from 25 to 29.9), and obese (BMI 30 or greater) [22]. Groups were balanced for gender.

2.2 Data Collection

Prior to commencing the study, procedures were approved by the University's Institutional Review Board. Participants provided written informed consent prior to their participation. Height and weight were measured to confirm BMI and participants completed the physical activity readiness questionnaire. Prior to arrival for data collection, participants were instructed to maintain normal hydration, and to abstain from exercising 12 hours prior to coming to the lab and eating four hours prior to coming to the lab. Body composition was measured using segmental bioelectrical impedance analysis (Tanita BC-418, Tanita Corporation of America, Inc., Arlington Heights, Ill). To determine the participant's current knee pain and function they completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire [23]. Participants also rated their current knee pain in each knee using a visual analog scale [24].

Participants completed functional activity tests consisting of the six-minute walk test [25] and timed up and go [26]. Participants prepared for gait analysis by changing into laboratory shorts, socks and footwear (BITE Footwear, Redmond, WA) and were instrumented with retro-reflective anatomical and tracking markers while standing in a standard position [27]. Anatomical markers were placed bilaterally on the iliac crest, greater trochanter, medial and lateral epicondyles, medial and lateral malleoli, and the first and fifth metatarsal heads. Four non-collinear tracking markers were attached to molded thermoplastic shells on the pelvis, thighs and shanks [28] and three separate non-collinear markers on the heels.

Kinematic data (120 Hz) and kinetic data (1200 Hz) were collected using a seven camera three-dimensional motion capture system (Vicon Inc., Centennial, CO) synchronized with two force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA). Initially, a standing trial was collected in a standard position [27]. The anatomical markers were then removed. Participants walked overground across a ten-meter walkway contacting two force platforms in the center of the walkway, one with each foot. They walked at their self-selected velocity for a total of five good trials. This was followed by walking at a standardized walking velocity, within five percent of 1.0 m/s, for five acceptable trials. A good trial consisted of the participant contacting both force platforms without appearing to alter their stride. Walking velocity was monitored using two photo-cells which were placed three meters apart on either side of the force platforms and attached to a timer. Prior to data collection at each walking velocity, participants completed practice walking trials as needed to contact the force platforms without targeting.

2.3 Data Analysis

Sample size was estimated using G*Power3 software [29] based on an alpha level of 0.05 and a beta of 0.80. Sample size calculations were based on data for knee flexion excursion and knee flexion moment reported by Zeni et al. and knee adduction moment reported by Baliunas et al. [7, 13]. The sample size to detect differences between healthy individuals and individuals with osteoarthritis reported previously in the literature was calculated. A minimum of six participants per group was indicated. Therefore, inclusion of ten participants per group should be adequate to detect significant differences among conditions.

Data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). Marker coordinate data were filtered using a 6 Hz low-pass recursive Butterworth filter. Force platform data were filtered using a 50 Hz low-pass recursive Butterworth filter. Heel contact and toe-off were identified during each trial using a threshold of 20 N for the vertical ground reaction force. Customized laboratory software (Matlab, The Mathworks Inc., Natick, MA) extracted the dependent variables from the stance phase data for each of the five trials in each condition. Weight acceptance was defined as the first half of the stance phase. Knee flexion excursion was the difference between the peak knee flexion angle during weight acceptance and the knee flexion angle at footstrike. Peak knee flexion angle, peak external knee flexion moment, peak knee adduction angle, and peak external knee adduction moment were the maximum value of each during weight acceptance. Joint moments were normalized to participant's height and fat free body weight determined from BIA. For all participants, the mean of five trials was calculated for each variable in each condition. The group mean value for each variable in each condition was then determined.

Descriptive statistics were calculated for each of the five dependent variables. Two-way mixed analysis of variance (group by velocity) was used to compare each of the five dependent variables across the three groups and two walking velocities (SPSS Inc., Chicago, Ill), with walking velocity as a repeated measure. When a significant omnibus F-ratio was observed ($p < 0.05$), post-hoc pairwise comparisons were made to determine where the differences occurred.

3. Results

Descriptive statistics for group demographics are included in Table 4-1. The groups were similar in age and height. As expected, the obese group had greater body mass index, greater body fat percentage, slower preferred walking velocity and reduced performance on functional activity tests than the normal group (Table 4-2). The overweight group fell between the obese and normal groups for most of these variables, but was similar to the normal group in the functional tests. The groups were similar in that they did not report knee pain or symptoms according to the visual analog pain scale or the KOOS.

Sagittal plane variables were similar among the normal weight, overweight and obese groups, with no interaction between velocity and group (Table 4-3). However, there were differences due to walking velocity. Knee flexion excursion was greater at preferred walking velocity compared to the 1 m/s condition ($p < 0.0001$). Knee flexion excursion was similar among all groups ($p= 0.886$), with no interaction ($p = 0.363$). Peak knee flexion angle was significantly greater at preferred walking velocity than when participants walked at 1 m/s ($p < 0.0001$). Peak knee flexion angle was similar among groups ($p = 0.908$), with no interaction ($p = 0.061$). Peak external knee flexion moment was greater when participants walked at their preferred walking velocity than when they walked at 1 m/s ($p < 0.0001$). Peak external knee flexion moment was similar among groups (p = 0.865) with no velocity by group interaction (p = 0.628).

The differences in frontal plane variables across groups and velocities varied (Table 4-3). Peak knee adduction angle was similar between walking velocities (p = 0.351), but significantly different among groups (p = 0.004). The obese group had a lower peak knee adduction angle than the normal (p = 0.005) and overweight groups (p = 0.017) which were not different from one another (p = 0.858). There was no significant interaction between group and velocity for peak knee adduction angle (p = 0.690). Peak external knee adduction moment was greater during preferred walking velocity compared to 1 m/s (p = 0.018) but was similar among groups (p = 0.104). There was no significant group by velocity interaction for peak external knee adduction moment (p = 0.388).

4. Discussion

The purpose of this study was to determine whether young adults who are overweight or obese exhibit biomechanical risk factors for osteoarthritis compared to normal weight young adults during walking. The gait of normal, overweight and obese individuals was similar, except for peak knee adduction angle, at both the participants' preferred walking velocity and at 1 m/s. Walking velocity had a significant effect on the gait of all groups.

Participants in all three groups reported having asymptomatic knees. The KOOS scores of all three groups were similar to, or higher than, the score of 477 reported previously in healthy adults [7]. A larger KOOS score indicates higher function and less pain. All three groups also reported very low knee pain scores. Despite a lack of symptoms, the obese group had lower functional ability than the normal weight group. They were unable to cover as much distance in the six-minute walk test, and had a slower timed-up-and-go time than the normal group.

Sagittal plane variables were similar among normal, overweight and obese groups. This is similar to findings reported by Browning and Kram and Lai et al. [18, 20]. Lai et al. [18] reported no differences in sagittal plane kinematics between obese and normal weight adults. This included knee angles during loading response, at mid-stance, during terminal stance and overall maximum. Browning and Kram [20] also observed similar values between obese and normal participants for their sagittal plane variable of interest, midstance peak knee flexion. From data reported graphically we were also able to determine that the magnitude of differences between their groups for knee flexion excursion and peak knee flexion during weight acceptance were similar to those we observed. Contrary to these findings, DeVita and Hortobagyi [19] observed a significantly higher peak knee flexion during weight acceptance in normal adults compared to obese adults (25.2° and 17.3° respectively) walking at 1.5m/s. Peak knee flexion moment was also similar among groups. Browning and Kram [20] reported similarities between obese and normal weight groups for both absolute moments as well as moments normalized to height and body mass. DeVita and Hortobagyi [19] reported differing relationships between normal weight and obese groups for knee flexion moment, absolute joint moments were similar, but when normalized to body mass, normal weight participants had a peak knee flexion torque that was nearly twice that of the obese group. Moments in the current study were normalized to fat free weight measured during bioelectrical impedance analysis to determine the relationship between lean mass and joint moment.

