Effects of Increased Step Width on Knee Biomechanics During Inclined and Declined Walking

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Daniel William Sample

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Dedication

This thesis is dedicated to my family and friends who have supported me every step of the way. I am eternally grateful for the love and support of my parents Dave and Beth Sample who have made countless sacrifices to make sure I am able to pursue my dreams. There are a lot of things I could not have accomplished without their help and support. I also want to thank my advisor Dr. Zhang and committee members Dr. Weinhandl and Dr. Strohacker for their advice and guidance during this process. Finally, I want to thank my friends and colleagues Paula Ferarra, Tanner Thorsen, Mike O'Dwyer, Alec Genter, and everyone else in the biomechanics department for helping me whenever I had questions.

Abstract

The purpose of this study was to investigate effects of preferred step width and increased step width modification on knee biomechanics, specifically peak knee abduction and extension moments, of obese and healthy-weight participants during incline and decline walking. Seven healthy weight participants and six obese participants categorized by BMI values performed five walking trials on level ground and a 10° inclined and declined instrumented ramp system. Two AMTI force platform(s) were used to collect GRF data (1200 Hz, AMTI,). 3D kinematic data were collected a motion capture system (240 Hz, Vicon). All data were imported into 3D data analysis software, Visual3D (version 2.6, C-Motion, Inc., Germantown, MD, USA) for 3D kinematic and kinetic analysis. A 2 x 2 (step-width x group) mixed model ANOVA was used to examine selected variables. There were significant increases in step width (SW) between the preferred and wide SW conditions for all three walking conditions (all $p<0.001$). An interaction was found for peak KEM ($p=0.048$) and KAbM ($p=0.025$) in uphill walking. During downhill walking, there were no interaction effects. As SW increased, KAbM was reduced ($p=0.007$). In level walking there were no interaction effects for peak mediolateral GRF and KAbM ($p=0.007$). There was a SW main effect for KAbM ($p=0.007$). As SW increased, peak mediolateral GRF and peak KEM increased, while KAbM decreased for both groups. It was found that increasing SW may be a useful strategy for reducing KAbMs in healthy, young populations.

Table of Contents

Chapter I Introduction **1**

Background **1**

Statement Of Purpose **4**

Hypothesis **4**

Delimitations **4**

Limitations **5**

Chapter II Literature Review **6**

Obesity Epidemic And Its Effect On Daily Living **6**

Changes In Gait Mechanics Due To Obesity **7**

Influence Of Ramp Walking On Gait Biomechanics **14**

Overall Effects Of Walking On An Incline **22**

Altering Step Width **23**

Level Walking / Running **24**

Stair Ascent / Descent **25**

Conclusion **29**

Chapter III Materials And Methods **30**

Participants **30**

Instrumentation **31**

Experimental Procedures **33**

Data Analysis **34**

Statistical Analysis **36**

Chapter IV Effects of Increased Step Width on Knee Biomechanics During Inclined and Declined Walking **37**

Abstract **38**

Introduction **39**

Materials and Methods **41**

Instrumentation **42**

Data analysis **35**

Results **47**

Discussion **48**

References **53**

Appendices **57**

Vita..... 90

List of Tables

Table 1. Participant (N=13) Demographic Information: Mean ± Std. 75

Table 2. Uphill, Downhill And Level Walking Step Widths (M) And Speeds (M/S): Mean ± Std. 76

Table 3. Peak Loading-Response Grfs (N), Knee Extension And Knee Abduction Moments (Nm) For Uphill, Downhill And Level Walking: Mean ± Std. 78

Table 4. Peak Knee Extension/Flexion And Knee Adduction Angles (Deg) And Rom (Deg) For Uphill, Downhill And Level Walking. 79

Table 5. Step Width (M) 81

Table 6. Walking Speed (M/S) 82

Table 7. Participant Demographics 83

Table 8. Peak Loading-Response Knee Abduction Moments (Nm) For Uphill, Downhill And Level Walking. 83

Table 9. Knee Adduction Rom (Deg) For Uphill, Downhill And Level Walking. 84

Table 10. Knee Flexion Rom (Deg) For Uphill, Downhill And Level Walking. 85

Table 11. Peak Mediolateral Load-Response Grf (N) For Uphill, Downhill And Level Walking. 86

Table 12. Peak Knee Extension Moments (Nm) For Uphill, Downhill And Level Walking. 87

Table 13. Peak Knee Extension Angle (Deg) For Uphill, Downhill And Level Walking. 88

Table 14. Peak Vertical Grf (N) For Uphill, Downhill And Level Walking. 89

List of Figures

Figure 1. An incline ramp with handrail and instrumented platforms attached 80

Chapter I

Introduction

Background

Obesity is currently a serious health issue in our country, as over one third of the U.S. population is considered obese with a prevalence rate among adults of approximately 35.6% (Flegal et al., 2012). Obesity can lead to a myriad of other diseases including diabetes, high blood pressure, cardiovascular disease (CVD), or osteoarthritis (OA). OA is a degenerative disease that occurs when the joint cartilage becomes worn down and lost over time, resulting in increased pain and loss of mobility in the affected joint. Knee OA, specifically, is the most common joint affected by OA and can be found in 10% of men and 13% of women over the age of 60 (Freedman Silvernail et al., 2013). This loss of cartilage often leads to an increase in knee pain further inhibiting exercise, active lifestyles, and ability to perform daily tasks, which compounds the obesity problem Mendes et al. (2018).

Obese participants often present more extreme gait biomechanics including increased ground reaction forces and joint contact forces compared to healthy weight participants, while also walking at slower speeds (de Souza et al., 2005). It is suspected that obese participants often use this slower walking speed as a protective mechanism to reduce detrimental knee joint loading. This decrease in velocity will also decrease the vertical ground reaction forces (VGRF) experienced by the individual. It is also hypothesized that this reduction in walking speed is a strategy for reducing peak knee abduction moments, in obese populations (Freedman Silvernail et al., 2013).

Several studies have found that obese participants present increased knee abduction and extension moments during level walking compared to healthy weight participants (Blazek et al.,

2013; Yocum et al., 2018,). This is important to consider as knee joint moments are the most common indicator of knee joint loading and development of knee osteoarthritis (Paquette et al., 2014).

Gait biomechanics can also be affected by the environment, such as ambulating on an incline or up and down stairs. Walking is commonly prescribed as a form of exercise to assist with weight loss, especially for obese participants (Haight et al., 2014). To reduce abnormal knee joint loading, several studies have examined how walking on an incline affects gait biomechanics in healthy weight and obese populations, as incline walking has been shown to reduce knee joint loading. Ehlen et al., (2011) and Haggerty et al., (2014) also noted significant increases in knee flexion angle while walking on an incline compared to level walking.

Walking up or down an incline has also been shown to affect knee kinetics. Ehlen et al. (2011) found that as inclination increased, first and second peak ground reaction forces were decreased compared to level walking. However, this study also had slower walking speeds while incline walking, which may also contribute to the reduction in ground reaction forces. This is supported by Wen et al., (2018) who reported decreases in VGRFs experienced by both healthy weight and obese participants as incline angle increased from level walking to 5˚, 10˚ and 15˚ incline. In the sagittal plane, Ehlen et al., (2011) found a significant reduction in peak knee extension moments when walking on a 6˚ incline compared to level walking. However, in a slight disagreement, Haight et al., (2014) reported that peak knee flexion moments were not greater during incline walking compared to level walking. Wen et al. (2018) also reported that peak knee abduction moment at load response and push-off decreased as incline increased from level walking to 5˚, 10˚, and 15˚ in participants with and without knee replacements and that peak knee extension moment was significantly increased in only participants with knee

replacements in level walking compared to 10˚ incline. However, there were no significant changes in peak knee extension moment as incline increased in participants without knee replacements.

Contrary to incline walking, decline walking has been shown to cause increases in VGRF (Ehlen et al., 2011; Wen et al., 2018) . Decline walking also affects joint moments. Wen et al., (2018) reported that a significant increase in peak knee abduction moment occurred at push-off in both populations while walking downhill.

There have been several approaches to implementing various gait modification to reduce knee joint moments such as abduction and external rotation moments. Such modifications include changing walking speed or stride length. One modification that has not been widely investigated is how altering step width (SW) will affect gait biomechanics. Altering step width may be useful in further reducing the knee abduction moments, indicative of medial compartment loading in the knee, during incline walking which may further reduce the risk of injury or onset of disease. During level walking, a study conducted by Yocum et al. (2018) reported that as step width increased, knee abduction moment was significantly decreased in obese populations. Specifically, it was reported by Yocum et al. (2018) that increasing step width significantly reduced peak knee adduction angle at loading response in both healthy weight and obese participants. A different study, concerned with the effects of increased step width during level running, conducted by Brindle et al. (2014) also found that at the wider step width, peak knee abduction moment and knee abduction impulse were significantly reduced. These results supported those found by Yocum et al. (2018) that as step width was increased, knee abduction moment was significantly decreased in obese populations.

Statement of Purpose

This study will add critical data to the literature concerning the effects of altering step width on knee joint biomechanics during level, incline, and decline walking. The purpose of this study was to investigate effects of preferred step width and increased step width modification on knee biomechanics, specifically peak knee abduction and extension moments, of obese and healthy-weight participants during incline and decline walking.

Hypothesis

We hypothesized that:

- When increasing step width, peak knee abduction moment would be reduced when walking up a 10˚ incline and down a 10˚ decline compared to the preferred step width in both healthy weight and obese groups
- When increasing step width, peak knee extension moment would be unaffected compared to preferred step width across all conditions in both healthy weight and obese groups

Delimitations

Inclusion Criteria for Healthy Weight Participants:

- Men and Women over the age of 18
- BMI value from 19 to 24

Inclusion Criteria for Obese Participants:

- Men and Women over the age of 18
- BMI value between 30 to 38

Exclusion Criteria for all participants:

- Diagnosed with any joint disease in the lower extremity

- Any conditions affecting the participant's ability to walk
- Must be able to walk without assistance of aid
- Any previous history of lower extremity surgery
- Any previous history of lower extremity fracture fixation (medial/lateral malleolus fracture), ligament/tendon (ACL/MCL) repair, or meniscus injury/repair
- Any minor lower extremity injury, not requiring surgery, (grade 1-2 sprain/strain) in the past 6 months

Limitations

- The tests were conducted in a laboratory setting.
- Skin marker placement in obese participants may not accurately reflect the location of bony landmarks due to increased amounts of adipose tissue.
- The obese group was limited to a BMI of 38 kg/m^2 because higher BMI levels decrease

  tracking accuracy of skin mounted markers.
- Reflective markers used to track the feet were placed on the shoe, and therefore might not have accurately reflected the motion of the foot within the shoe.
- There was no randomization of incline/decline trials due to the amount of time needed to install and remove the ramp. All participants began with incline/decline trials and ended with level walking to speed up the data collections.
- There was no randomization of step width trials, as increased step width was calculated based on the individuals preferred step width.

Chapter II

Literature Review

Obesity Epidemic and Its Effect On Daily Living

Obesity is currently a significant health issue in our country. Over one third of the entire U.S. population is considered obese and a 2010 study found that the average prevalence rate among adults was approximate 35.6% (Flegal et al., 2012). Obesity is a serious disease than can impact the quality of life of those affected. Participants who are classified as obese are at a greater risk of developing chronic diseases such as heart disease, strokes, high blood pressure, sleep apnea, CVD), diabetes, and finally osteoarthritis (OA).

OA can be defined with three different techniques: radiographic confirmation of OA, clinical analysis of the individual, and finally pathologically. OA is the most common joint disease in the United States, and knee OA can be found in 10% of men and 13% of women over the age of 60 in the United States alone. This makes knee OA the most common form of the disease and these numbers are only expected to increase due to the increasing prevalence of obesity (Freedman Silvernail et al., 2013). OA occurs when the protective cartilage covering the joint surface becomes worn down and is lost over time. OA is a progressive, degenerative cartilage disease that can lead to increased pain and loss of function and mobility over time. OA is responsible for increased difficulty in normal walking and traversing stairs than any other disease (Freedman Silvernail et al., 2013).

A number of risk factors including age, previous injury, and obesity all lead to an increased risk of onset of knee OA. The main problems with OA present as onset of pain, stiffness, loss of flexibility and perhaps bone spurs (Freedman Silvernail et al., 2013).

Furthermore, previous studies have found that as BMI increases, an individual is more

likely to experience loss of strength, mobility, and the capacity to perform tasks required for day to day living (Li et al., 2017; Jung et al., 2006; Jenkins et al., 2004). An increase in body mass will also lead to joint damage and degradation over time, usually at the lower extremity joints. Severe knee cartilage damage has been seen in 28.7% of participants that have been previously diagnosed with OA (Browning and Kram, 2007; Keng et al., 2017). This loss of cartilage often leads to an increase in knee pain (Mendes et al., 2018), further inhibiting exercise, active lifestyles, and ability to perform daily tasks, which compounds the obesity problem. Finally, an increase in body mass can also lead to an increase in knee joint loading. This increase in joint loading most often occurs on the medial compartment of the knee joint, causing excess cartilage damage to that side and increased Varus alignment (Messier et al., 2014). Varus alignment may also lead to an increase in internal knee abduction moment, resulting in more pain compared to normally aligned obese participants (Messier et al., 2014). These changes in gait biomechanics will be further discussed in this literature review.