There is limited literature reporting the impact of obesity on lower extremity frontal plane kinematics. Lai et al. [18] observed higher peak knee adduction angles in obese compared to normal weight individuals. As obese individuals are more likely to develop osteoarthritis than normal weight individuals [2], we hypothesized that they would have similar kinematics to individuals with osteoarthritis, primarily greater peak knee adduction angle [11]. Conversely, in the current study, the obese group had a smaller peak knee adduction angle than the overweight and normal weight adults. As this was a surprising result, we further investigated the characteristics of the obese group. A portion of the obese group not only had low peak knee adduction angles, but also had larger peak knee abduction angles than the other participants in the study, suggesting a shift towards knee abduction. Similar results were also observed in an investigation of overweight children [30]. McMillan et al. [30] reported that healthy weight children had a higher knee adduction angle than overweight children. They also reported a shift towards knee abduction in overweight children. It has been reported that an increased knee adduction angle is associated with greater knee adduction moments and increased medial compartment loading [31]. Obese participants in the current study may have shifted towards knee abduction in order to maintain lower knee adduction moments. This type of neuromuscular adaptation was initially suggested [19] as a means for obese individuals to reduce peak joint moments. In fact, peak knee adduction moment was similar among groups in the current study. Similarly, normal and obese adults in the Lai et al. [18] investigation also had similar peak knee adduction moments, normalized to the individuals' body mass and height. This provides further support for the hypothesis that obese individuals altered their frontal plane kinematics in order to maintain peak knee joint moments comparable to normal despite greater body weight.

While knee flexion excursion, peak knee flexion angle and peak external knee flexion moment were similar among groups, they were influenced by walking velocity. Specifically, the slower 1 m/s condition led to a stiff-knee gait characterized by decreased peak knee flexion angle and knee flexion excursion compared to preferred walking velocity. It has been demonstrated previously that walking velocity alters sagittal plane kinematics and kinetics [7, 20, 32]. As walking velocity decreases, associated decreases in knee flexion excursion [7], peak knee flexion angle [32], and peak knee flexion moment [7, 20, 32] have been observed. In the frontal plane the influence of walking velocity varied. Peak knee adduction angle was similar between walking velocities. This was different from a previous study which observed increases in peak knee adduction angle with increasing walking velocity [7]. Peak knee adduction moment was lower at 1 m/s than at preferred walking velocity. This is similar to reports that have observed lower peak knee adduction moments at slower walking velocities in adults [7]. Furthermore, knee joint moments were not higher in obese individuals compared to normal weight individuals at preferred walking velocity, despite increased body weight. However, it is worth noting that the preferred walking velocity of obese individuals was slower than that of normal weight participants. Obese individuals may have selected a slower preferred walking velocity than normal weight individuals to reduce the magnitude of peak joint moments. A limitation of the current study was that participants were asked only to walk at their preferred velocity or slower. Therefore, it is not known how obese individuals would respond if they were asked to walk at the same velocity as the normal group.

While walking biomechanics were similar among groups overall, there was, of course, some variability within the groups. Some individuals had gait characteristics suggesting an increased risk of knee osteoarthritis, but these differences were lost at the group level. For example, seven of the 30 participants exhibited at least two of the five variables associated with osteoarthritis risk (two in the normal group, three were overweight and two were obese). This suggests that there is a sub-group of individuals who may already be at increased risk of developing knee osteoarthritis due to their gait biomechanics. Future efforts should aim to identify this sub-group for intervention to reduce their risk of developing osteoarthritis. Interventions may include weight loss to reduce loading or gait retraining to alter walking biomechanics.

5. Conclusion

The similarities in gait variables between the normal, overweight and obese groups suggest that obese young adults overall do not exhibit biomechanical risk factors of osteoarthritis development compared to normal weight young adults. The decreased magnitude of all variables, with the exception of peak knee adduction angle, from preferred walking velocity to 1 m/s, reinforces the influence velocity has on gait parameters. With a slower preferred walking velocity, obese participants may be decreasing velocity to protect themselves from higher frontal plane knee joint moments.

Table 4-1: Participant Demographics (mean ± standard deviation)

Group	Normal	Overweight	Obese
Age (years)	23.0 ± 4.1	22.6 ± 1.3	23.8 ± 5.6
Height (m)	1.74 ± 0.08	1.77 ± 0.09	1.72 ± 0.10
Mass (kg)	67.6 ± 10.0	84.7 ± 10.0	101.85 ± 13.57
BMI (kg/m^2)	22.4 ±2.1	26.9 ± 1.3	34.4 ± 3.9
Body Fat %	17.1 ± 8.6	26.7 ± 7.8	33. 0 ± 10.5

BMI: Body mass index.

Table 4-2: Functional activity characteristics (mean ± standard deviation)

Group	Normal	Overweight	Obese
Preferred Walking Velocity (m/s)	1.44 ± 0.16	1.35 ± 0.13	1.21 ± 0.13
6 Minute Walk (m)	700.1 ± 80.7	670.1 ± 52.0	618.1 ± 57.9
Timed Up and Go (s)	7.30 ± 0.68	7.87 ± 1.21	8.47 ± 1.18
Visual Analog Scale	0.0 ± 0.0	0.2 ± 0.3	0.0 ± 0.0
KOOS	474.7 ± 35.0	479.3 ± 39.0	491.59 ±13.32

Table 4-3: Sagittal and frontal plane variables of interest (mean ± standard deviation)

	Normal		Overweight		Obese	
	PWV	1m/s	PWV	1m/s	PWV	1m/s
Knee Flexion Excursion (°)*	14.0 ± 3.7	9.3 ± 4.6	14.1 ± 5.3	11.0 ± 4.5	13.6 ± 3.7	10.5 ± 3.0
Peak Knee Flexion Angle (°)*	18.8 ± 6.0	11.6 ± 6.9	17.0 ± 7.7	13.6 ± 8.6	16.1 ± 5.5	12.1 ± 8.6
External Knee Flexion Moment (Nm/ffw*ht)*	0.052 ± 0.013	0.025 ± 0.016	0.054 ± 0.029	0.034 ± 0.022	0.052 ± 0.032	0.034 ± 0.022
Knee Adduction Angle (°)^	6.2 ± 1.7	6.1 ± 1.1	5.3 ± 1.9	5.9 ± 2.3	2.4 ± 2.3	2.9 ± 4.1
External Knee Adduction Moment (Nm/ffw*ht)*	-0.051 ± 0.014	-0.041 ± 0.006	-0.055 ± 0.011	-0.052 ± 0.009	-0.044 ± 0.017	-0.040 ± 0.017

ffw: Fat-free weight; ht: Height

*PWV was significantly different from 1 m/s ($p < 0.05$)

^Obese group was significantly different from normal and overweight groups

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PART 3

CHAPTER V

Performance Effects of Gait Instruction on Biomechanical Risk Factors for Knee Osteoarthritis

Abstract

The increased incidence of osteoarthritis leads to a greater importance of research to investigate methods of preventing its development and progression. Biomechanical risk factors have been identified in the development of osteoarthritis. If these biomechanics can be altered, disease progression may be able to be prevented. Gait retraining is used in rehabilitation settings and may be able to correct abnormal gait. Therefore, the purpose of this study was to determine whether young adults could perform a modified walking pattern in which biomechanical risk factors for osteoarthritis are reduced during a single session of gait instruction. Nine young adults who exhibited stiff-knee gait were included in this investigation. Baseline gait analyses were performed prior to gait instruction period. After instruction an immediate gait analysis was collected followed by a short-term retention test 20 minutes later. Individuals were able to increase knee flexion excursion and peak knee flexion angle in the trained knee and were able to maintain this change. Individuals were able to maintain the healthy peak knee adduction angle and peak knee adduction moment they exhibited at baseline, after instruction. Similarly, they were able to maintain healthy gait in the untrained knee. This investigation suggests that this method of gait instruction may be successful in altering sagittal plane gait, while maintaining healthy gait in the frontal plane and the contralateral knee. This research suggests that young adults with stiff knee gait have the ability to perform normal knee kinematics.