Changes in Gait Mechanics Due to Obesity

There is a clear consensus on the changes in spatiotemporal characteristics in obese participants compared to healthy weight participants. For example, it has been well established that obese participants prefer walking at speeds slower than healthy weight participants (de Souza et al., 2005). However, there is still much debate on how obesity effects the joint kinetics, specifically at the knee. It is suspected that due to the increased ground reaction forces obese participants experience the joint kinetics would also be higher than healthy weight participants. However, there is no clear evidence supporting this. While previous studies have found that obese participants present gait biomechanics that differ from healthy weight individual according to BMI values (Blazek et al., 2013; de Souza et al., 2005; Haight et al., 2014; Lai et al., 2008;

Spyropoulos et al., 1991; Wen et al., 2018) there are disagreements on how gait biomechanics differ specifically.

Spatiotemporal Changes

Spatiotemporal characteristics that describe how a person moves in through space and time. These characteristics can include walking speed, stride length, step length, and step width: all of which are affected by body mass (de Souza et al., 2005; Ehlen et al., 2011; Li et al., 2017). For example, the average walking speeds of healthy weight participants was faster than obese participants (de Souza et al., 2005). This reduction in walking speed is similar to results found by Lia et al. (2017) and Silvernail et al. (2013) who noted a decrease in speed from 1.27 m/s to 1.12 m/s in obese participants and 1.44 m/s to 1.21 m/s in healthy weight participants. This decrease in walking speed can be attributed to the added mass the individual must support. In order to experience less detrimental knee joint loading, obese participants must decrease velocity to account for the increased mass. This decrease in velocity will also decrease the ground reaction forces (GRF) experienced by the individual, as well as reducing energy expenditure while walking. It is also hypothesized that this reduction is walking speed is a strategy for reducing lower extremity joint moments in obese populations.

This will lead to reduced risk of injury or onset of disease by decreasing fatigue and adverse forces acting on the knee joint by reducing ground reaction forces. However, this decrease in speed will reduce the viability of walking for exercise. The compendium of physical activity states that to achieve moderate intensity activity when walking on a level surface, a speed of 1.78m/s must be maintained (Ainsworth et al., 2011).

Differences have also been found in the step and stride length of obese participants compared to healthy weight participants. Stride length is defined as the distance from the heel

strike of one leg to the next heel strike of that same leg. For example, one stride would be the distance or time from the right leg heel strike to the next right leg heel strike. Obese participants walking at their self-selected speed and cadence exhibited a stride length of 1.07m (de Souza et al., 2005). This is significantly lower than the stride length of healthy weight participants of 1.32 m. This reduction in stride length is expected with a reduction in speed. With a decrease in stride length, a decrease in step length is also seen. Step length is defined as the distance from one heel strike to the next subsequent heel strike. For example, this would be the distance from the right leg heel strike to the left leg heel strike. Obese participants show a decreased step length of 0.55 m versus 0.66 m in healthy weight participants. These findings are again corroborated by Lai et al. (2017) who found a decreased stride length of 0.71 m compared to 0.77 m in healthy weight participants when normalized to body height. It is again hypothesized that this reduction in stride length may be necessary to reduce knee joint moments and reduce risk of injury or onset of disease. However, these gait adaptations further reduce the viability of walking for exercise (Lai et al., 2008).

Kinetics

Kinetic gait measurements focus on the joint moments experienced at the knee. A joint moment occurs when the muscles surrounding the joint are activated to produce movements. This is known as an internal moment, caused by forces produced from inside the body. An external moment occurs when a participant performs a task and must withstand forces experienced from the environment and counteract them. Joint moments are measured perpendicular to the axis of rotation about the joint, and is calculated by multiplying the perpendicular force by the distance from the axis of rotation, or joint. For example, when

calculating a knee joint moment, one would measure the length of the shank and multiply by the ground reaction force.

When evaluating knee biomechanics in participants with different body masses, a common technique used is to normalize any data values to that participant's body mass. This normalization allows for a comparison between participants with different masses without the data being skewed by the mass values. Joint moments are an important variable to measure because they are indicative of joint loading. Increased joint moments in obese populations can indicate increased joint loading in these populations (Freedman Silvernail et al., 2013). While it is suspected that increased mass, which leads to increased GRF's will result in increased joint moments, this is still widely debated as mentioned earlier.

Frontal Plane

The main movements in the frontal plane are adduction and abduction, elevation and depression, and inversion and eversion. Knee abduction and adduction moments are a critical measurements as peak knee abduction moment is the most common indicator of knee joint loading and development of medial knee osteoarthritis (Paquette et al., 2014). Moreover, peak knee adduction torques are a critical measurement to take when attempting to measure loading of the medial compartment of the knee (Zhao et al., 2007). Unlike the spatiotemporal characteristics of gait, there is no clear consensus on how obesity effects gait biomechanics in the frontal plane. For example, the study by Freedman Silvernail et al., (2013) found that obese participants presented a significantly lower knee adduction moment in the preferred walking speed when compared to healthy weight participants. Specifically, knee adduction moment, normalized to height and fat free mass was significantly increased in obese populations with an average of -0.044 from -0.051 in healthy weight populations. However, a more recent study conducted by

Blazek et al. (2013) reported increases in adduction moment, normalized to percent bodyweight x height to account for differences in body size, which directly opposes the findings by Silvernail et al. (Freedman Silvernail et al., 2013).

Furthermore, this study is contradicted by two studies who found no difference in abduction or adduction moments in obese participants. A study conducted by DeVita et al. (DeVita and Hortobagyi, 2003) who did not normalize kinetic data, concluded that there is no difference in knee joint power and torques based on BMI values. Another study conducted by Lai et al., (2008) reported no significant differences in peak hip or peak knee joint moments, normalized to body mass and height, in level walking between normal and obese populations (Lai et al., 2008).

Sagittal Plane

The main movements in the sagittal plane are flexion and extension, and plantarflexion and dorsiflexion. Like frontal plane motion, many studies have not agreed that an increase in body mass will also result in an increase in sagittal plane moments (Lai et al., 2008; Browning et al. 2007; Freedman Silvernail et al. 2013). A study by Browning et al. (2007) reported significant increased peaks in hip and knee extension moments in an ankle plantarflexion moments in obese populations. Specifically, post hoc tests revealed that peak hip extensor moments were significantly increased at all speeds except for the 0.75 m/s speed, while peak knee extension moments were significantly increased only at the 1.75 m/s speed. As speed decreased to 1.50 and 1.00 m/s, peak knee extension moments in obese populations were 43% smaller than normal populations suggesting that decreased walking speeds reduces knee extension moments.

On the contrary, the study by Silvernail et al. (Freedman Silvernail et al., 2013) found no difference in knee flexion moments of obese participants when walking at preferred speed. Both

healthy weight and obese individual's presented knee flexion moments, normalized to fat free mass and height, of 0.052 Nm/kgm at their preferred walking speed. The lack of significant difference found here is also supported by a study conducted by (Lai et al., 2008) who reported no significant differences in the sagittal plane (Lai et al., 2008). However, when normalizing speeds to 1 m/s, obese participants presented knee flexion moments greater than healthy weight participants at 0.034 Nm/kgm compared to 0.025 Nm/kgm respectively when normalized to fat free body mass and height (Freedman Silvernail et al., 2013). This shows the importance of normalization in research and the need for future studies to gather more data and form a definitive picture.

Overall, this data suggests that obese participant's slower walking velocities helped reduce the knee joint moments to more normal loads. This gives support to recommending walking speeds to obese participants who are seeking to walk for exercise by lowering risk of injury or onset of disease. Conversely, knee adduction moments were greater in healthy weight participants when walking at preferred speeds with values of -0.051 Nm compared to -0.044 in obese participants. When normalizing walking speeds, both groups presented similar knee adduction moments (Freedman Silvernail et al., 2013).

Kinematics

Joint kinematics are measurements of joint motion without respect to the forces which cause them. Kinematic gait measurements focus on the joint angles and joint movement, and joint angles are measured using segments on either side of the joint. For example, knee angle is calculated using the locations of the thigh and shank tracked by cluster markers on those segments. Such measurements include peak hip, knee, and ankle angles as well as the total range of motion of each joint during certain tasks such as walking. Many studies have been conducted

to examine and compare the mechanics of healthy weight and obese participants to determine if obesity is detrimental to gait kinematics. Kinematic data can be a useful tool as studies have found that peak joint angles can be an accurate predictor of respective joint moment (Paquette et al., 2014). For example, peak knee adduction angle can be used to predict peak knee abduction moment during walking (Paquette et al., 2014). This is useful information as joint moments are not precisely calculated without in vivo measurements with instrumented joints and are often predictors of joint injury or disease. Similar to joint kinetics, there is disagreement in the literature about the differences in kinematics of obese participants.

Frontal Plane

In the frontal plane, peak adduction and abduction angles can be indicative of joint moment values in the respective joints. For example, at the knee, a study conducted by Lai et al. (2008) reported increased adduction angles in both the stance and swing phases of obese adults compared to healthy weight adults. It was reported that obese populations presented maximal adduction angles of 6.96˚ and 12.30˚ compared to 2.18˚ and 2.27 in healthy weight participants during the stance and swing phases respectively. On the contrary, Freedman Silvernail et al., (2013) reported that obese populations presented decreased peak knee adduction angles. It was found that obese participants walked with peak adduction angles of 2.4˚ at preferred walking speed and 2.9˚ at controlled speeds of 1 m/s. This is lower than the healthy weight results of 6.2˚ and 6.2˚ for preferred walking speed and controlled speed of 1 m/s respectively.

Sagittal Plane

Similar to joint angles measured in the frontal plane, joint angles in the sagittal plane such as knee flexion angle can be a good tool to predict respective joint moments. There is much

more data concerning the sagittal plane of motion, however disagreement still exists in the literature.

At the knee, Freedman Silvernail et al. (2013) reported knee flexion angles for obese populations were decreased compared to healthy weight populations at their preferred walking speed, but when walking speed was controlled the knee flexion angle in obese populations was larger than healthy weight populations. This shows that when controlled for speed, obese populations present lower knee flexion than healthy weight participants. However, Lai et al. (2008) found no significant difference between healthy weight and obese populations in any sagittal plane movements. This lack of difference is supported by Browning et al. (2007) who reported that knee kinematics in the sagittal plane were similar for both obese and healthy weight groups.

Influence of Ramp Walking on Gait Biomechanics

There have been several studies conducted to analyze how walking either up an incline or down a decline will affect gait mechanics in healthy weight and obese populations (Strutzenberger et al., 2017; Spyropoulos et al., 1997; Freedman Silvernail et al., 2013; Flegal et al., 2012). Specifically, those participants categorized as obese showed an increased knee flexion while walking uphill (Strutzenberger et al., 2017; Spyropoulos et al., 1997; Freedman Silvernail et al. 2013) while indicating a decrease in knee joint moments and powers in the sagittal and frontal planes (Haight et al., 2014; Spyropoulos et al., 1997; Freedman Silvernail et al., 2013). Finally, it has been found that walking speed and stride length also increase (Flegal et al., 2012) to approach values seen in participants with a healthy weight. However, there is some disagreement in the literature concerning the effects of gradient on walking mechanics. In a study examining walking during ramp ascent by Strutzenberger et al. (2017), an increase in both

knee extension and knee flexion moments can be seen in both obese and healthy weight participants.

Uphill Walking

Walking is the most common form of physical activity in the world (Ehlen et al., 2011) and the most commonly prescribing form of exercise to assist with weight loss, especially for obese participants (Haight et al., 2014). Walking for exercise is limited in obese populations due to abnormal joint loading, which results in a number of factors that decrease an obese individual's ability to exercise such as knee pain (Strutzenberger et al., 2017). To reduce this abnormal knee joint loading, several studies have examined how walking on an incline affects gait biomechanics in healthy weight and obese populations, as incline walking can reduce knee joint loading (Haight et al., 2014; Strutzenberger et al., 2017; Haggerty et al., 2014). This was examined using either an inclined ramp that is several meters long (Wen et al., 2018), or an instrumented treadmill that can change incline angles.

Spatiotemporal Changes

There is some debate over how walking on an incline or decline may affect spatiotemporal characteristics or healthy weight and obese populations. Multiple studies show that as incline increases, step length and stride length decrease (Ehlen et al., 2011; Kimel-Naor et al., 2017; McIntosh et al., 2006). This is expected, as all of these characteristics are dependent on walking speed. Specifically, stride length has been shown to increase from 1.41 m to 1.60 m from level walking to 10˚ ramp walking (McIntosh et al., 2006). However, this is disputed by other studies which reported no significant changes in stride length (Lay et al., 2006; Kimel-Noar et al., 2017). Lay et al. (2006), who reported stride length, normalized by leg length, reported that there are no significant changes in stride length during level walking compared to walking

on 15% gradient (approximately 8.5˚). These data are supported by the results from by Struzenberger et al. (2017) who controlled for speed and found that there was no significant change in step length as gradient increased from level walking to 6˚ and 12˚. This study was conducted on adolescents, and noted that this younger population could explain the differences found in this study compared to adults. However, a study conducted by Kimel-Noar et al. (2017) also reported no significant changes occurred in both step and stride length when walking incline was increased from level walking to 10˚.

In addition to step length and stride length, speed and step frequency have also been shown to decrease as incline increases (Ehlen et al., 2011), however these results are also disputed. McIntosh et al., (2006) reported an increase in walking speed from 1.57 m/s to 1.73 m/s when increasing incline from level to 10˚ incline. These findings are supported by Wen et al., (2018) Who found that healthy weight participants show an increase in walking speed during uphill walking of 1.02 m/s and downhill walking of 0.99 m/s. Conversely, Kimel-Noar et al., (2017) reported a decrease in walking speed from 1.5 m/s to 1.2 m/s using the same level walking and 10˚ incline conditions.