1. Introduction

Osteoarthritis is a major problem in the United States and has been reported to be the leading self-reported cause of disability in adults (CDC, 2001). Walking is the most common daily activity affected by osteoarthritis. Several biomechanical risk factors associated with osteoarthritis development and progression have been identified during walking. Peak knee adduction angle, peak knee adduction moment, knee flexion excursion and knee flexion moment during stance differ between age-matched adults with and without knee osteoarthritis (Baliunas, et al., 2002; Kaufman, et al., 2001; McKean, et al., 2007). Specifically, adults with knee osteoarthritis exhibit greater stance phase peak knee adduction angles (Astephen & Deluzio, 2005), greater peak external knee adduction moments (Baliunas, et al., 2002; Kaufman, et al., 2001; Lynn, et al., 2007; McKean, et al., 2007; Mündermann, et al., 2005; Schipplein & Andriacchi, 1991), decreased knee flexion excursion (Kaufman, et al., 2001; Zeni & Higginson, 2009a, 2009b) and decreased peak external knee flexion moments (Kaufman, et al., 2001) than healthy adults.

If these risk factors can be modified in young adults who exhibit them, perhaps to the onset of osteoarthritis can be prevented or delayed. Several studies provides support for the ability of individuals with increased knee osteoarthritis risk to change the way they walk with various forms of instruction (Barrios, et al., In Press; Fregly, et al., 2009; Fregly, et al., 2007; Mündermann, et al., 2008).

Although investigations of gait retraining for risk of knee osteoarthritis have utilized different methods, they have generally proven successful in altering gait performance, at least in the short-term. Fregly et al. (Fregly, et al., 2007) used gait analysis and optimization models to create a target walking pattern specific to the participant of their case study. By having him focus on increasing the knee flexion moment and decreasing the hip adduction moment, the participant was able to decrease the peak knee adduction moment by 39%. Barrios and colleagues (Barrios, et al., In Press) provided concurrent visual feedback using real-time gait analysis and faded verbal feedback to participants who walked on a treadmill. At a one month follow-up, participants had decreased their knee adduction angle by 2° and knee adduction moment by 19% when walking with the modified pattern. In a case study by Fregly and colleagues (Fregly, et al., 2009) an individual was asked to increase knee flexion and keep his leg in close to his body. They observed decreases in the force on the medial compartment of the knee (between 7-28%) when performing the modified gait. Mundermann et al. (Mündermann, et al., 2008) found that individuals decreased knee adduction moments by 65% after increasing trunk sway. Therefore, our gait retraining approach may benefit young adults who exhibit risk factors of knee osteoarthritis.

Previous investigations have not reported how their retraining altered the kinetics and kinematics of the contralateral limb. The body is a linked chain, therefore, altering gait of one side of the body is likely to alter gait on the contralateral side. Thus this should be monitored during investigations.

The structure of gait retraining is important in relation to motor performance and learning. Following a systematic review of gait retraining studies, Tate and Milner (Tate & Milner, 2010) recommended that motor learning concepts be incorporated into gait retraining protocols. They suggest this will enhance learning through feedback without the negative effects of providing constant feedback (Tate & Milner, 2010). It is well established in the motor learning literature that the frequency and the type and frequency of feedback are important aspects of learning a new skill (Nicholson & Schmidt, 1991; Schmidt, 1991; Vander Linden, et al., 1993; Weeks & Kordus, 1998). Feedback can be categorized as either extrinsic or intrinsic. During gait instruction extrinsic feedback is that which the study provides the participant. Frequent extrinsic feedback is important in the early stages of learning, but harmful as learning progresses because the learner begins to rely on receiving feedback (Nicholson & Schmidt, 1991; Schmidt, 1991). Intrinsic feedback comes from an individual's sensory information that is available after performing a movement (Van Vliet & Wulf, 2006). Developing intrinsic feedback will allow participants to self-regulate their knee flexion during gait when extrinsic feedback is not provided. Most Previous investigations of gait retraining addressing knee osteoarthritis have not explicitly incorporated motor learning principles, with the exception of Barrios et al. (Barrios, et al., In Press).

The purpose of this study was to determine whether young adults exhibiting a stiff knee gait could increase knee flexion excursion during a single session of gait instruction. A secondary aim of the study was to determine whether the instructions would also lead to changes in other biomechanical risk factors of osteoarthritis: peak knee flexion angle, peak knee flexion moment, peak knee adduction angle and peak knee adduction moment. We also aimed to determine whether gait instruction would lead to changes in the untrained knee. We investigated whether the variables differed between baseline, immediate retention and delayed retention time points.

2. Methods

2.1 Participants

Twenty-six individuals between 18 and 35 years old were recruited from the university and the surrounding community to participate in this study and brought in for screening. Participants were excluded if they had neurological impairments or were not able to follow instructions, if they were currently injured, or if they required the use of a walking aid. To be included in this study, participants had to walk with a stiff knee gait during the screening session. Nine individuals (three male, six female) qualified to continue in the study after the screening. The nine qualified individuals were 25.8 ± 4.3 years old. They were 1.71 ± 0.10 meters tall and had a mass of 82.61 ±12.48 kg.

2.2 Screening

Participants provided written informed consent as approved by the university's institutional review board. Participants completed the physical activity readiness questionnaire (Shepard, et al., 1991). If they answered "yes" to any of the questions their participation ended. Body composition was measured using segmental bioelectrical impedance analysis (Tanita BC-418, Tanita Corporation of America, Inc., Arlington Heights, Ill). Prior to arrival for data collection, participants were instructed to maintain normal hydration, and to abstain from exercising 12 hours prior to coming to the lab and eating four hours prior to coming to the lab. This was confirmed verbally prior to body composition measurement.

Participants were given laboratory shorts, socks and footwear (BITE Footwear, Redmond, WA) to change in to and were prepared for data collection. Participants were instrumented with retro-reflective anatomical and tracking markers while standing in a standard position (McIlroy & Maki, 1997). Anatomical markers were placed bilaterally on the iliac crest, greater trochanter, medial and lateral epicondyles, medial and lateral malleoli, and the first and fifth metatarsal heads. Four non-collinear tracking markers were attached to molded thermoplastic shells on the posterior pelvis, proximal posterior-lateral thighs and distal posterior shanks (Manal, et al., 2000) and as three separate non-collinear markers on the heels. Initially, a standing trial was collected in the standard position. The anatomical markers were then removed and only tracker markers were left on the participant.

A baseline gait analysis was then conducted (Baseline). Position (120 Hz) and ground reaction force data (1200 Hz) were collected using a seven camera three-dimensional motion capture system (Vicon Inc, Centennial, CO) which was synchronized with two force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA). Participants walked overground across a ten-meter walkway contacting two force platforms in the center of the walkway, one with each foot at their self-selected velocity. Walking velocity was monitored using two photo-cells which were placed three meters apart on either side of the force platforms. Five good walking trials were completed with the participant contacting both force platforms without appearing to alter their stride. While participants rested, data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). The knee flexion excursion was determined for each trial by subtracting the knee flexion angle at footstrike from the peak knee flexion angle in the first half of stance. It was calculated for the five walking trials. The knee flexion excursion threshold for stiff-knee gait was operationally defined as one standard deviation less than the mean knee flexion excursion of healthy adults (Freedman, et al., In Preparation). The mean of this group was 14.0° with a standard deviation of 3.7°. Therefore, the threshold for inclusion was a knee flexion excursion equal to or less than 10.3°. If the participant exhibited stiff-knee gait in both knees, the knee that had the least knee flexion excursion was selected for gait instruction. Prior to gait instruction, marker shells were removed from the participant's leg and thigh and they completed the six-minute walk test (Enright, et al., 2003).