Kinematics

Many previous studies have found that participants present increased knee flexion when walking on an incline (Ehlen et al., 2011; Haggerty et al., 2014; Lay et al., 2006; McIntosh et al.,, 2006). However, some debate in the literature is still present.

Sagittal Plane

In the sagittal plane, Ehlen et al. (2011) noted significant increases in knee flexion angle during early stance phases of walking at 0.50 m/s on a 9˚ incline compared to level walking at 1.75 m/s. These results are supported by several other studies (Haggerty et al., 2014; McIntosh et

al., 2006; Silder et al., 2012; Lay et al., 2006), which all reported significant increases in knee flexion as inclination increased in comparison to level walking. Specifically, Haggerty et al. (2014) reported a significant increase of knee flexion at heel strike from -1.06˚ in level walking to 2.21˚, 15.45˚, 27.34˚, and 37.15˚ at 5%, 10% 15% and 20%, respectively. McIntosh et al. (2006) reported knee flexion at heel strike increased from 7° to 33° at 0° and 10° incline, respectively, and maximum knee flexion also increased in early stance from 19° to 41° at 0˚ and 10˚ incline, respectively. Silder et al. (2012) reported an increase in knee flexion during stance phase from 21˚ in level walking to 25˚ and 34˚ flexion in 5˚ and 10˚ incline, respectively. Finally, Lay et al. (2006) reported that during incline walking, knee flexion increased at heel strike along with increased knee extension during mid-stance. The authors also reported their findings from decline walking and found that knee flexion also increased during stance phase.

It is thought that increased knee flexion and extension during incline walking is needed to help propel the individual up the incline. Increased knee flexion is also required during decline walking to help walk down the incline (Lay et al., 2006), perhaps by allowing for increases and decreases in speed as needed, as well as addressing the need for greater vertical descent. It was also found that this increase in flexion is needed to insure the foot does not drag on the ground during the gait cycle due to the change in elevation (Haggerty et al., 2014). It has also been noted that this change in elevation causes the participant's center of mass height to decrease, or move closer to the ground, as grade increases causing the change in joint flexion during incline walking.

Contrary to these results, Wen et al., (2018) reported that as incline angle increased, knee flexion ROM decreased in participants without previous knee replacements. Specifically, knee flexion ROM in the left and right legs decreased from -43.4˚ and -44.7˚ at level walking to -41.3˚

and -40.4˚ at 5˚ incline, -38.2˚ and -37.0˚ at 10˚ incline, and -35.7˚ and -34.4˚ at 15˚ incline respectively.

While walking downhill, Wen et al., (2018) reported significant increases in knee flexion ROM as angle decreased from level walking to 15˚ decline in participants without knee replacements. Specifically, these participants presented knee flexion ROMs of -43.4˚ and -44.9˚ in the left and right legs at level walking respectively to -53.6˚ and -54.2˚ at 5˚ decline, -62.8˚ and -62.9˚ at 10˚ decline, and-71.0 in both legs at 15˚ decline respectively.

Frontal Plane

In the frontal plane, Haggerty et al. (2014) reported no significant changes in knee abduction angle, suggesting that knee alignment in the frontal plane is not significantly altered while walking on incline angles of 5˚ 10˚ 15˚ and 20˚. It should be noted that this study was comprised of healthy weight participants who had normal knee alignment. These results suggest that walking on an incline does not significantly affect knee angle in the frontal plane during walking, and therefore does not increase the risk of injury or onset of disease.

Conversely to these findings, Wen et al., (2018) reported that participants without knee replacements had a significant increase in knee abduction angle ROM as incline increased with -3.5˚ at 5˚ incline to -5.1˚ at 10˚ incline and -8.1 at 15˚ incline. During downhill walking, Wen et al., (2018) reported that there is a significant increase in knee adduction angle ROM as decline changes from level walking to 10˚ and 15˚ decline. Specifically, at level walking, participants without knee replacements presented adduction ROMs of 3.4˚ and 3.1˚ in the left and right legs which increased to 4.2˚ and 4.6˚ at 10˚ decline and 5.5˚ and 6.1˚ at 15˚ decline. Notably, participants who had a prior knee replacement had the same trend, with 3.8˚ in the replaced limb and 4.6˚ in the healthy limb at level walking, which increased to 4.2˚ and 5.9˚ at 10˚ decline at

5.5˚ and 6.8˚ at 15˚ decline, respectively. The lack of frontal-plane kinematic data in literature presents a need for further testing to be supported in these studies.

Kinetics

Vertical GRF

There is evidence to suggest that walking on an incline may be a useful strategy to reduce knee joint vertical ground reaction force (VGRF) experienced by the participant (Ehlen et al., 2011). It was found that peak VGRF decreased as inclination increased from 1.50 m/s at 0˚ incline compared to 0.5 m/s at 9˚, and that VGRF loading rates decreased from 19,237 N/s at 1.75 m/s at 0˚ walking to 3,758 N/s at 0.5 m/s at 9˚ (Ehlen et al., 2011). This reduction in VGRF is supported by Wen et al., (2018) who reported decreases in VGRF experienced by both participants with and without knee replacements as incline angle increased from level walking to 5˚, 10˚ and 15˚ incline. Specifically, participants without knee replacements experienced peak VGRF of 1.07 BW and 1.09 BW in the left and right legs at level walking respectively compared to 1.05 BW in both legs at 5˚, 1.04 BW in both legs at 10˚, and 1.03 BW and 1.04 BW in the left and right legs at 15˚ incline respectively. The reductions in VGRF and VGRF loading rates can be explained by both the reduction in walking speed and the change in inclination. As a walking surface changed from level walking to an incline, preferred walking speed decreases which will result in a decrease in force production.

Contrary to incline walking, decline walking has been shown to cause increases in VGRF (Wen et al., 2018, Ehlen et al. 2011). Specifically, during decline walking, Wen et al., (2018) reported significant increases in VGRF as decline angle increased. Participants without knee replacements showed an increased peak VGRF of 1.07 BW and 1.09 BW for left and right limbs, respectively, in level walking to 1.13 BW and 1.15 BW in 5˚ decline, 1.19 BW and 1.22 BW in

10˚ decline, and 1.20 BW and 1.22 BW in 15˚ decline, respectively. This increase in VGRF can be attributed to the increases in walking speed. As the participant is moving down the slope with aid of gravity, the walking speed will increase as a result.

Sagittal Plane

When examining knee joint moments, Ehlen et al. (2011) found a significant reduction in peak internal knee extension moments when walking at 0.75 m/s on a 6˚ incline compared to at 1.50 m/s on a 0˚ incline. These results are supported by Silder et al. (2012) who saw a reduction in knee extension moments as inclination increased from 0˚ (-0.94 N/m) to 5˚ (-0.67 N/m) and 10˚ (-0.36N/m) at constant walking speeds. This reduction of joint loading will be beneficial for reducing risk of injury and disease onset, as well as reducing pain, which promotes a more effective method of walking for physical activity in obese populations.

However, in a slight disagreement from these results, Haight et al. (2014) reported that peak external knee flexion moments were not greater during incline walking compared to level walking in both healthy weight and obese adults. These findings are partially supported by Wen (Wen) who reported that there was no significant change in peak knee extension moment as incline increased in participants without knee replacements. Wen et al., (2018) also directly opposes the findings by Ehlen et al. (2011) and Silder et al. (2012) by reporting an increase in peak knee extension moment. Specifically, there was a significant increase from 0.33 Nm/Kg at level walking to 0.45 Nm/Kg at 15˚ incline and from 0.30 Nm/Kg at 5˚ incline to 0.39 Nm/Kg at 10˚ incline and 0.45 Nm/Kg at 15˚ incline. Notably, the author also reported no significant changes in knee abduction moment at loading response as angle decreased from level walking to 5˚, 10˚, and 15˚ decline Wen et al., (2018).

Frontal Plane

In the frontal plane, this study conducted by Ehlen et al. (2011) examined the effects of inclined treadmill walking in obese adults, and found that as incline angle increased and speed decreased, peak knee abduction moment significantly decreased. Specifically, there was a 26% and 54% reduction in peak knee abduction moment when walking at 0.75 m/s on 6˚ incline (47.3 N*m) and at 0.50 m/s on 9˚ incline (38.7 N*m) respectively, compared to 0˚ incline at 1.50 m/s (59.4 N*m) (Ehlen et al., 2011). This reduction in joint moment is supported by Haggerty et al. (2014) who also found a significant reduction in peak knee abduction moments of 0.46 Nm/kg at 10˚ incline, 0.42 Nm/kg at 15˚ incline and 0.37 Nm/kg at 20˚ incline compared to 0.54 Nm/kg at 0˚, respectively (Haggerty et al., 2014). Further support is lended by Wen et al., (2018) who reported that peak knee abduction moment at loading response and push-off decreased as incline increased from level walking to 5˚, 10˚, and 15˚ in both participants with and without previous knee replacements. Specifically, participants without previous knee replacements produced knee abduction moments of -0.43 Nm/Kg and 0.43 Nm/Kg in the left and right legs at level walking compared to -0.39 Nm/Kg and -0.38 Nm/Kg at 10˚ incline, and -0.37 Nm/Kg and -0.36 Nm/Kg at 15˚ incline respectively at load response. The same trend was present in participants with knee replacements with values of -0.36 Nm/Kg and -0.43 Nm/Kg in the replaced and healthy limbs at level walking compared to -0.32 Nm/Kg and -0.37Nm/Kg at 10˚ incline and -0.31 Nm/Kg and -0.36 Nm/Kg at 15˚ incline, respectively.

During decline walking, Wen et al., (2018) reported no significant changes in peak knee abduction moment at loading response in both participants with and without prior knee replacements as angle decreased from level walking to 5˚, 10˚, and 15˚ decline. However, it was reported that a significant increase in peak knee abduction moment occurred at push-off in both

populations. Specifically, participants without knee replacements produced values of -0.25 Nm/Kg and -0.27 Nm/Kg in the left and right legs at level walking respectively compared to -0.28 Nm/Kg and -0.31 Nm/Kg at 5˚ decline, -0.30 Nm/Kg and -0.32 Nm/Kg at 10˚ decline, and -0.33 Nm/Kg and -0.36 Nm/Kg at 15˚ decline, respectively. Those with knee replacements followed the same trend with increases from -0.29 Nm/Kg and -0.32 Nm/Kg in the healthy and replaced limb at level walking respectively to -0.32 Nm/Kg and -0.36 Nm/Kg at 5˚ decline, -0.35 Nm/Kg and -0.40 Nm/Kg at 10˚ decline, and -0.38 Nm/Kg and -0.40 Nm/Kg at 15˚ decline, respectively.

Overall Effects of Walking On an Incline

While there is much dispute about how walking on an incline affects walking gait biomechanics, there is strong agreement that incline walking reduces ground reaction forces as well as knee joint moments in the sagittal and frontal planes, indicating a reduction in knee joint loading in obese adults. In the sagittal plane, it has been found that there is a reduction of knee extension moments as inclination increases (Ehlen et al., 2011; Silder et al.,, 2012). In the frontal plane, it has been found that a reduction in knee abduction moment during walking occurs as inclination increases. All of this occurs while the energy expenditure increases, compared to level walking. While uphill walking does reduce joint loading, there is no research examining the effects of increasing step width while walking uphill. Increasing step width may be another strategy to further decrease medial knee joint loading, a strong indicator for risk of developing knee OA, in both healthy weight and obese populations and as a result further decrease the risk of injuries such as stress fractures or onset of chronic diseases such as knee OA in obese populations who are seeking to walk for exercise.

Altering Step Width

Step width is a variable in biomechanical analysis, measured in the frontal plane, that can be manipulated to influence frontal-plane gait biomechanics. There are several ways step width can be calculated. For example, it can be defined as the distance between two points on the participant's feet at initial ground contact (Brindle et al., 2014), usually the mid-heel, or it can be defined as the mediolateral distance between the center of mass of the feet during the midstance phase of two consecutive steps (Yocum et al., 2018).

It was found by Donelan et al. (2001) that an participants preferred leg step width is approximately 13% of that individual's leg length. Leg length is an anthropometric measurement and is found by measuring the distance from the height of the greater trochanter to the ground while in a standing position. Step width is commonly normalized by measuring the participants leg length and preferred step width, and increasing from the preferred width by some percentage of the participant's leg length (Brindle et al., 2014; Paquette et al. 2014; Yocum et al. 2018). Conversely, from the previously mentioned characteristics, step width measurements in obese participants were greater than those of healthy weight participants with values of 0.13 m compared to 0.10 m in healthy weight participants during level walking (de Souza et al., 2005). An increase in body mass requires an increased support base to improve balance and stability during gait. An increase in body mass often results in increased thigh circumference, which will lead to a wider step width due to the wider distance between each femur. This increased stability and balance provides a reduction in knee joint moments and reduces risk of falling during gait further reducing the risk of injury (de Souza et al., 2005).

Altering step width has been studied in conditions of level walking, running, and stair ascent and descent; however, to our knowledge there has not been a study conducted that

examines the effects of altering step width while walking up and down an incline. As discussed previously, it is known that obese populations have increased joint loading compared to healthy weight populations, putting them at an increased risk of injury or disease during walking. A common approach to lower this risk is to walk up an incline which reduces joint loading and also increases energy expenditure. Altering step width while walking up an incline may be useful in further reducing the knee abduction moment, indicative of medial compartment loading in the knee, which may further reduce the risk of injury or onset of disease even more.