2.3 Gait Instruction

Next, all static markers, with the exception of the medial knee, were placed on the participant. For gait instruction a dual inclinometer (Acumar, Lafayette Instrument Co., Lafayette, IN) was attached to the thigh and leg surrounding the knee joint using neoprene wraps and velcro. The dual inclinometer was attached on the thigh with the axis of the inclinometer parallel to the line between the greater trochanter and the lateral epicondyle. On the leg it was attached so that the axis of the inclinometer was parallel to the line between the lateral epicondyle and the lateral malleolus. Instruction consisted of four blocks of ten single step practice trials (Figure 5-1) followed by 100 walking steps. Participants were encouraged to develop self-regulation via intrinsic feedback by asking them to pay attention to how it felt to bend their knee more during practice steps and apply this during walking steps. Participants were free to rest as needed during instruction. Extrinsic feedback was tapered over the blocks (Figure 5-2), and none was provided during the 100 walking steps. Extrinsic feedback during the single steps indicated whether knee flexion should increase ("a little bit more"), decrease ("a little bit less") or was within the desired range ("that was good"). Target knee flexion excursion was between 15-20°. Actual knee flexion excursion was indicated to the instructor by the inclinometer display. Participants were asked to rate their own performance on one trial per block, in each practice block.

Immediately after the practice blocks were completed, medial knee and shell markers were added and a new static trial was collected. The three-dimensional gait analysis was then repeated to assess improvements in performance (Immediate retention). Following this, participants completed the Knee Injury and Osteoarthritis Outcome Score (KOOS) questionnaire (Roos, et al., 1998) during a 20 minute rest period. Participants then completed a final gait analysis to assess short-term retention of the modified gait pattern within the session (Delayed retention).

2.4 Data Processing

Data were processed using Visual 3D software (C-Motion Inc., Rockville, MD). Marker coordinate data were filtered using a 6 Hz low-pass recursive Butterworth filter. Force platform data were filtered using a 50 Hz low-pass recursive Butterworth filter. Heel contact and toe-off were identified during each trial using a threshold of 20 N in the vertical ground reaction force. Customized laboratory software (Matlab, The Mathworks Inc., Natick, MA) extracted the dependent variables from the stance phase data for each of the five trials in each condition. Weight acceptance was defined as the first half of stance. Peak knee flexion angle was the maximum flexion angle during weight acceptance. Knee flexion excursion was the difference between the peak knee flexion angle and the knee flexion angle at footstrike. Peak external knee flexion moment was the maximum value during weight acceptance. Peak knee adduction angle was the maximum value during weight acceptance. Peak external adduction moment was the maximum value during weight acceptance. Joint moments were normalized to subject's height and fat free body weight as obtained from bioelectrical impedance analysis. For all participants, the mean of five steps was calculated for each variable in each condition. The group mean value for each variable in each condition was then determined.

Repeated measures one-way ANOVA were completed for each dependent variable for each knee comparing within participants and among time points (SPSS Inc., Chicago, Ill). When a significant omnibus F-ratio was observed ($p < 0.05$), post-hoc pairwise comparisons were made to determine where the differences occurred.

3. Results

Participants reported having relatively asymptomatic knees in spite of the fact that they walked with stiff-knee gait. They reported low pain scores according to the visual analog pain scale (trained knee: 0.2 ± 0.4; untrained knee: 0.1 ±0.3) and according to the KOOS questionnaire (474.3 ±48.0). Participants were able to walk 580.3 ±182.3m in the six-minute walk test.

Sagittal plane variables of the trained knee were altered via gait retraining (Table 5-1). Knee flexion excursion increased after instruction ($p = 0.020$). Knee Flexion excursion at baseline was less than both immediate retention ($p = 0.011$) and delayed retention ($p = 0.014$), which were similar to each other ($p = 1.00$). Peak knee flexion angle of the trained knee increased after instruction ($p = 0.019$). Baseline peak knee flexion angle was less than immediate retention ($p = 0.018$) but was similar to delayed retention ($p = 0.063$). Immediate retention and delayed retention peak knee flexion angle were similar to each other ($p = 1.000$). Peak external knee flexion moment increased after instruction ($p = 0.038$). Peak external knee flexion moment at baseline was significantly less than immediate retention ($p = 0.039$) but was similar to delayed retention (p = 0.087). The immediate retention and delayed retention peak external knee flexion moment were similar (p = 1.000).

Frontal plane variables did not change with instruction (Table 5-2). Peak knee adduction angle (p = 0.371) and peak external knee adduction moment (p = 0.294) were similar at all time points.

Sagittal (Table 5-1) and frontal (Table 5-2) plane variables in the untrained knee did not change after instruction. In the sagittal plane, knee flexion excursion (p = 0.066), peak knee flexion angle (p = 0.163) and peak external knee flexion moment (p = 0.100) were similar at all time points. In the frontal plane, peak knee adduction angle (p = 0.110) and peak external knee adduction moment were similar at all time points (p = 0.435).

4. Discussion

The purpose of this study was to determine whether young adults exhibiting a stiff knee gait could increase knee flexion excursion during a single session of gait instruction. Participants improved sagittal plane kinematics and kinetics of the trained knee over a single session of gait instruction. Some changes were maintained during a short-term retention test occurring 20 minutes after instruction.

In spite of exhibiting stiff knee gait, participants reported having relatively asymptomatic knees. They reported low pain scores and had KOOS scores similar to that reported for healthy adults (Zeni & Higginson, 2009a). They did exhibit poorer functional ability as they were unable to cover as much distance in the six-minute walk test (580.3m) as normal healthy young adults (700.1m) (Freedman, et al., In Preparation).

Gait instruction was successful at altering sagittal plane gait in the trained knee. In particular, stiff knee gait was reduced. Knee flexion excursion of the trained knee was larger in both the immediate retention and delayed retention compared to at baseline. Participants achieved a normal knee flexion excursion of 14° with gait instruction targeting 15-20°. Similarly, participants began with a peak knee flexion angle (6.3°) comparable to that reported in individuals with knee osteoarthritis (4.4°) (Al-Zahrani & Bakheit, 2002). After instruction participants were able to immediately improve peak knee flexion angle (14.1°) to be similar to values reported in healthy adults (14.3°) (Al-Zahrani & Bakheit, 2002). Participants had healthy peak knee flexion following instruction which led to healthy knee flexion excursion following instruction. This indicates that participants did not alter gait at foot contact that would have led to abnormal gait. This showed that the gait instruction was effective in leading to desired gait.

As with improvements in sagittal plane kinematics, peak knee flexion moment of the trained knee also improved with gait instruction. This increase in peak knee flexion moment was hypothesized. As knee flexion increases individuals must increase eccentric quadriceps contraction to overcome the larger moment arm of the ground reaction force, and prevent the knee from collapsing. Therefore, an individual with stiff-knee gait needs to increase knee flexion moment to be able to achieve a healthy knee flexion excursion. Healthy individuals have been reported to have peak knee flexion moments 50% greater than individuals with knee osteoarthritis. The individuals in the current study were able to improve to the point of doubling this magnitude of difference with a 100% increase in peak knee flexion moment after instruction. In spite of this improvement the peak knee flexion moment after instruction, it was still lower than has been observed in our lab in healthy young adults (Freedman, et al., In Preparation).

Frontal plane variables of the trained knee were not influenced by gait instruction. Peak knee adduction angle in the trained knee was similar to peak knee adduction values that have been reported for healthy individuals (0.8°) (Freedman, et al., In Preparation) and were considerably lower than reported for individuals with knee osteoarthritis (5.66°) (Schmitt & Rudolph, 2007). Peak knee adduction moment was also similar to reported values in healthy adults (Freedman, et al., In Preparation). In order to compare peak knee adduction moment to other studies, it was recalculated to be normalized to body weight and height. The recalculated peak knee adduction moment was lower than had been reported for both healthy older adults and adults with knee osteoarthritis (Baliunas, et al., 2002). The lack of changes were contrary our hypothesis that peak knee adduction angle and peak knee adduction moment would be lower after instruction. However, since peak knee adduction moment was already normal, this is not a cause for concern. This study shows showed that stiff knee gait and abnormal gait in the frontal plane are not necessarily linked. The participants did not exhibit all biomechanical risk factors of osteoarthritis. It is possible that frontal plane alterations are not made until later in the disease development process. This is in line with previous research that observed increases in peak knee adduction moment as the severity of knee osteoarthritis increased (Mündermann, et al., 2005). It is not known whether frontal plane changes would have occurred as a result of instruction had participants exhibited a gait at baseline that was different in the frontal plane from healthy adults.