Level Walking / Running

Kinematics

During walking, it was reported by Yocum et al., (2018) that increasing step width significantly reduced peak knee adduction angle at loading response in both healthy weight and obese participants. Specifically, healthy weight participants experienced a reduction from 1.3˚ ± 2.2˚ at their preferred step width to 0.6˚ ± 2.3˚ at the wide step width. The healthy weight group also had a significantly lower adduction angle than the obese group at the wide step width condition.

A study conducted by Brindle et al., (2014) examined the effect increased step width would have on the leg during running. It was found that as step width increased from narrow to wide, peak knee internal rotation angles increased. While only one knee angle was reported, this study also reported decreases in peak hip adduction angles when step width was increased (Brindle et al., 2014).

Kinetics

In the frontal plane, Brindle et al., (2014) found that at the wider step width, peak knee abduction moment was significantly reduced from 62.1 Nm/BW × ht to 53.8 Nm/BW × ht and

knee abduction impulse was significantly reduced from 7.2 Nm/BW × ht to 6.2 Nm/BW × ht. These results are supported by Yocum et al., (2018), who reported that as step width increased, knee abduction moment significantly decreased in obese populations. Specifically, the obese group saw a reduction in abduction moment from −45.1 ± 12.7 N/m to −38.9 ± 11.8 N/m. These results are further supported by Zhao et al., (2007) who conducted a study on a single, elderly male who had an instrumented knee replacement during level walking. It was found that a wide step width reduced knee abduction moments from 0.75 Nm/kg at preferred walking to 0.66 Nm/kg at a wide step width.

Stair Ascent / Descent

Kinematics

In the study conducted by Yocum et al., (2018) the effect of increasing step width was measured during stair ascent and descent. For the healthy weight participants, the average preferred step width was 0.14 ± 0.04 m while the wide step width was 0.30 ± 0.07 m. For the obese group, average preferred step width was 0.17 ± 0.04 m and the wide step width was 0.35 ± 0.07m. In the frontal plane, Yocum et al., (2018) found that peak knee abduction angles increase as step width increases. It was also found that obese participants experience a larger increase in this angle compared to healthy weight participants. This study reported an increase from -3.8˚ to -5.8˚ in the preferred and wide step width conditions, respectively. These values are still significantly greater than healthy weight populations in the same conditions who saw an increase in knee abduction angles from -1.6˚ to -2.1˚. It was also reported that the increased step width resulted in a decrease of the knee abduction ROM. The range of motion decreased from -14.2˚ to -12.8˚ in obese participants, and from -12.6˚ to -9.0˚ in healthy weight participants (Yocum et al., 2018).

A similar study by Bennett et al., (2017) examined the effects of increased toe-in angle and increased step width on lower limb biomechanics during stair ascent and also took into account different knee alignments. This study did not examine obese participants; however, the effects of gait modifications are still worth including in this literature review. Similar to the study by Yocum et al., (2018), this study found that peak knee adduction angles increased and knee adduction ROM increased with both increased toe-in and toe-in plus wide step width gait modifications (Bennett et al., 2017). These conditions are noteworthy as with an increase in toe-in during gate, an increase in step width occurs. As the toe-in angle increases, center of mass will also change and affect step width.

Paquette et al., (2014), examined the effects of increased step width during stair descent in older populations and reported both first and second peak knee adduction angles during stair descent. During this study, step width was measured in a fashion similar to Yocum et al., (2018) and was increased based on percentages of leg length (26% and 39% for wide and wider conditions). It was found that as step width increased, both first and second peak knee adduction angles decreased. The first peak knee adduction angle decreased from 5.9˚ to 4.7˚ and 4.6˚ in the wide and wider conditions, respectively, and the second peak knee adduction angle decreased from 8.4˚ to 6.0˚ and 4.9˚, respectively. It is this decrease in knee adduction angle that may explain the reduction in peak knee abduction moment as described by Paquette et al. (2014a) and Barrios et al., (2009).

Kinetics

Step width has been investigated during stair ambulation in a recent study by Yocum et al., (2018) who found that increasing step width had an effect on several characteristics of gait

during stair ascent. This study also reported that mediolateral GRF significantly increased with an increase in step width.

In the frontal plane, it was reported that as step width increased, knee abduction moments were significantly reduced from -25 Nm to -18 Nm which is lower than that of the healthy weight participants with a value of -20.7 Nm in the same condition (Yocum et al., 2018). This is to be expected based on the kinematic results which reported significant decreases in peak knee abduction angle and abduction ROM. These results support those reported by Zhao et al,. (2007) who also reported decreases in knee abduction moments as step width is increased.

In the sagittal plane, Yocum et al,. (2018) reported that as step width increased, knee extension moments healthy weight and obese populations were significantly different from each other. It was found that healthy weight participants showed significantly lower extension moments in both preferred step width, 104.1 Nm compared to 153.8 Nm in obese populations, and wide step width, 105.3 Nm compared to 159.7 Nm in obese populations. Contradicting Yocum et al., (2018) it was reported that an increase in step width resulted in decreased vertical GRF with a value of 1.50 BW at preferred step width to 1.45 BW and 1.48 BW at wide and wider step widths, respectfully Paquette et al., (2014).

In the frontal plane, there was agreement between Paquette et al., (2014) and Yocum et al., (2018) who both found that knee abduction moment decreased as step width increased. It was also found that first and second peak abduction moments both decreased as step width increased. The first peak abduction moment was reduced from -0.77 Nm/Kg at the preferred step width to -0.73 Nm/Kg in both the wide and wider conditions, the second peak abduction moment was reduced from -0.48 Nm/Kg at the preferred step width to -0.44 Nm/Kg and -0.38 Nm/Kg in the wide and wider step width conditions, respectfully (Paquette et al., 2014).

Other studies (Brindle et al., 2014; Zhao et al., 2007; Barrios et al., 2009) either chose to not collect or not to report knee extension moments. This could be due to the importance of knee abduction and adduction moments when attempting to estimate knee joint loading. However, there is a noticeable trend in reduction of knee abduction moments across all movement conditions tested; walking, running, stair ascent, and stair descent. This reduction in knee abduction moment could be attributed to the change in the frontal GRF vector, which acts as the moment arm. As step width increases, the length from this GRF vector to the knee joint center decreases (Paquette et al., 2014). This is a good indicator that the joint loading at the knee is also being reduced, decreasing the risk of injury or disease occurring during exercise while adopting the step width gait modification.

In the sagittal plane during stair descent, Yocum et al., (2018) reported no significant differences in knee extension moment as step width increased. This is supported in a separate paper published by (Paquette et al., 2014) sought to examine the effect of increasing step width on the medial compartment loading of the knee in patients with knee osteoarthritis. This study reported that as step width increased, there was no significant change in knee extension moment at both wide and wider step widths. There is a noticeable lack of reported knee joint kinetics in the sagittal plane during stair descent.

Walking speeds

The speeds participants walk at during this study will be dictated by the individuals through the use of self-selected walking speeds (SSWS). Walking speed can be measured at either an (SSWS) or maximal walking speed and is appropriate for use with a wide range of populations SSWS can be useful as it may provide understanding of an individual's overall current health as well as risk of suffering a fracture or other injury (Middleton et al., 2016). To

determine the participants SSWS, a similar method to the Middleton study was used. Participants were instructed to walk at a "comfortable speed" up and down the ramp for a total of three trials. An average walking speed was taken over these trials and that value was used as their SSWS.

Conclusion

Overall, knee joint loading has been established as an indicator for knee osteoarthritis later on (Paquette et al., 2014). Of different possible gait modifications that can be used such as stride length, step length, toe in gait, and others as mentioned previously, step width has been shown as an effective modification in reducing knee abduction moments during level walking and stair ascent and descent. To the primary researcher's knowledge, there is currently no study examining preferred and wider step widths during ramp ascent and descent. As such, this study will add critical data to the literature concerning the effects of a step width gait modification and will either aid in confirming the effectiveness or suggest that further examination is needed.

Chapter III

Methods and Materials

Participants

For this study, 21 participants between the ages of 18 and 30 years old were recruited through email, flyers, and word of mouth. Those who were recruited and met the criteria for inclusion and exclusion were asked to participate and separated into two groups based on BMI value (healthy or obese). Thirteen adult participants, seven healthy weight (BMI: 21.76±1.78) and six obese (BMI: 32.21±2.53) met the inclusion criteria and participated in the study. An *a priori* power analysis based on peak knee abduction from previous research (Yocum et al., 2018) was conducted to determine the number of participants needed in the study. It was found that a population of 14 participants, 7 per group were needed for an *alpha* of 0.05, a *beta* of 0.20, and an effect size of 0.8. To conduct the power analysis, a paired samples t-test was used with the G-Power software.

Inclusion Criteria for Healthy Weight Participants:

- Men and Women over the age of 18
- BMI value from 19 to 24

Inclusion Criteria for Obese Participants:

- Men and Women over the age of 18
- BMI value between 30 to 38

Exclusion Criteria for all participants:

- Diagnosed with any joint disease in the lower extremity
- Any conditions affecting the participant's ability to walk
- Must be able to walk without assistance of aid

- Any previous history of lower extremity surgery
- Any previous history of lower extremity fracture fixation (medial/lateral malleolus fracture), ligament/tendon (ACL/MCL) repair, or meniscus injury/repair
- Any minor lower extremity injury, not requiring surgery, (grade 1-2 sprain/strain) in the past 6 months

Instrumentation

For three-dimensional (3D) motion data collection during the test trials, a twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used. Participants wore spandex shorts that were either the lab shorts or their own personal shorts, a tight fitting shirt, and standardized lab shoes (Nike Pegasus). Retroreflective anatomical markers were placed on bony landmarks bilaterally on the participant's acromion process, iliac crest, greater trochanter, medial femoral epicondyle, lateral femoral epicondyle, medial malleolus, lateral malleolus, 1st metatarsal head, 5th metatarsal heads and the 2nd toe. These landmarks served as the anatomical landmarks needed during the static calibration trials. For the tracking markers, four of the retroreflective markers attached to a thermoplastic plate were placed on the posterior trunk, posterior aspect of the pelvis (two- marker cluster on each side), lateral surface of thighs and shanks, and finally on the top of the foot.

Two AMTI force platform(s) were used to collect GRF data (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) during level and ramp walking trials. A customized instrumented ramp system fitted with the two force platforms, with a walkway 3 meters long and 1-meter-wide, was used in the ramp walking trials. The ramp was installed around the force platforms and two separate walking surfaces mounted on top of two separate welded aluminum frames were bolted into two the force platforms individually (Figure

1). However, due to the lab setup, it may be possible that the left leg may not fully strike the force plate during ramp walking. If this occurred for any participant, mid-stance would be found by examining when the GRF vector was aligned vertically with the participant's torso. The ramp has an attached hand rail to provide security for the participants if they ever lose balance (Wen et al., 2018). This hand rail was located on the participant's right side during ramp ascent. For the level walking trials, the force platform(s) were used. The step width was marked with masking tape for the participant to use to guide their step widths during respective wide step width test conditions.

In a previous study, Donelan et al., (2001) reported that a participant's preferred step width was 13% of the participant's leg length, which was defined as the height from the greater trochanter to the floor while in a standing position. In a different study, de Souza et al., (2005) reported that obese populations have an increased preferred step width compared to healthy weight populations with an average value of 12.5cm compared to 10.0cm, respectively.
Prior to data collection, the participant was asked to complete a participant information form in which demographic information such as height, weight, shoe size, etc. were collected. The participant was asked to also fill out a survey, Knee Injury and Osteoarthritis Outcome Score (KOOS), about knee functions and finally a PAR-Q survey to determine the activity levels of participants and if any participants have had any major surgery or injury in the lower extremity in the past 6 months. Participants were then asked to practice ascending and descending the ramp at a self-selected (preferred) speed for three to five trials. This was used to obtain an average walking speed and placement of the respective foot on the force platform or step without targeting. Data from the practice trials were exported to a biomechanical analysis software suite (Visual3D, 2.6, C-Motion, Inc., Germantown, MD, USA). Preferred step widths were calculated

by finding the mediolateral distance between the center of masses of both feet during their respective midstance.

To measure and control for walking speed, two photocells (63501 IR, Lafayette Instrument Inc., IN, USA) and two electronic timers (54035A, Lafayette Instrument Inc., IN, USA) were used, the photocells were placed 3 meters apart across the force platform and kept at the participant's shoulder height. A speed range, preferred walking speed ±10%, was used to control speeds for each condition.

Experimental Procedures

Once the surveys were completed, the participant was fitted into a pair of the running shoes and spandex shorts. Next, the participant was asked to perform a 3–minute warm–up walking at a self-selected speed on a treadmill. Following this warmup, retroreflective markers were attached to participant as previously mentioned, and measurements of leg length and shoulder height were taken. In this study, leg length was measured from the participant's greater trochanter to the medial malleolus. These measurements were needed to determine step width and the appropriate height for the photocells during testing.

Before the actual data collection, a static trial was taken, after which the anatomical markers were removed. A total of six test conditions were performed by each participant. Due to the time required for the installation of the ramp, the ramp conditions were collected prior to level walking. Two to three practice trials were performed to allow the participant to become comfortable waking up and down the ramp and ensure they could properly strike the force plates with the correct foot. During these practice trials, speed was also monitored and recorded to determine their preferred walking speeds. The speed ranges were plus and minus 10% of the preferred walking speed. During conditions 1, 3, and 5, the participant walked freely within this

speed range, and these trials were imported to Visual 3D to determine the average preferred step width for ascent, descent, and level walking. For the wide step width conditions, 13% of the participant's leg length were added to the participant's preferred step width determined during the preferred step width trials. This would allow for consistent increases in step width for all participants. For the participant's convenience, lines of masking tape were placed on the floor to mark out the desired step width for the wide condition beginning just prior to and ending just after the force plates.