Gait in the untrained knee was similar to baseline after gait instruction. The untrained knee at baseline did not qualify as stiff-knee gait according to our criteria. Therefore, we would not anticipate changes in the untrained knee. As with the similarities in frontal plane gait in the trained knee, the lack of change in the untrained knee shows that the instruction was successful in increasing knee flexion excursion without deleterious changes in the untrained knee.

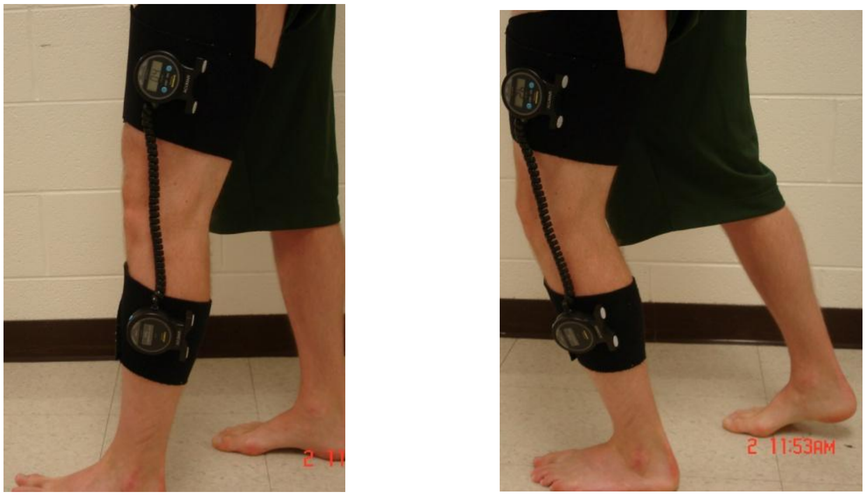
This investigation was designed as a single-session to determine whether performance could be modified during gait with our instruction protocol. However, by observing improvements in performance, we were able to determine that young adults are capable of changing how they walk with instruction. This is an important first step in developing a gait retraining program that will promote motor learning. Successful single sessions of gait instruction have been reported in the literature. Mundermann et al. (Mündermann, et al., 2008) utilized a single-session design to alter gait and observed a 65% change in knee adduction moment. Fregly et al. (Fregly, et al., 2009) also completed a single-session study, and were successful in decreasing the force on the knee by up to 28%. Achieving a 55% improvement in knee flexion excursion of the trained knee, the current study showed similar success to previous single session investigations.

A limitation of the current study was that a dual inclinometer provides less precise measurements than 3-dimentional kinematic data collection. Yet the dual inclinometer allows for measurement outside of a laboratory setting, making it more applicable for clinical use. Measurements during gait instruction may not have been as precise as during gait analyses. However, the observed improvement in sagittal plane gait suggests that the dual inclinometer was adequate in addressing the desired gait changes.

As it has been established that this form of gait instruction is successful in modifying performance, future steps must be taken to determine whether these changes can be learned and maintained over the long-term. If so, gait retraining may be able to reduce the risk osteoarthritis development by eliminating stiff knee gait. Therefore, future studies should include a long-term gait retraining program that consists of repeated instruction sessions over a period of months.

5. Conclusions

In conclusion, gait instruction focusing on reducing stiff-knee gait was successful. Increases in knee flexion excursion and peak knee flexion angle were able to be maintained following a 20 minute retention period. There were no changes in the gait of the untrained leg after instruction. This research suggests that young adults with stiff knee gait have the ability to perform normal knee kinematics.



(a) (b)

Figure 5-1: Single Step for Gait Instruction: a) Starting position with weight on the back leg. b) Ending position with weight shifted to front (trained) leg. Note digital inclinometer attached to shank and thigh.

Figure 5-2: Feedback schedule for gait instruction

: Feedback was provided to participant

: Participant was asked to rate their own performance

Table 5-1: Knee sagittal plane dependant variables (mean ± standard deviation)

	Knee Flexion Excursion (°)			Peak Knee Flexion Angle (°)			Peak Knee Flexion Moment (Nm/ffw*ht)		
	Base	Imm	Delayed	Base	Imm	Delayed	Base	Imm	Delayed
Trained Knee	7.7 ± 3.1	13.9 ± 4.9*	13.9 ± 4.5*	6.3 ± 3.8	14.1 ± 7.3*	13.8 ± 7.5	0.016 ± 0.014	0.037 ± 0.022*	0.039 ± 0.025
Untrained Knee	10.9 ± 4.5	14.6 ± 3.1	15.7 ± 4.0	9.8 ± 5.7	15.1 ± 5.8	16.4 ± 7.1	0.025 ± 0.016	0.047 ± 0.020	0.054 ± 0.025

ffw: Fat-free weight; ht: Height; Base: Baseline; Imm: Immediate retention; Delayed: Delayed retention

* Significantly different from baseline ($p < 0.05$)

Table 5-2: Knee frontal plane dependant variables (mean ± standard deviation)

	Peak Knee Adduction Angle (°)			Peak Knee Adduction Moment (Nm/ffw*ht)		
	Base	Imm	Delayed	Base	Imm	Delayed
Trained Knee	-0.4 ± 3.7	0.2 ± 3.9	0.5 ± 3.4	-0.038 ± 0.015	-0.041 ± 0.015	-0.040 ± 0.016
Untrained Knee	-1.3 ± 3.2	3.1 ± 3.6	2.3 ± 4.1	-0.036 ± 0.012	-0.036 ± 0.012	-0.034 ± 0.011

ffw: Fat-free weight; ht: Height; Base: Baseline; Imm: Immediate retention; Delayed: Delayed retention

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Conclusion

Obese and overweight young adults do not exhibit biomechanical risk factors for knee osteoarthritis compared to normal weight young adults. There was a sub-group of individuals who did exhibit biomechanical risk factors, but body mass index was not adequate in identifying this group. Young adults who with the biomechanical risk factor of stiff-knee gait were able to perform normal knee gait following gait instruction.

APPENDICES

APPENDIX A. Physical Activity Readiness Questionnaire

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____ DATE ________________________

SIGNATURE OF PARENT ________________________________ WITNESS ________________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

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APPENDIX B. Study 1: Institutional Review Board

INFORMED CONSENT FORM
The Effect of Body Type on Walking Gait in Young Adults

Principal Investigator: Julia A. Freedman
Address: Dept of Exercise, Sport & Leisure Studies
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Phone: (865) 974-2091

Purpose
You are invited to take part in a research study entitled "The Effect of Body Type on Walking Gait in Young Adults"**. This study aims to see whether the way you walk places you at a greater risk of osteoarthritis. This study involves one visit to our laboratory for about an hour and a half.**

You have been invited to take part in this study because you are a healthy adult who has not had a significant lower extremity injury. To take part in the study, you should not have any current or previous injuries or surgeries that might affect the way you walk. You should feel well enough to walk for short distances overground. You will be allowed to rest in between walking if you need to.

If you meet these criteria and agree to participate, we will measure your body mass index (a combination of height and weight) to see which one of the study groups you fit into. You will also be asked to complete a health questionnaire so that we can determine that you do not have health risks that would prohibit you from participating. If you do not meet all of these criteria or choose not to participate in the study, your visit will end.

Laboratory Visit
If you meet the inclusion criteria, you will stay at the lab for around an hour and a half for the data collection. We will begin by measuring your body composition. First we will measure around your thighs, waist and hips. This will be followed by measuring your body composition. You will stand in light clothing and bare feet on a scale while holding two handles. A small and unnoticeable current will go through the scale and your body to measure body composition. You will then move to the biomechanics lab where you will complete a questionnaire asking about the health of your knees.

Following completion of the questionnaire, you will complete two tests of everyday activities. First you will walk around a 50 meter loop in the hallway for six minutes. You will walk around the loop as many times as possible within the six minutes. Next you will be asked to get up from a seated position, walk three meters, and turn around and return to the chair. You will be timed during this task and will be allowed to practice first.

We will then provide you with a pair of laboratory shoes and socks, as well as loose-fitting shorts for you to wear. You will then have small silver balls attached to your waist, hips, legs and feet using medical tape and plastic shells. These will not interfere with your ability to walk. The cameras in our lab record the position of these balls as you walk across the lab space. We will take some measurements of you standing still.

Next, you will walk on at your usual walking speed across the laboratory floor. You will walk across a ten meter walkway, between five to ten times. Next we will ask you to walk at a fixed slow speed. You will have time to practice the new speed and then you will again walk across the walkway between five and ten times. You will be allowed to rest as often as you need.

Potential Risks

The potential risks associated with this study include trips and falls as you walk. We will do our best to minimize these risks during walking by explaining what will happen in the session and letting you practice how fast or slow to walk. You will be able to ask questions at any time during the data collection if you are unsure about anything.

If you become injured during the data collection, standard first aid procedures would be carried out as needed. In the event of physical injury as a result of taking part in this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

While there are no immediate benefits to you following participation in this study, the results of the study will provide information about the characteristics of walking in young adults who have different body types. This will provide information that may lead to the development of measures to reduce the risk of osteoarthritis.

Confidentiality

Your identity will be kept confidential by using code numbers to identify your information. These numbers will be used during all processing and analysis of the data and reports of the study and its results.

Contact Information

If you have any questions at any time about the study you can contact Julia Freedman. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Questions and/ or Withdrawal

You may ask questions and/ or withdraw your consent at any time and discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

____________________________ ________________ __________

Participant's Signature **Date** **Participant #**

___________________________ ________________

Investigator's Signature **Date**

APPENDIX C. Knee Osteoarthritis Outcome Score Questionnaire

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 1

KOOS KNEE SURVEY

Today's date: _____/______/______ Date of birth: _____/______/______

Name: ____

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.

APPENDIX D. Study 1: Dependant Variable Data

Normal	PWV Knee Flx Exc	PWV Peak Knee Flx	PWV Peak Knee Add	PWV Peak Flx Mom	PWV Peak Add Mom	1ms Knee Flx Exc	1ms Peak Knee Flx	1ms- Peak Knee Add	1ms- Peak Flx Mom	1ms- Peak Add Mom
Subject 4	8.9	9.3	4.0	0.038	-0.046	3.6	1.7	6.1	0.012	-0.043
Subject 5	13.2	17.5	6.5	0.051	-0.057	12.0	14.6	6.1	0.034	-0.051
Subject 6	10.5	15.6	4.2	0.041	-0.044	5.1	7.7	5.3	0.013	-0.046
Subject 7	12.2	13.4	5.1	0.042	-0.039	3.0	1.8	4.8	0.003	-0.031
Subject 8	10.3	15.0	7.4	0.065	-0.077	7.7	10.0	6.5	0.045	-0.045
Subject 11	16.0	23.3	7.9	0.076	-0.077	6.9	9.3	7.8	0.019	-0.050
Subject 15	18.4	28.6	7.6	0.048	-0.042	15.4	19.1	7.9	0.031	-0.041
Subject 21	15.6	17.4	7.3	0.044	-0.041	11.5	11.8	5.6	0.017	-0.038
Subject 26	20.5	25.8	8.3	0.063	-0.047	13.8	20.6	6.5	0.043	-0.039
Subject 27	14.8	22.0	3.7	0.050	-0.042	13.9	19.6	4.7	0.039	-0.036
Mean	14.0	18.8	6.2	0.052	-0.051	9.3	11.6	6.1	0.026	-0.042
Standard Deviation	3.7	6.0	1.8	0.012	0.014	4.6	6.9	1.1	0.014	0.006

Overweight										
Subject 2	20.8	20.6	7.9	0.058	-0.053	18.2	17.6	8.6	0.039	-0.046
Subject 12	12.7	9.1	7.1	0.020	-0.045	8.2	2.7	7.7	0.003	-0.037
Subject 13	13.1	14.5	3.7	0.044	-0.058	13.6	14.5	4.7	0.043	-0.060
Subject 14	12.3	25.2	7.2	0.066	-0.053	10.4	19.9	7.1	0.047	-0.047
Subject 18	19.8	25.2	7.1	0.080	-0.049	13.8	25.2	7.1	0.052	-0.048
Subject 20	12.9	12.2	3.7	0.055	-0.045	8.1	6.2	6.0	0.032	-0.044
Subject 23	11.6	13.1	5.9	0.046	-0.050	4.5	4.5	8.3	0.012	-0.055
Subject 24	18.1	25.0	2.8	0.086	-0.076	14.6	20.0	2.0	0.051	-0.062
Subject 28	2.5	3.2	3.4	-0.005	-0.074	4.9	3.2	2.8	0.001	-0.069
Subject 30	17.1	21.9	4.6	0.087	-0.050	13.4	21.9	5.0	0.059	-0.048
Mean	14.1	17.0	5.3	0.054	-0.055	11.0	13.6	5.9	0.034	-0.052
Standard Deviation	5.3	7.7	1.9	0.029	0.011	4.5	8.6	2.3	0.021	0.010

PWV: Preferred walking velocity; Flx: Flexion; Exc: Excursion; Add: Adduction; Mom: Moment; 1ms: 1 meter/second

Obese	PWV -Knee Flx Exc	PWV -Peak Knee Flx	PWV -Peak Knee Add	PWV -Peak Flx Mom	PWV- Peak Add Mom	1ms - Knee Flx Exc	1ms- Peak Knee Flx	1ms- Peak Knee Add	1ms- Peak Flx Mom	1ms- Peak Add Mom
Subject 9	15.4	19.1	1.1	0.084	-0.040	12.3	18.4	1.2	0.075	-0.059
Subject 10	7.7	4.5	-1.0	0.016	-0.020	7.2	3.7	-0.2	0.011	-0.029
Subject 19	16.3	16.3	7.0	0.055	-0.062	7.9	5.7	12.6	0.014	-0.061
Subject 22	16.0	16.9	5.0	0.065	-0.037	12.9	12.5	5.1	0.045	-0.036
Subject 31	10.5	11.7	2.8	0.021	-0.029	7.7	8.5	4.9	0.002	-0.032
Subject 32	7.5	13.5	3.0	0.015	-0.035	8.0	3.3	-2.2	0.013	-0.034
Subject 33	17.1	19.5	0.0	0.070	-0.054	13.4	19.5	3.0	0.029	-0.042
Subject 34	16.8	22.8	2.9	0.079	-0.068	15.9	21.3	3.8	0.062	-0.067
Subject 35	15.5	22.5	2.2	0.099	-0.067	8.9	17.7	0.2	0.037	-0.028
Subject 36	13.6	14.1	1.3	0.016	-0.029	10.7	10.2	0.9	0.005	-0.014
Mean	13.6	16.1	2.4	0.052	-0.044	10.5	12.1	2.9	0.029	-0.040
Standard Deviation	3.7	5.5	2.3	0.032	0.017	3.0	6.8	4.1	0.025	0.017

PWV: Preferred walking velocity; Flx: Flexion; Exc: Excursion; Add: Adduction; Mom: Moment; 1ms: 1 meter/second