For each participant, five successful trials were taken in each condition: preferred and wide step width in level walking and ramp walking. A trial was deemed successful when the participant maintained an appropriate walking speed within the designated speed range, contacted the force platform(s) with the right foot at the designated step width (for wide step width trials only), and did not use the handrail in ramp walking.

Data Analysis

3D kinematic trajectories were analyzed in the Nexus (2.3, Vicon Motion Analysis Inc., Oxford, UK) to ensure that all markers were correctly labelled, no gaps were present in the data, and any ghost markers were removed from the data. If gaps were found, they were filled with either a rigid body fill or pattern fill technique based on the other markers around the gaps. Once this was complete, all data were imported into a 3D data analysis software suite, Visual3D (version 2.6, C-Motion, Inc., Germantown, MD, USA) for 3D kinematic and kinetic analysis. For kinematic analysis, all data were computed with an x-y-z Cardan rotational sequence. Conventions for joint angles and moments were expressed with the right hand rule such that positive values were indicative of hip extension and adduction, knee extension and adduction, and ankle dorsiflexion and inversion angles. Raw marker coordinates data were filtered via a

zero-lag fourth-order Butterworth low-pass filters at a cutoff frequency of 8 Hz. GRF data was filtered at a cutoff frequency of 50 Hz.

In order to improve the accuracy of the joint kinetics calculations, an anthropometric model developed by de Leva et al., (1996) was used. This model was developed to adjust the mean relative center of mass (COM) positions and radius of gyration (RoG) as found by Zatsiorsky et al. (Dempster et al., 1955; Zatsiorsky et al., 1990). One adjustment to calculate segment length was made by applying equations (discussed below) across the sagittal and transverse axis of the segment. The first equation, $T = \bar{r}_{abs} / \bar{r}_{rel}$, was used to find the mean length of the segment (T) where $\bar{r}_{abs}$ is the mean absolute RoG of that segment for the given axis, and $\bar{r}_{rel}$ is the respective mean ratio between segment RoG and length. For each segment, $\bar{r}$ is estimated from the second equation, $\bar{r} = \sqrt{I/\bar{m}}$, where I is the mean segment moment of inertia about the given axis and $\bar{m}$ is the mean segment of mass (de Leva et al., 1996). This model is more accurate than previous models it uses joint centers rather than bony landmarks as seen in the Dempster and Zatsiorsky models (Dempster et al., 1955; Zatsiorsky et al., 1990).

When working with obese populations, it is common to not normalize GRF and joint moment data by body weight and body mass, respectively, as doing so will limit the obesity effects on the joint kinetics and GRF (Browning and Kram, 2007).

In order to identify important critical events and peak values of selected variables from the output of the Visual3D, a customized computer program (VB_V3D, Microsoft VisualBASIC) was used. This program allows researchers to determine the events interactively to ensure accuracy and consistency. The kinetic variables examined in this study were the first and second peaks of vertical GRFs, and peak knee extension and abduction moments, as well as peak knee extension, adduction, and abduction angles, and related ranges of motions (ROM).

Statistical Analysis

Means and standard deviations for both kinematic and kinetic data were calculated for the level walking, and ramp conditions separately. To reduce complications and potential errors during statistical analysis, only data from the normal walking speeds for each condition were used for analysis. A 2 × 2 (Group × Step Width) two-way mixed designed ANOVA was used to determine how obesity and step width, affected the peak knee joint kinematics, moments, and ground reaction forces separately, for level walking, ascent and descent. In additional, when significant interactions were observed, post hoc comparisons using pairwise a t-test were conducted. Significant results were defined as having a p value < 0.05.

Chapter IV

Effects of Increased Step Width on Knee Biomechanics During Inclined and Declined Walking

Abstract

The purpose of this study was to investigate effects of preferred step width and increased step width modification on knee biomechanics, specifically peak knee abduction and extension moments, of obese and healthy-weight participants during incline and decline walking. Seven healthy weight participants and six obese participants categorized by BMI values performed five walking trials on level ground and a 10° inclined and declined instrumented ramp system. Two AMTI force platform(s) were used to collect GRF data (1200 Hz, AMTI,). 3D kinematic data were collected a motion capture system (240 Hz, Vicon). All data were imported into 3D data analysis software, Visual3D (version 2.6, C-Motion, Inc., Germantown, MD, USA) for 3D kinematic and kinetic analysis. A 2 x 2 (step-width x group) mixed model ANOVA was used to examine selected variables. There were significant increases in step width (SW) between the preferred and wide SW conditions for all three walking conditions (all $p<0.001$). An interaction was found for peak KEM ($p=0.048$) and KAbM ($p=0.025$) in uphill walking. During downhill walking, there were no interaction effects. As SW increased, KAbM was reduced ($p=0.007$). In level walking there were no interaction effects for peak mediolateral GRF and KAbM ($p=0.007$). There was a SW main effect for KAbM ($p=0.007$). As SW increased, peak mediolateral GRF and peak KEM increased, while KAbM decreased for both groups. It was found that increasing SW may be a useful strategy for reducing KAbMs in healthy, young populations.

Introduction

Obese individuals often present more extreme gait biomechanics including increased ground reaction forces (GRF) and joint contact forces compared to healthy weight individuals (de Souza et al., 2005). Obesity can lead to many other diseases, one of which being osteoarthritis (OA). Knee, specifically, is one of the most common joints affected by OA and can be found in 10% of men and 13% of women over the age of 60. Development of OA in the medial compartment of the knee is directly associated with medial compartment knee loading, which is commonly assessed through knee abduction moments (KAbM) (Freedman Silvernail et al., 2013).

It is suspected that obese individuals often use this slower walking speed as a protective mechanism to reduce detrimental knee joint loading. Obese participants often present increased ground reaction forces and joint moments, such as knee extension and abduction moments, compared to healthy weight participants, while also walking at slower speeds (de Souza et al., 2005). Previous literature has found that this reduction in walking speed may be a strategy for reducing KAbM in obese populations (Freedman Silvernail et al., 2013). During level walking, a study conducted by Yocum et al., (2018) reported that as step width increased, peak knee adduction angles at loading response were reduced in both healthy weight and obese individuals and KAbM was significantly decreased in obese populations.

In the frontal plane, several studies have found that obese individuals present increased peak KAbM during level walking compared to healthy weight individuals (Blazek et al., 2013; Yocum et al., 2018,). Ehlen et al., (2011) examined treadmill incline and level walking found that as inclination increased first and second peak vertical GRFs decreased compared to level walking. However, the participants also had slower walking speeds while incline walking, which

may also contribute to the reduction in peak GRFs. Wen et al., (2018) reported decreases in VGRFs experienced by both healthy controls and older individuals with total knee replacements as incline angle increased from level walking to 5˚, 10˚ and 15˚ incline. They also reported that peak KAbM at loading-response and push-off decreased as incline increased from level walking to 15˚.

In the sagittal plane, several studies have found that obese individuals presented increased peak knee extension moments (KEM) during level walking compared to healthy weight individuals (Blazek et al., 2013; Yocum et al., 2018,). Wen et al., (2018) reported that KEM was significantly increased in only participants with knee replacements in level walking compared to 10˚ incline. However, there were no significant changes in peak knee extension moment as incline increased in healthy individuals. Ehlen et al., (2011) also found a significant reduction in peak internal KEM when walking on a 6˚ incline compared to level walking. However, in a slight disagreement, Haight et al., (2014) reported that peak external knee flexion moments were not greater during incline walking compared to level walking.

Gait biomechanics can also be affected by the environment, such as ambulating up and down a ramp or stairs. Walking is commonly prescribed as a form of exercise to assist with weight loss, especially for obese individuals (Haight et al., 2014). To reduce abnormal knee joint loading, several studies have examined how walking on an incline affects gait biomechanics in healthy weight and obese populations, and have found that incline walking has been shown to reduce knee joint loading (Ehlen et al., 2011; Haggerty et al., 2014; Wen et al., 2018).

Contrary to incline walking, decline walking has been shown to cause increases in vertical GRF (Ehlen et al., 2011; Wen et al., 2018). Wen et al., (2018) reported significant increases in VGRF as decline angle increased and control participants showed an increased peak

vertical GRF. Previous literature on knee kinetics has presented mixed results. Wen et al., (2018) reported no significant changes in peak loading-response KAbM in both participants with and without prior knee replacements as angle decreased from level walking to 5˚, 10˚, and 15˚ decline. However, it was reported that a significant increase in peak KAbM occurred at push-off in both populations. There were no significant changes in loading-response KAbM as decline angle changed from level walking to 15˚ decline (Wen et al., 2018).

There have been several approaches to implementing various gait modification to reduce knee joint moments such as abduction and external rotation moments. One modification that has not been widely investigated is how altering step width (SW) will affect gait biomechanics. Altering SW may be useful in further reducing the KAbM, indicative of medial compartment loading in the knee, during incline walking which may further reduce the risk of developing knee OA. One major finding in a study by Yocum et al., (2018) is that as step width was increased, KAbM was significantly decreased in both healthy weight and obese participants.

The purpose of this study was to investigate how increasing step width will affect KAbM and KEM of obese and healthy-weight participants during incline and decline walking. Our first hypothesis was that peak KAbM will be reduced in both healthy weight and obese groups for the incline and decline walking conditions. Our second hypothesis was that as SW increases, there will be no change in peak KEM.

Materials and Methods

Participants

Thirteen adult participants, seven healthy weight (Age: 23.29±2.60 years; BMI: 21.76±1.78) and six obese (Age: 25.33±2.81 years; BMI: 32.21±2.53), classified by BMI values, were recruited from the campus community. An *a priori* power analysis based on peak knee

abduction from previous research (Yocum et al., 2018) was conducted to determine the number of participants needed in the study. It was found that a population of 14 participants, 7 per group were needed for an *alpha* of 0.05 and a *beta* of 0.20. A total of 16 participants participated in the study. Sixteen individuals participated, however several participant's data were excluded from the statistical analyses for the following reasons: one participant's data had technical issues in tracking a limb during level walking, one participant was found to have not met the BMI requirements after data collection, and finally one participant's vertical GRF data was an extreme outlier. Prior to data collection, all participants reviewed and signed and informed consent form which was approved by the University Institutional Review Board.

Instrumentation

For three-dimensional (3D) motion data collection during the test trials, a twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used. Participants wore spandex shorts that were either the lab shorts or their own personal shorts, a tight fitting shirt, and standardized lab shoes (Nike Pegasus). Retroreflective anatomical markers were placed on bony landmarks bilaterally on the participant's acromion process, iliac crest, greater trochanter, medial femoral epicondyle, lateral femoral epicondyle, medial malleolus, lateral malleolus, 1st metatarsal head, 5th metatarsal heads and the 2nd toe for both the left and rides sides of the body. These landmarks served as the anatomical landmarks needed during the static calibration trials. For the tracking markers, four of the retroreflective markers attached to a thermoplastic plate were placed on the posterior trunk, posterior aspect of the pelvis (two-marker cluster on each side), lateral surface of thighs and shanks, and finally on the top of the foot.

Two AMTI force platform(s) were used to collect GRF data (1200 Hz, BP600600 and OR-6-7, American Mechanical Technology Inc., Watertown, MA, USA) during level and ramp walking trials. A customized instrumented ramp system fitted with the two force platforms, with a walkway 3 meters long and 1-meter-wide, was used in the ramp walking trials. The ramp was installed around the force platforms and two separate walking surfaces mounted on top of two separate welded aluminum frames were bolted into two the force platforms individually (Figure 1). Step width was marked with masking tape for the participant to use to guide their step widths during the wide step width test conditions.

Prior to data collection, participants were asked to complete a participant information form in which demographic information such as height, weight, shoe size, etc. were collected. The participant was asked to also fill out a survey, Knee Injury and Osteoarthritis Outcome Score (KOOS), about knee functions and finally a PAR-Q survey to determine the activity levels of participants and if any participants have had any major surgery or injury in the lower extremity in the past 6 months. Participants were then asked to practice ascending and descending the ramp at a self-selected (preferred) speed for two to three trials. This was used to obtain an average walking speed and placement of the respective foot on the force platform or step without targeting. Step widths were calculated by finding the mediolateral distance between the center of masses of both feet during their respective midstance.

To measure and control for walking speed, two photocells (63501 IR, Lafayette Instrument Inc., IN, USA) and the Universal Timer software was used. The photocells were placed 3 meters apart across the force platform and kept at the participant's shoulder height. A speed range, mean slow and fast speeds ±5%, was used to monitor the movement trials for each condition.

Experimental Procedures

Once the surveys were completed, the participant was fitted into a pair of the running shoes and spandex shorts. Next, the participant was asked to perform a 3–minute warm–up walking at a self-selected speed on a treadmill. Following this warmup, retroreflective markers were attached to participant as previously mentioned, and measurements of leg length and shoulder height were taken.

In this study, leg length was measured from the participant's greater trochanter to the medial malleolus with measuring tape. These measurements were needed to determine step width. A total of six test conditions were performed by each participant. Due to the time required for the installation of the ramp, the ramp conditions were collected prior to level walking. Two to three practice trials were performed for the ramp and level walking conditions to obtain an average walking speed (plus or minus 10%) for uphill, downhill, and level walking. During preferred SW conditions the participant walked freely within this speed range. Trials in which the speed requirements were met were imported to visual 3D to determine the average preferred step width for ascent, descent, and level walking.

Preferred SW was determined from the average SW of the 5 trials of the preferred SW condition, found using a pipeline in Visual3D. For the wide SW conditions, 13% of the participant's leg length was added to the participant's preferred SW. For the participant's convenience, lines of tape were used to mark out the desired SW for the wide condition and placed on the floor beginning just prior to and ending just after the force plates. Prior to the wide SW conditions, two to three additional practice trials were performed to ensure the participant was able to reach the targeted wide SW consistently for both level walking and on the ramp. For each participant, five successful trials were taken in each condition: preferred and wide SW in

level walking and ramp walking. A trial was deemed successful when the participant maintained an appropriate walking speed within the designated speed range, contacted the force platform(s) with the right foot at the designated SW, and did not use the handrail in ramp walking.

Data Analysis

3D kinematic trajectories were analyzed in the Nexus (2.3, Vicon Motion Analysis Inc., Oxford, UK) to ensure that all markers were correctly labelled, no gaps were present in the data, and any ghost markers were removed from the data. Once this was complete, all data were imported into a 3D data analysis software suite, Visual3D (version 2.6, C-Motion, Inc., Germantown, MD, USA) for 3D kinematic and kinetic analysis. For kinematic analysis, all data were computed with an x-y-z Cardan rotational sequence. Conventions for joint angles and moments were expressed with the right hand rule such that positive values were indicative of hip extension and adduction, knee extension and adduction, and ankle dorsiflexion and inversion angles. Kinematic data were filtered via a zero-lag fourth-order Butterworth low-pass filters at a cutoff frequency of 6Hz, while GRF data were filtered at a cutoff frequency of 50Hz, to remove any noise from the data.

In order to improve the accuracy of the joint kinetics calculations, an anthropometric model developed by de Leva et al., (1996) was used. This model was developed to adjust the mean relative center of mass (COM) positions and radius of gyration (RoG) as found by Zatsiorsky et al., (1990). One adjustment to calculate segment length was made by applying equations (discussed below) across the sagittal and transverse axis of the segment. The first equation, $T = \bar{r}\ abs\ /\bar{r}\ \bar{r}el$, was used to find the mean length of the segment (T) where $\bar{r}\ abs$ is the mean absolute RoG of that segment for the given axis, and $\bar{r}\ \bar{r}el$ is the respective mean ratio between segment RoG and length. For each segment, $\bar{r}$ is estimated from the second equation, $\bar{r}$

$= \sqrt{I/\bar{m}}$, where I is the mean segment moment of inertia about the given axis and $\bar{m}$ is the mean segment of mass (de Leva et al., 1996). This model is more accurate than previous models it uses joint centers rather than bony landmarks as seen in the Dempster and Zatsiorsky models (Dempster et al., 1955; Zatsiorsky et al., 1990) When working with obese populations, it is common to not normalize GRF and joint moment data by body weight and body mass, respectively, as doing so will limit the obesity effects on the joint kinetics and GRF (Browning and Kram, 2007).

In order to identify important critical events and peak values of selected variables from the output of the Visual3D, a customized computer program (VB_V3D, Microsoft VisualBASIC) was used. This program allows researchers to determine the events interactively to ensure accuracy and consistency. The kinetic variables examined in this study were the first and second peaks of vertical GRFs, and peak knee extension and abduction moments, as well as peak knee extension, adduction, and abduction angles, and related ranges of motions (ROM).

Statistical Analysis

Means and standard deviations for both kinematic and kinetic data were calculated for the level walking, and ramp conditions separately. A 2 x 2 (Group x Step width) mixed design ANOVA was used to determine how obesity and step width affected the peak knee joint kinematics, moments, and ground reaction forces separately, for level walking, ascent and descent. In additional, when significant interactions were observed, post hoc comparisons were conducted using a pairwise t-test. Significant results were defined as having a p value < 0.05.

Results

Obese participants had greater mass ($p<0.001$) and BMI ($p<0.001$) than healthy weight participants (Table 1). There were significant increases in step width (SW) between the preferred

and wide SW conditions for all three walking conditions (all $p<0.001$, Table 2). As SW increased, there were no significant differences in walking speeds in all uphill, downhill and level walking conditions.

For the kinetic variables of uphill walking (Table 3), peak vertical GRF was greater for obese participants compared to healthy weight participants ($p=0.012$). Peak mediolateral GRF was increased with increased SW ($p=0.001$). An interaction was found for peak KEM ($p=0.048$) and KAbM ($p=0.025$). Post hoc t-tests showed that peak KEMs were higher in wide SW compared to preferred SW for the healthy weight participants only ($p=0.027$), but not for the obese participants. Peak KAbMs were higher ($p=0.006$) for the obese participants compared to healthy weight participants. Post hoc comparison showed that peak KAbM was higher on preferred SW than wide SW only for obese group ($p=.0.018$).

During the downhill walking (Table 3), there were no interaction effects. Peak vertical GRF was greater for obese compared to healthy weight participants ($p=0.044$). Peak mediolateral GRF was greater in wide SW compared to preferred SW ($p=0.001$). As SW increased, KAbM was reduced ($p=0.007$).

In level walking, there were also no interaction effects (Table 3). There were group effects for peak vertical GRF ($p=0.003$), peak mediolateral GRF ($p=0.021$), and KAbM ($p=0.007$). Obese participants had greater peak vertical GRF ($p=0.003$), KEM (0.021) and KAbM (0.007) compared to healthy weight participants. A SW main effect was found for peak mediolateral GRF ($p<0.001$), peak KEM ($p=0.021$), and KAbM ($p=0.007$). As SW increased, peak mediolateral GRF and peak KEM increased, while KAbM was reduced.

For the knee joint kinematics during uphill walking (Table 4), there were no interaction effects for any of the variables. There was a group difference in peak adduction angle, with obese

participant's having a great peak adduction angle than healthy weight participant's (p=0.009). During downhill walking (Table 4), there were no interaction, group, or SW main effects in any of the kinematic variables examined.

For level walking (Table 4), there was an interaction for adduction ROM (p=0.021, Table 4). Post hoc T-tests showed that it was reduced in healthy weight participants only (p=0.001). Finally, peak adduction angle was reduced in wide SW compared to preferred SW (p=0.016).

Discussion

The purpose of this study was to investigate effects of preferred step width and increased step width modification on knee biomechanics, specifically peak knee abduction and extension moments, of obese and healthy-weight participants during incline and decline walking. Our first hypothesis was that peak KAbM would be reduced in both healthy weight and obese groups for the ascent and descent conditions.

The results supported the first hypothesis for both healthy weight and obese populations. There was a significant reduction in peak loading-response KAbMs as SW increased from preferred to wide SW for all walking conditions for both groups. These reductions may be attributed to several factors. First, as SW increased, there was also an increase in medial GRF during the uphill and level walking conditions. It is worth noting here that there was not a significant difference in SW during the downhill conditions which may explain relatively smaller, yet still significant, reduction of KAbM during the downhill conditions. KAbM is calculated from the frontal-plane GRF and its moment arm to the knee joint center, and this frontal-plane GRF is calculated from the vertical and mediolateral GRFs which is projected onto the tibia reference frame. These increases in medial GRF coupled with lack of significant changes in the peak vertical GRF suggest that the moment arm was most likely reduced with

increased SW. An increase in SW may cause the knee joint center to move more laterally, reducing the distance from the knee joint center to the resultant GRF in the frontal plane. Previous literature proposed that this increase in medial GRF leads to a reduction in the frontal plane GRF moment arm at the knee (Jenkyn et al., 2008; Paquette, 2014; Yocum, 2018).

The results concerning medial GRF in the present study are supported by previous literature, as there was also an increase in medial GRF during stair ascent and descent as SW increased in both healthy weight and obese populations ($p=0.001$) (Paquette et al., 2014; Yocum et al., 2018). This is the first study to the researcher's knowledge, which directly examines increasing SW during uphill and downhill walking. In this study, there was also a decrease in peak knee adduction angles as SW increased during the level walking conditions. This reduction in peak knee adduction angles during level walking may be related to the reduction of the moment arm in the frontal plane (Bennett et al., 2017; Paquette et al., 2015; Yocum et al., 2018). Our KAbM results are also supported by the previous stair ambulation study by Yocum et al., (2018) who focused on a similar, younger population, and found that as SW increased, there was a reduction in loading-response KAbM in the obese group, and the obese groups preferred SW was significantly different from the healthy weight group during this condition. These results are also supported by Paquette et al., (2014) who also found that increasing SW reduced loading-response KAbM during stair ascent and descent in both healthy and knee OA participants.

We also hypothesized that as SW increases, there would be no change in peak KEM across both step width conditions. The hypothesis was only partially supported, as there was an increase in peak KEM during level walking, for the both groups as SW increased from preferred to wide. As SW increased, no increases in vertical GRF were observed for any of the conditions. This lack of change may explain why there was no change in peak KEM with increasing step

width in uphill and downhill conditions. During the gait cycle, the knee extensors must activate at heel strike and during a majority portion of the stance phase to provide posture support and attenuate the vertical GRF. If there had been significant changes in peak KEM as SW increased, the knee extensors would have increased activation compared to normal to attenuate any increase in vertical GRF. Although we did not collect EMG data, it can be assumed that, since there are no significant changes in peak KEM for uphill and downhill walking Because the knee extensors are activating at the same intensity for all trials, there would not be an increase in this peak KEM, there would not be an increase in this peak KEM. Moreover, the sagittal-plane moment arm for knee extensors is unlikely affected by an increase in SW.

In level walking, our results are similar to the study by Yocum et al., (2018) who also found that increasing SW will lead to increased peak loading-response KEM for both populations. In the present study, it was found peak KEM was increased during level walking for both groups. An interaction was also found, as the healthy weight group had a significantly lower KEM during uphill walking compared to the same SW of the obese group. This was unexpected as SW was thought to only impact the frontal plane variables, and there was no change in surface inclination which could affect the KEM as was the case during downhill walking.

Our results showed increased peak vertical GRFs for obese participants in all three modes of gait compared to healthy weight participants. This is expected as increased body mass directly affects the GRF magnitudes in gait. However, there were no significant increases in KEM for obese participants compared to healthy weight. These results are unexpected. Previous research in stair ascent and descent showed obese participants also had greater peak KEM than healthy weight participants (Yocum et al., 2018). The p values for KEM in downhill ($p=0.078$) and level walking ($p= 0.097$) were close to be significant and showed a trend of higher KEM for obese

compared to healthy weight participants (Table 3). If the sample size had been larger, perhaps a significantly higher KEM would be achieved for the obese participants. In addition, both participant groups walked at similar speed, which may also partially explain the similar KEM values.

There are several limitations that are present in this study. First, sample size for the study is considered to be small although the power analysis showed a sample size of sever for each group would be sufficient. Although the number of participants in the obese group (n=6) did not meet the required minimum of estimated sample size and the observed power reached an acceptable level. Several participant's data were not included in the statistical analysis. The data from one of the obese participants was excluded due to technical difficulty in tracking a segment during the level walking conditions. Another obese participant was excluded because it was later found BMI did not meet the obese BMI requirement. Finally, one healthy participant was excluded as the data of key loading variables were shown to be outlier. Second, the average BMI (32.2) of the obese group was on the lower end of the obese range. Furthermore, it is common knowledge that bony landmarks are much harder to palpate on participants with excessive adipose tissue than lean participants. It was difficult to accurately palpate some bony landmarks and place anatomical markers on the obese participants. Finally, we did not account for differences in body composition for the obese population. It is possible that obese participants might have a large lean body mass and not increased adipose tissue.

In summary, increasing SW resulted in reduced peak KAbM for uphill, downhill and level walking. There was also an increase in mediolateral GRF for both groups across all three gait conditions as SW increased. In level walking, as SW increased, there was an increase in KEM. The healthy weight group also had a lower peak KEM during uphill walking compared to

the same SW condition for the obese group. Increasing SW may be a useful strategy for reducing KAbMs, in a healthy and young population.

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Appendices

Appendix A: Informed Consent

Consent for Research Participation Research Study Title: Effects of Increased Step Width on Knee Biomechanics in Healthy-

weight and Obese Populations during Inclined and Declined Walking at Different Speeds
Researcher(s): Daniel Sample, University of Tennessee, Knoxville

Faculty Advisor: Dr. Songning Zhang, University of Tennessee, Knoxville

Why am I being asked to be in this research study?

We are asking you to be in this research study because you have met all the inclusion and exclusion criteria and we believe you will be a good candidate for this study. The inclusion and exclusion criteria include:

Inclusion Criteria for Healthy Weight Participants: • Men and Women between the ages of 18 and 30 years old • BMI value from 19 – 24kg/m2 Exclusion Criteria for Healthy Weight Participants: • Diagnosed with any joint disease in the lower extremity • Any conditions affecting the participant's ability to walk • Must be able to walk without assistance of aid • Any previous history of major lower extremity surgery • Any major lower extremity injury • Any minor lower extremity injury in the past 6 months Inclusion Criteria for Obese Participants: • Men and Women between the ages of 18 and 30 years' old • BMI value between 30 – 38 kg/m2 • Does not meet the guidelines for physical activity set by the ACSM (≤ 150 mins/week) Exclusion Criteria for Obese Participants: • Diagnosed with any joint disease in the lower extremity • Any conditions affecting the participant's ability to walk • Must be able to walk without assistance of aid • Any previous history of major lower extremity surgery • Any major lower extremity injury in the past 6 months • Meets the guidelines for physical activity set by the ACSM (≥ 150mins/week)

What is this research study about?

The purpose of this study is to investigate effects of preferred step width and increased step width modification on knee biomechanics of obese and healthy-weight participants during incline walking.