APPENDIX E. Study 1: ANOVA tables

Knee Flexion Excursion

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
speed	Pillai's Trace	.649	49.975[a]	1.000	27.000	.000
	Wilks' Lambda	.351	49.975[a]	1.000	27.000	.000
	Hotelling's Trace	1.851	49.975[a]	1.000	27.000	.000
	Roy's Largest Root	1.851	49.975[a]	1.000	27.000	.000
speed * Category	Pillai's Trace	.072	1.052[a]	2.000	27.000	.363
	Wilks' Lambda	.928	1.052[a]	2.000	27.000	.363
	Hotelling's Trace	.078	1.052[a]	2.000	27.000	.363
	Roy's Largest Root	.078	1.052[a]	2.000	27.000	.363

a. Exact statistic

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	8760.165	1	8760.165	281.790	.000
Category	7.576	2	3.788	.122	.886
Error	839.365	27	31.088		

Peak knee flexion angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
speed	Pillai's Trace	.672	55.197[a]	1.000	27.000	.000
	Wilks' Lambda	.328	55.197[a]	1.000	27.000	.000
	Hotelling's Trace	2.044	55.197[a]	1.000	27.000	.000
	Roy's Largest Root	2.044	55.197[a]	1.000	27.000	.000
speed * Category	Pillai's Trace	.187	3.106[a]	2.000	27.000	.061
	Wilks' Lambda	.813	3.106[a]	2.000	27.000	.061
	Hotelling's Trace	.230	3.106[a]	2.000	27.000	.061
	Roy's Largest Root	.230	3.106[a]	2.000	27.000	.061

a. Exact statistic

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	13250.370	1	13250.370	145.122	.000
Category	17.785	2	8.892	.097	.908
Error	2465.234	27	91.305		

Peak Knee Flexion Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
speed	Pillai's Trace	.703	64.025[a]	1.000	27.000	.000
	Wilks' Lambda	.297	64.025[a]	1.000	27.000	.000
	Hotelling's Trace	2.371	64.025[a]	1.000	27.000	.000
	Roy's Largest Root	2.371	64.025[a]	1.000	27.000	.000
speed * Category	Pillai's Trace	.034	.473[a]	2.000	27.000	.628
	Wilks' Lambda	.966	.473[a]	2.000	27.000	.628
	Hotelling's Trace	.035	.473[a]	2.000	27.000	.628
	Roy's Largest Root	.035	.473[a]	2.000	27.000	.628

a. Exact statistic

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.101	1	.101	97.059	.000
Category	.000	2	.000	.145	.865
Error	.028	27	.001		

Peak Knee Adduction Angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
speed	Pillai's Trace	.032	.901[a]	1.000	27.000	.351
	Wilks' Lambda	.968	.901[a]	1.000	27.000	.351
	Hotelling's Trace	.033	.901[a]	1.000	27.000	.351
	Roy's Largest Root	.033	.901[a]	1.000	27.000	.351
speed * Category	Pillai's Trace	.027	.376[a]	2.000	27.000	.690
	Wilks' Lambda	.973	.376[a]	2.000	27.000	.690
	Hotelling's Trace	.028	.376[a]	2.000	27.000	.690
	Roy's Largest Root	.028	.376[a]	2.000	27.000	.690

a. Exact statistic

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1400.398	1	1400.398	139.493	.000
Category	140.776	2	70.388	7.011	.004
Error	271.058	27	10.039		

Multiple Comparisons

MEASURE_1
Tukey HSD

(I) Category	(J) Category	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
N	OB	3.482*	1.0020	.005	.997	5.966
	OW	.530	1.0020	.858	-1.954	3.014
OB	N	-3.482*	1.0020	.005	-5.966	-.997
	OW	-2.952*	1.0020	.017	-5.436	-.468
OW	N	-.530	1.0020	.858	-3.014	1.954
	OB	2.952*	1.0020	.017	.468	5.436

Based on observed means.
The error term is Mean Square(Error) = 5.020.

*. The mean difference is significant at the .05 level.

Peak Knee Adduction Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
speed	Pillai's Trace	.703	64.025[a]	1.000	27.000	.000
	Wilks' Lambda	.297	64.025[a]	1.000	27.000	.000
	Hotelling's Trace	2.371	64.025[a]	1.000	27.000	.000
	Roy's Largest Root	2.371	64.025[a]	1.000	27.000	.000
speed * Category	Pillai's Trace	.034	.473[a]	2.000	27.000	.628
	Wilks' Lambda	.966	.473[a]	2.000	27.000	.628
	Hotelling's Trace	.035	.473[a]	2.000	27.000	.628
	Roy's Largest Root	.035	.473[a]	2.000	27.000	.628

a. Exact statistic

Tests of Between-Subjects Effects

Measure:MEASURE_1
Transformed Variable:Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.101	1	.101	97.059	.000
Category	.000	2	.000	.145	.865
Error	.028	27	.001		

APPENDIX F. Study 2: Informed Consent

INFORMED CONSENT FORM
Gait Retraining for Stiff-Knee Gait in Younger and Older Adults

Principal Investigator: Julia A. Freedman
Address: **Dept of Exercise, Sport & Leisure Studies**
University of Tennessee
1914 Andy Holt Avenue, HPER 136
Knoxville, TN 37966
Phone: **(865) 974-2091**

Purpose
You are invited to take part in a research study entitled "Gait Retraining for Stiff-Knee Gait in Younger and Older Adults"**. This study aims to see whether we can improve the bend in your knee when you walk. This study involves one visit to our laboratory for about two and a half hours.**

You have been invited to take part in this study because you are a healthy adult who has stiff and achy knees. You should feel well enough to walk for short distances overground and should be able to follow instructions. You will be allowed to rest in between walking if you need to.

If you meet these criteria and agree to participate you will be asked to complete a short health questionnaire to make sure it will be safe for you to participate. If you do not meet all of the criteria or choose not to participate in the study, your visit will end.

Laboratory Visit

<u>Screening</u>
If you meet the inclusion criteria, you will stay at the lab for screening and then data collection if you qualify. We will begin by going through a final screening to measure how you walk. We will attach small silver balls to your ankle, knee and hip to record their position while you walk through the lab. You will have a short break while we process the data to determine whether you exhibit stiff knee gait. If you do not, your visit will end at this point. If you meet the criteria we will continue with data collection.

Data collection will continue in the Exercise Physiology lab with the completion of body measurements. First we will measure around your thighs, waist and hips. This will be followed by measuring your body composition. You will stand in light clothing and bare feet on a scale while holding two handles.

You will then walk around a 100 meter loop in the hallway for six minutes.

<u>Gait Analysis and Retraining</u>

We will then begin the gait retraining where we will ask you to take single steps followed by continuous walking. During the practice we will give you feedback about how you are using your knee and have you adjust your movement accordingly. After the retraining you will walk across the lab several times until we have five good trials for each leg, followed by a twenty minute break where you will also complete a questionnaire discussing your knee pain and stiffness. Following the break you will walk through the lab for one more set of trials while we measure how you are walking.

Potential Risks

The potential risks associated with this study include trips and falls as you walk. We will do our best to minimize these risks during walking by explaining what will happen in the session and letting you practice how fast or slow to walk and choose your own walking speed. You will be able to ask questions at any time during the data collection if you are unsure about anything.

If you become injured during the data collection, standard first aid procedures would be carried out as needed. In the event of physical injury as a result of taking part in this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

The immediate benefits of a single gait retraining session for you are minimal. The study will provide preliminary data for use in the development of future gait retraining programs to help individuals adopt a more normal walking pattern.

Confidentiality

Your identity will be kept confidential by using code numbers to identify your information. These numbers will be used during all processing and analysis of the data and reports of the study and its results.