IRB NUMBER: UTK IRB-18-04828-XP IRB APPROVAL DATE: 12/03/2018

How long will I be in the research study?

If you agree to participate, your participation will last approximately 1-1.5 hours.

What will happen if I say “Yes, I want to be in this research study”?

If you agree to be in this study, we will ask you to schedule a time and date for data collection. All data collection will take place in the Biomechanics/Sports Medicine Laboratory (HPER 139). Upon your arrival to the lab, you will be provided with the informed consent document as well as surveys to assess your ability to complete the data collections, these surveys include the PAR-Q+ and Knee Injury and Osteoarthritis Outcome Score (KOOS). You will also be asked to fill out an information sheet which collects demographic and past major pathological and injury history information.

After the surveys are completed, your eligibility to participate will be determined based upon your answers to the questions. The primary investigator will be present to assist you with these forms and discuss any questions you may have if needed. If you are not eligible to participate, we will immediately destroy and documents containing your personal information and thank you for your time thus far. If you are eligible to participate and still wish to continue, you will be asked to:

- Change into appropriate clothing provided by either yourself or the lab
- Complete a brief 3-minute walking warmup on a treadmill
- Be fitted with retroreflective markers and have a calibration trial taken
- Complete 5 successful walking trials per each of 6 test conditions for incline, decline, and level walking What happens if I say “No, I do not want to be in this research study”? Being in this study is up to you. You can say no now or leave the study later at any time. Either way, your decision won’t affect your grades, your relationship with your instructors, or standing with the University of Tennessee, Knoxville. What happens if I say “Yes” but change my mind later? Even if you decide to be in the study now, you can change your mind and stop at any time. If you decide to stop before the study is completed, please inform the primary investigator to end your participation. Once the primary investigator is informed, your collected data, and any data identifying you directly will be destroyed immediately. Are there any possible risks to me?

Potential risk associated with this study is minimal, and there are safety rails to support you if need be. The researchers are also certified in first aid to render care if needed. It is also possible that someone could find out you were in this study or see your study information, but we believe this risk is small because of the procedures we use to protect your information. These procedures are described later in this form.

Are there any benefits to being in this research study?

There is a possibility that you may benefit from being in the study, but there is no guarantee that will happen. Possible benefits include the identification of any possible abnormalities of gait, balance and other physical functions as a result of their participation in the study which may serve as valuable information for correcting these abnormalities, which may improve their physical functions. Both Obese and healthy-weight participants will be provided with opportunity to review their personal data if they so choose. Even if you don't benefit from being in the study, your participation may help us to learn more about the gait deficits that are present with differences in body mass when adopting different gait patterns. Identifying the gait abnormalities in younger populations is a useful step in reducing risk of adverse effects developing later in life. We hope the knowledge gained from this study will benefit others in the future.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your information by de-identifying data such that only participant numbers will be collected and attributed to your data. Only the principal investigators and Biomechanics/Sports Medicine Laboratory personnel will have access to the respective participant information and data. The de-identified data will be stored on hard drives of password protected computers in the Biomechanics/Sports Medicine Lab for a minimum of three years after the completion of the study and will be backed up onto DVDs, flash drives, and/or data backup cartridges, and then deleted from all hard drives. All participant data will be coded numerically and referred to only by the code and not by participant name at the time of data collection. Identity of the participants will be held in strict confidence through the use of the coded participant numbers during data collection, analysis, and in all references made to data, both during and after the study, and in the reporting of the results. If information from this study is published or presented at scientific meetings, your name and other personal information will not be used. We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information or what information came from you. Although it is

unlikely, there are times when others may need to see the information we collect about you. These include:

- People at the University of Tennessee, Knoxville oversee research to make sure it is conducted properly.

- Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research.

- If a law or court requires us to share the information, we would have to follow that law or final court ruling. What will happen to my information after this study is over? We will not keep your information to use for future research purposes. Your name and other information that can directly identify you will be deleted from your research data collected as part of the study. We may share your research data with other researchers without asking for your consent again, but it will not contain information that could directly identify you. Who can answer my questions about this research study? If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Daniel Sample via email at dsample1@vols.utk.edu, or via phone at (865) 974-2091. You may also contact my faculty advisor, Dr. Songning Zhang via email at szhang@utk.edu.

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board The University of Tennessee, Knoxville 1534 White Avenue Blount Hall, Room 408 Knoxville, TN 37996-1529 Phone: 865-974-7697 Email: utkirb@utk.edu

STATEMENT OF CONSENT

I have read this form and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am agreeing to be in this study. I will receive a copy of this document after I sign it.

Name of Adult Participant Signature of Adult Participant Date

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

Name of Research Team Member Signature of Research Team Member Date

_____ _____ _____

_____ _____ _____

Appendix B: Recruitment Flyer

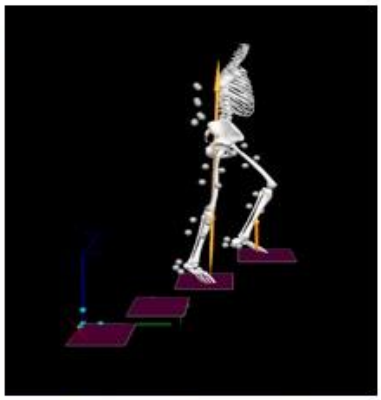
RESEARCH PARTICIPANTS NEEDED FOR A STUDY ON THE EFFECTS OF BODY MASS AND STEP WIDTH DURING RAMP ASCENT AND DESCENT

Qualifications to participate in the study include:

- Between the ages of 18 and 30 yrs.
- Healthy with a BMI between 19 – 24 or 30 – 38.
- No major lower extremity injuries within the past 6 months.
- No chronic condition affecting balance or leg function.
- No lower extremity surgery. Able to walk up and down a ramp without use of handrail.
- Do not meet the guidelines for physical activity set by the ACSM (≤ 150 mins/week).

Researchers from the Department of Kinesiology at UT are conducting research to understand the effects of body mass and step width during stair ascent and descent on the knee joint. Participants will attend a 1-1.5 hour testing session in the Biomechanics/Sports Medicine lab.

If you would like to participate or for more information contact Daniel Sample at the UT Biomechanics/Sports Medicine Lab.
Office: 865-974-3340
Email: dsample1@vols.utk.edu



Contact: Daniel Sample
P: 974-3340
E: dsample1@vols.utk.edu

Contact: Daniel Sample
P: 974-3340
E: dsample1@vols.utk.edu

Appendix C: Recruitment Email

Hello, are you an adult between the ages of 18-30? Are you free from major lower extremity surgery? Are you interested in helping to advance the understanding recreational and therapeutic exercise and disease risk minimization? If so, we have a research participation opportunity for you! A group of researchers from the Biomechanics/Sports Medicine Lab in the Department of Kinesiology, Recreation, and Sports Studies are conducting a research protocol examining the effects of increased step width on knee functionality. Participation involves one visit (lasting between 1 and 1.5 hours) to the biomechanics lab in the HPER building. During the visit, you will perform small bouts (about 30 minutes **total**) of walking across different environments (level, uphill and downhill) at your own pace. If you are interested in participating or if you have any additional questions, please email Daniel Sample (dsample1@vols.utk.edu) or contact him by phone at (423) 863-6094. Please see the attached flyer for more

details. Thank you for your interest!

IRB NUMBER: UTK IRB-18-04828-XP IRB APPROVAL DATE: 12/03/2018

Appendix D: Par-Q+

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

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.

No	Yes	
☐	☐	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 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 of heart condition?
		7. Do you know of any other reason why you should not do physical activity?

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

If you answered YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active of BEFORE you have a fitness appraisal. Tell you 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 to 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.

If you answered NO to all questions

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

Delay becoming much more active if:

- You are not feeling well because of a temporary illness such

- Start becoming much more physical active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part if 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.

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.

I understand that my signature signifies that I have read and understand all the information on the questionnaire, that I have truthfully answered all the questions, and that any question/concerns I may have had have been addressed to my complete satisfaction.

_____

Name (please print)

_____

Signature

_____

Date

Appendix E: Demographic Questionnaire

Demographic Questionnaire

Participant #: Age: Height:_____ Gender (circle one):

Any major lower extremity injuries of surgeries? If yes, please explain further: Injury: Date:

Any lower extremity joint disease diagnosed by a physician? If yes, please explain further: Diagnosis:

Date (MM/DD/YYYY): ____/_____/_____ Shoe Size (US): Weight:_____

_____ _____ _____

Female Male

(Circle One)

Yes No

_____

_____ _____

_____

(Circle One)

Date:

Yes No

_____

_____ _____

_____

Any disorder affecting gait or balance? (Circle One)

Any lower extremity injuries within the past six months? (Circle One) Yes No If yes, please explain further: Date of injuries : Injury:

Any pain while performing common activities of daily living, such as walking or biking?

(Circle One) Yes No

Yes No

IRB NUMBER: UTK IRB-18-04828-XP IRB APPROVAL DATE: 12/03/2018

Appendix F: Knee injury and Osteoarthritis Outcome Score (KOOS)

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

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 3

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

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 4

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 G: Chapter 4 Data Tables and Figures

Table 1. Participant (n=13) Demographic Information: mean ± STD.

	Healthy	Obese	p
Age (years)	23.3±2.81	25.3±3.08	0.326
Height (m)	1.70±0.07	1.79±0.103	0.122
Mass (kg)	66.46±8.49	103.07±14.37	**0.002**
BMI (kg/m^2)	21.76±1.92	32.20±2.78	**<0.001**

BFP: Body Fat Percent, BMI: Body Mass Index. **Bold:** p-values indicate significance.

Table 2. Uphill, Downhill and Level Walking Step Widths (m) and Speeds (m/s): mean ± STD.

	Healthy		Obese		Int.	Grp.	SW
Variable	Preferred SW	Wide SW	Preferred SW	Wide SW	p	p	p
Ascent SW	0.115±0.017[a]	0.220±0.019	0.153±0.047[a]	0.249±0.066	0.312	0.166	**<0.001**
Ascent Speed	1.30±0.078	1.28±0.098	1.35±0.202	1.32±0.192	0.873	0.360	0.163
Descent SW	0.134±0.045[a]	0.219±0.016	0.157±0.033[a]	0.247±0.063	0.817	0.250	**<0.000**
Descent Speed	1.37±0.116	1.33±0.166	1.37±0.177	1.30±0.205	0.764	0.865	0.133
Level Walking SW	0.136±0.039[a]	0.248±0.043	0.171±0.052[a]	0.267±0.073	0.437	0.336	**<0.001**
Level Walking Speed	1.39±0.091	1.44±0.185	1.48±0.213	1.40±0.146	0.794	0.369	0.063

[a]: Significantly different from Wide SW of the same participant group, [#]: Significantly different from Obese of the same SW, Int.: Interaction, Grp.: Group Main Effect, SW: Step Width, **Bold:** p-values indicate significance.

Table 3. Peak Loading-Response GRFs (N), Knee Extension and Knee Abduction Moments (Nm) for Uphill, Downhill and Level Walking: mean ± STD.

	Healthy		Obese		Int.	Grp.	SW
Variable	Preferred SW	Wide SW	Preferred SW	Wide SW	p	p	p
			Uphill				
Vertical GRF	713.0±146.2 [#]	697.6.2±120.9[#]	1073.4±271.2	1041.0±283.9	0.635	**0.012**	0.198
Mediolateral GRF	-45.1±29.2 [a]	-58.1±10.4	-50.0±25.7 [a]	-89.4±38.6	0.054	0.221	**0.001**
Knee Extension Moment	45.4±28.7 [a]	55.7±29.2	78.3±37.8	72.2±42.3	**0.048**	0.219	0.573
Knee Abduction Moment	-21.8±9.0	-20.7±7.1	-47.1±16.3[a]	-39.0±14.3	**0.025**	**0.006**	**0.006**
			Downhill				
Vertical GRF	869.0±123.1[#]	852.7±124.9[#]	1326.9±293.6	1159.4±124.9	0.344	**0.044**	0.254
Mediolateral GRF	-52.0±78.2 [a]	-94.8±106.8	-70.0±36.5 [a]	-95.7±49.1	0.274	0.823	**0.001**
Knee Extension Moment	79.8±24.3	73.4±29.2	109.1±34.5	112.1±40.2	0.219	0.078	0.645
Knee Abduction Moment	-41.1±12.8[#]	-33.6±10.3[#]	-65.0±17.4	-62.6±18.9	0.315	**0.007**	0.062
			Level				
Vertical GRF	728.4±87.7[#]	727.3±86.7[#]	1178.6±274.4	1153.3±303.2	0.242	**0.003**	0.203
Mediolateral GRF	-47.8±11.5 [a #]	-77.9±17.2[#]	-76.3±18.3 [a]	-119.9±48.2	0.361	**0.021**	**<0.001**
Knee Extension Moment	38.9±17.8 [a]	48.3±19.9	74.0±43.0 [a]	77.5±43.1	0.252	0.097	**0.021**
Knee Abduction Moment	-38.3±9.9 [#]	-36.0±8.9[#]	-65.4±16.1[a]	-56.2±17.3	0.075	**0.007**	**0.007**

[a]: Significantly different from Wide SW of the same participant group, [#]: Significantly different from Obese of the same SW, Int.: Interaction, Grp.: Group Main E

Table 4. Peak Knee Extension/flexion and Knee Adduction Angles (deg) and ROM (deg) for Uphill, Downhill and Level Walking: mean ± STD.