Contact Information

If you have any questions at any time about the study you can contact Julia Freedman. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Questions and/ or Withdrawal

You may ask questions and/ or withdraw your consent at any time and discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

____________________________	________________	__________
Participant's Signature	**Date**	**Participant #**
___________________________	________________	
Investigator's Signature	**Date**	

APPENDIX G. Study 2: Dependant Variable Data

Subject	Base Knee Flex Exc	Base Peak Knee Flex	Base Peak Knee Add	Base Peak Flex Mom	Base Peak Add Mom	Imm Knee Flex Exc	Imm Peak Knee Flex	Imm Peak Knee Add	Imm Peak Flex Mom	Imm Peak Add Mom	Del Knee Flex Exc	Del Peak Knee Flex	Del Peak Knee Add	Del Peak Flex Mom	Del Peak Add Mom
2	11.6	14.1	2.0	0.036	-0.043	21.1	25.7	1.2	0.054	-0.037	24.5	28.5	2.1	0.074	-0.035
3	12.2	13.0	-7.2	0.023	-0.015	16.0	17.2	-7.7	0.045	-0.014	17.9	17.4	-8.4	0.056	-0.013
4	11.2	12.6	0.7	0.040	-0.050	13.0	10.6	0.2	0.063	-0.056	14.4	11.3	-0.6	0.061	-0.041
5	1.6	-1.3	-2.8	0.001	-0.044	14.2	21.5	-1.2	0.092	-0.041	14.9	25.5	1.9	0.110	-0.044
7	11.3	9.3	-2.5	0.046	-0.033	12.0	9.0	-5.7	0.035	-0.035	11.2	7.3	-6.1	0.033	-0.036
12	14.4	13.5	1.2	0.026	-0.033	16.9	16.3	-4.9	0.038	-0.027	17.7	18.7	-1.3	0.040	-0.027
14	15.0	13.6	-4.4	0.031	-0.045	10.9	8.9	-7.3	0.026	-0.038	12.0	12.5	-6.6	0.030	-0.036
22	5.4	1.9	-0.9	-0.001	-0.019	12.3	11.4	-3.7	0.033	-0.027	13.7	10.2	-3.9	0.047	-0.025
Mean	10.9	9.8	-1.3	0.025	-0.036	14.6	15.1	-3.1	0.047	-0.036	15.7	16.4	-2.3	0.054	-0.034
Std Dev	4.5	5.7	3.2	0.016	0.012	3.1	5.8	3.6	0.020	0.012	4.0	7.1	4.1	0.025	0.011

Std Dev: Standard Deviation; Base: Baseline; Flex: Flexion; Exc: Excursion; Add: Adduction; Mom: Moment; Imm: Immediate; Del: Delayed

APPENDIX H-1: Study 2 ANOVA Tables: Trained Knee

Knee Flexion Excursion

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.674	7.232[a]	2.000	7.000	.020
	Wilks' Lambda	.326	7.232[a]	2.000	7.000	.020
	Hotelling's Trace	2.066	7.232[a]	2.000	7.000	.020
	Roy's Largest Root	2.066	7.232[a]	2.000	7.000	.020

a. Exact statistic

Pairwise Comparisons

Measure:MEASURE_1

(I) factor1	(J) factor1	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	2	-6.256	1.547	.011	-10.920	-1.591
	3	-6.274*	1.614	.014	-11.140	-1.408
2	1	6.256*	1.547	.011	1.591	10.920
	3	-.018	.630	1.000	-1.917	1.880
3	1	6.274*	1.614	.014	1.408	11.140
	2	.018	.630	1.000	-1.880	1.917

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Peak Knee Flexion Angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.676	7.286[a]	2.000	7.000	.019
	Wilks' Lambda	.324	7.286[a]	2.000	7.000	.019
	Hotelling's Trace	2.082	7.286[a]	2.000	7.000	.019
	Roy's Largest Root	2.082	7.286[a]	2.000	7.000	.019

a. Exact statistic

Pairwise Comparisons

Measure:MEASURE_1

(I) factor1	(J) factor1	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	7.806*	2.096	.018	1.484	14.128
	3	7.506	2.616	.063	-.384	15.396
2	1	-7.806*	2.096	.018	-14.128	-1.484
	3	-.300	1.006	1.000	-3.332	2.733
3	1	-7.506	2.616	.063	-15.396	.384
	2	.300	1.006	1.000	-2.733	3.332

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Peak Knee Flexion Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.607	5.403[a]	2.000	7.000	.038
	Wilks' Lambda	.393	5.403[a]	2.000	7.000	.038
	Hotelling's Trace	1.544	5.403[a]	2.000	7.000	.038
	Roy's Largest Root	1.544	5.403[a]	2.000	7.000	.038

a. Exact statistic

Pairwise Comparisons

Measure:MEASURE_1

(I) factor1	(J) factor1	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.021	.007	.039	-.041	-.001
	3	-.024	.009	.087	-.051	.003
2	1	.021*	.007	.039	.001	.041
	3	-.003	.003	1.000	-.012	.007
3	1	.024	.009	.087	-.003	.051
	2	.003	.003	1.000	-.007	.012

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Peak Knee Adduction Angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.247	1.147[a]	2.000	7.000	.371
	Wilks' Lambda	.753	1.147[a]	2.000	7.000	.371
	Hotelling's Trace	.328	1.147[a]	2.000	7.000	.371
	Roy's Largest Root	.328	1.147[a]	2.000	7.000	.371

a. Exact statistic

Peak Knee Adduction Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.295	1.466[a]	2.000	7.000	.294
	Wilks' Lambda	.705	1.466[a]	2.000	7.000	.294
	Hotelling's Trace	.419	1.466[a]	2.000	7.000	.294
	Roy's Largest Root	.419	1.466[a]	2.000	7.000	.294

a. Exact statistic

APPENDIX H-2: Study 2 ANOVA Tables: Untrained Knee

Knee Flexion Excursion

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.540	4.115[a]	2.000	7.000	.066
	Wilks' Lambda	.460	4.115[a]	2.000	7.000	.066
	Hotelling's Trace	1.176	4.115[a]	2.000	7.000	.066
	Roy's Largest Root	1.176	4.115[a]	2.000	7.000	.066

a. Exact statistic

Peak Knee Flexion Angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.405	2.380[a]	2.000	7.000	.163
	Wilks' Lambda	.595	2.380[a]	2.000	7.000	.163
	Hotelling's Trace	.680	2.380[a]	2.000	7.000	.163
	Roy's Largest Root	.680	2.380[a]	2.000	7.000	.163

a. Exact statistic

Peak Knee Flexion Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.482	3.259[a]	2.000	7.000	.100
	Wilks' Lambda	.518	3.259[a]	2.000	7.000	.100
	Hotelling's Trace	.931	3.259[a]	2.000	7.000	.100
	Roy's Largest Root	.931	3.259[a]	2.000	7.000	.100

a. Exact statistic

Peak Knee Adduction Angle

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.467	3.072[a]	2.000	7.000	.110
	Wilks' Lambda	.533	3.072[a]	2.000	7.000	.110
	Hotelling's Trace	.878	3.072[a]	2.000	7.000	.110
	Roy's Largest Root	.878	3.072[a]	2.000	7.000	.110

a. Exact statistic

Peak Knee Adduction Moment

Multivariate Tests[c]

Effect		Value	F	Hypothesis df	Error df	Sig.
factor1	Pillai's Trace	.207	.911[a]	2.000	7.000	.445
	Wilks' Lambda	.793	.911[a]	2.000	7.000	.445
	Hotelling's Trace	.260	.911[a]	2.000	7.000	.445
	Roy's Largest Root	.260	.911[a]	2.000	7.000	.445

a. Exact statistic

VITA

Julia Freedman received her bachelor's degree in the field of Kinesiology from the University of Maryland, College Park. After working as a research assistant at the Uniformed Services University of the Health Sciences she returned to school. She received her master's degree in Kinesiology with a concentration in Biomechanics from the University of Nevada, Las Vegas. The focus of her dissertation was the biomechanical risk factors of knee osteoarthritis. She investigated the influence of obesity in young adults on biomechanical risk factors of knee osteoarthritis. She also investigated the ability of young adults with biomechanical risk factors of knee osteoarthritis to perform normal gait following gait instruction.