	Healthy		Obese		Int.	Grp.	SW
Variable	Preferred SW	Wide SW	Preferred SW	Wide SW	p	p	p
			Uphill				
Extension ROM	18.4±8.3	22.2±10.5	17.2±5.3	17.9±6.2	0.281	0.509	0.147
Peak Adduction angle	2.0±3.2[#]	2.0±2.3[#]	7.8±3.6	7.2±3.8	0.480	**0.009**	0.548
Adduction ROM	4.2±2.0	2.7±1.8	1.6±1.2	1.6±2.5	0.209	0.131	0.206
			Downhill				
Flexion ROM	-61.9±4.2	-60.5±4.8	-66.7±3.6	-62.9±13.3	0.612	0.307	0.276
Peak Adduction angle	2.1±2.0	2.0±3.3	4.7±3.5	3.5±4.1	0.343	0.259	0.308
Adduction ROM	6.6±2.1	4.8±2.1	3.9±1.5	4.2±2.9	0.073	0.161	0.214
			Level				
Flexion ROM	-46.4±3.1	-45.5±4.1	-49.2±6.6	-48.9±7.8	0.819	0.294	0.632
Peak Adduction angle	0.8±1.6	0.3±1.5	3.9±4.1	2.5±4.2	0.185	0.136	**0.016**
Adduction ROM	4.8±2.3[a]	3.9±2.3	2.8±0.7	2.7±1.3	**0.021**	0.146	**0.009**

[a]: Significantly different from Wide SW of the same participant group, [#]: Significantly different from Obese of the same SW, Int.: Interaction, Grp.: Group Main E

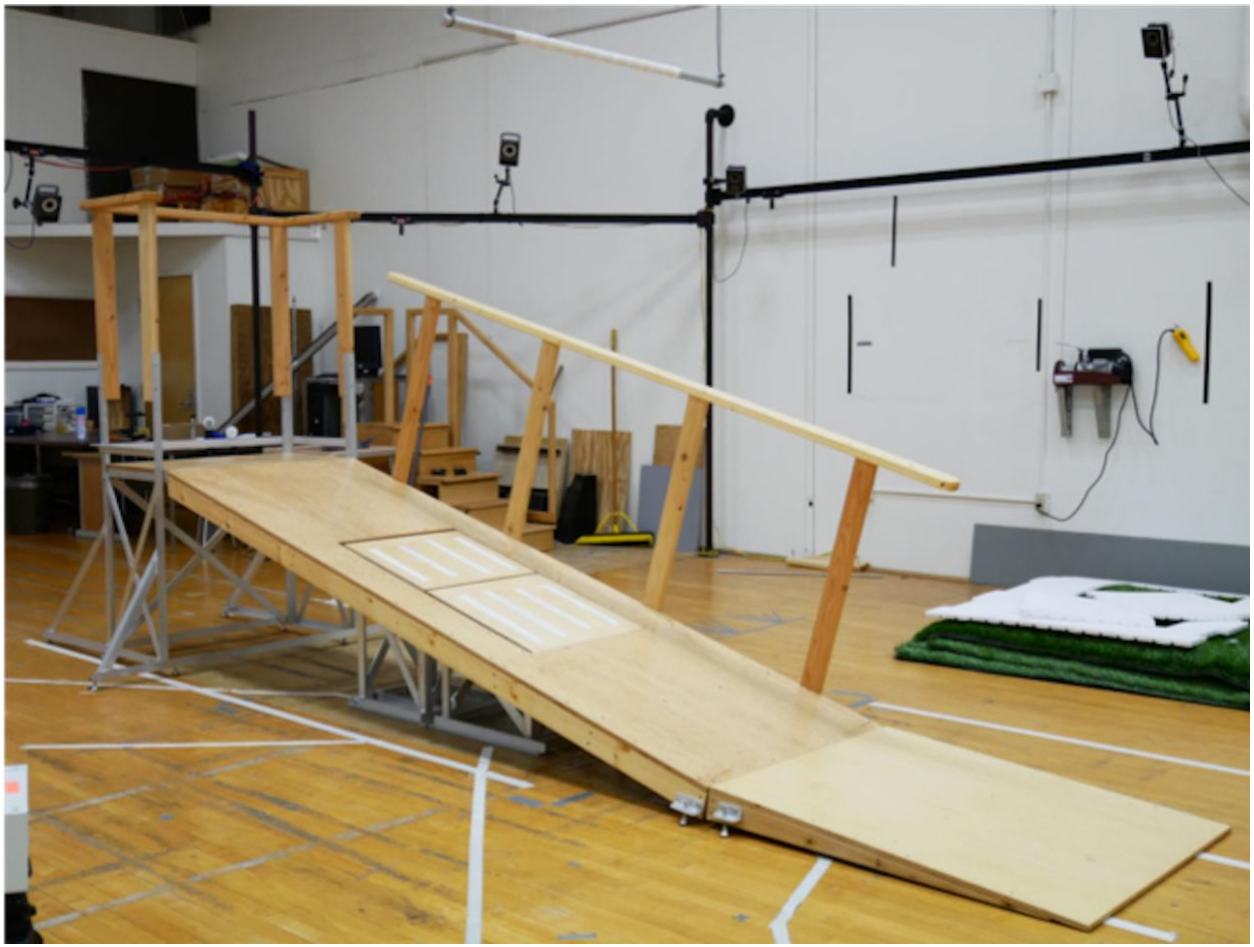


Figure 1. An incline ramp with handrail and instrumented platforms attached. The instrumented platforms are secured with a bolt in each corner of the force platform to ensure a sturdy connection.

Appendix H: Participant Tables

Table 5. Step width (m)

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	.14	.16	.25	.25	.16	.28
6	.10	.06	.21	.21	.10	.21
7	.12	.17	.21	.22	.16	.28
9	.12	.16	.21	.23	.17	.30
10	.12	.13	.22	.22	.13	.23
11	.13	.17	.24	.23	.15	.26
15	.09	.09	.20	.19	.07	.18
1	.12	.12	.22	.22	.12	.24
2	.11	.14	.17	.20	.20	.20
4	.11	.14	.18	.16	.11	.19
12	.19	.19	.31	.30	.19	.30
13	.22	.20	.32	.32	.24	.38
16	.17	.17	.28	.27	.17	.29

Table 6. Walking speed (m/s)

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	1.27	1.20	1.19	1.09	1.28	1.30
6	1.30	1.50	1.32	1.54	1.42	1.40
7	1.21	1.26	1.22	1.22	1.30	1.27
9	1.29	1.47	1.23	1.27	1.37	1.37
10	1.22	1.35	1.17	1.24	1.38	1.25
11	1.42	1.34	1.42	1.42	1.53	1.55
15	1.38	1.48	1.38	1.51	1.48	1.44
1	1.53	1.50	1.45	1.21	1.65	1.52
2	1.64	1.64	1.66	1.70	1.80	1.76
4	1.35	1.25	1.27	1.21	1.41	1.38
12	1.13	1.26	1.19	1.12	1.22	1.22
13	1.22	1.38	1.17	1.30	1.33	1.34
16	1.20	1.17	1.22	1.27	1.45	1.44

Table 7. Participant Demographics

Participant	Height (m)	Weight (kg)	BMI category	AGE (Years)
5	1.68	68	24.09	22
6	1.8	72.7	22.44	26
7	1.78	76	23.99	21
9	1.75	59	19.27	24
10	1.67	58.1	20.83	26
11	1.6	56.4	22.03	24
15	1.65	75	19.70	20
1	1.75	93	30.37	30
2	1.94	115	30.56	22
4	1.62	83	31.63	27
12	1.8	121.4	37.47	23
13	1.81	108	32.97	26
16	1.8	98	30.25	25

Table 8. Peak Loading-Response Knee Abduction Moments (Nm) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	-28.82	-42.37	-28.99	-40.62	-36.18	-42.27
6	-28.51	-68.30	-21.79	-52.17	-51.17	-46.00
7	-35.44	-40.26	-29.54	-31.73	-53.23	-47.20
9	-16.96	-27.87	-19.68	-26.80	-28.45	-27.49
10	-17.21	-37.18	-20.41	-21.30	-34.95	-29.70
11	-13.48	-36.35	-11.20	-35.56	-31.64	-32.92
15	-12.13	-35.68	-12.97	-27.28	-32.21	-26.38
1	-30.98	-55.10	-18.64	-53.34	-62.37	-41.08
2	-71.31	-97.26	-58.21	-98.46	-93.77	-89.70
4	-35.01	-68.54	-28.83	-64.77	-57.60	-53.00
12	-63.43	-53.25	-50.20	-58.95	-54.17	-49.61
13	-40.33	-66.08	-41.66	-43.74	-73.87	-57.12
16	-41.74	-50.04	-36.19	-56.26	-50.42	-46.88

PSW: Preferred Step Width, WSW: Wide Step Width

Table 9. Knee Adduction ROM (deg) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	.90	3.90	1.76	3.55	3.06	2.59
6	1.72	4.01	1.49	3.54	2.44	1.57
7	5.26	9.80	5.82	9.04	8.91	7.78
9	5.37	6.50	1.40	4.05	3.66	2.26
10	5.67	7.62	2.75	3.14	5.80	5.51
11	4.84	7.97	4.55	6.46	6.24	5.32
15	5.37	6.50	1.40	4.05	3.66	2.26
1	.54	3.23	.54	3.25	2.00	1.02
2	1.59	5.02	3.10	9.90	3.56	3.19
4	1.21	1.54	.99	1.58	1.84	1.34
12	3.74	4.84	5.86	3.25	3.43	4.41
13	.20	3.13	-1.12	3.55	2.76	2.73
16	2.38	5.51	.26	3.89	3.27	3.70

PSW: Preferred Step Width, WSW: Wide Step Width

Table 10. Knee Flexion ROM (deg) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhil l PSW	Uphill WSW	Downhil l WSW	Level PSW	Level WSW
5	19.84	-23.42	19.84	-33.24	-5.34	-7.29
6	8.19	-22.55	7.60	-23.58	-10.18	-7.84
7	22.66	-20.58	23.59	-20.39	-2.15	-3.59
9	14.78	-15.78	23.74	-22.76	-4.53	-2.49
10	9.25	-13.42	11.93	-8.83	-1.34	-.39
11	31.68	-31.85	34.77	-34.54	-4.29	-3.96
15	22.28	-24.26	35.41	-23.73	-1.17	-.77
1	13.26	-27.07	11.53	-24.79	.69	-2.13
2	18.85	-26.70	14.80	-21.26	-1.51	-.85
4	24.75	-16.17	25.98	-6.28	2.47	1.75
12	16.58	-25.00	11.38	-23.26	-12.34	-11.66
13	20.12	-21.16	23.54	-22.78	-3.77	-5.04
16	9.73	-19.52	19.89	-13.82	-3.71	-3.28

PSW: Preferred Step Width, WSW: Wide Step Width

Table 11. Peak Mediolateral Load-Response GRF (N) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	40.30	-51.93	40.30	-96.28	49.22	97.18
6	108.91	-55.76	65.91	-89.65	40.27	67.35
7	39.46	116.72	71.16	124.87	64.04	89.68
9	43.14	-68.39	65.87	-104.52	59.38	84.72
10	34.40	-119.38	56.82	-191.42	40.84	62.42
11	20.46	-99.65	53.24	-197.54	49.82	91.96
15	29.00	-85.88	53.51	-109.27	30.77	52.19
1	42.35	-143.21	70.31	-194.66	53.36	83.46
2	44.47	-65.04	78.38	-88.88	84.61	80.32
4	12.13	-45.67	34.97	-66.58	53.05	74.93
12	87.61	-50.95	141.07	-72.17	94.26	183.78
13	68.70	-56.34	125.92	-73.47	89.32	170.53
16	44.96	-58.71	86.08	-78.42	82.99	126.65

PSW: Preferred Step Width, WSW: Wide Step Width

Table 12. Peak Knee Extension Moments (Nm) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	74.69	66.61	74.69	71.93	27.76	52.06
6	24.50	86.08	33.60	90.75	40.54	56.85
7	89.94	109.75	104.43	82.75	51.50	48.87
9	33.00	104.57	61.92	97.86	67.22	81.74
10	11.08	40.17	15.53	10.13	13.35	16.55
11	55.20	86.39	63.96	84.20	44.06	46.55
15	29.58	65.07	35.93	76.15	27.55	35.40
1	54.49	89.45	59.36	98.79	77.60	68.03
2	119.22	148.15	98.59	153.95	115.35	113.80
4	33.80	76.64	37.98	68.98	3.84	9.29
12	94.60	106.55	88.14	109.78	58.35	66.00
13	119.91	154.73	132.34	166.04	122.12	133.15
16	47.65	78.95	17.01	74.92	66.45	75.01

PSW: Preferred Step Width, WSW: Wide Step Width

Table 13. Peak Knee Extension Angle (deg) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	-7.20	-33.04	-7.49	-32.89	-8.90	-9.25
6	-7.22	-32.89	-7.37	-29.66	-7.52	-6.64
7	.25	-18.31	1.15	-9.89	5.25	3.80
9	-15.95	-39.47	-17.02	-42.70	-15.11	-14.43
10	-4.27	-24.05	-4.25	-23.71	-9.38	-8.03
11	-5.95	-26.61	-7.64	-33.07	-9.13	-11.54
15	-5.47	-23.17	-3.19	-22.11	-6.12	-5.44
1	-6.06	-38.04	-8.18	-39.84	-9.01	-11.03
2	-2.43	-27.98	-2.43	-37.67	-1.66	-5.16
4	-7.80	-28.91	-8.34	-28.84	-13.96	-13.15
12	-5.64	-27.71	-7.34	-32.41	-10.70	-8.75
13	-5.72	-20.55	-4.53	-15.69	-6.05	-5.34
16	-5.46	-40.81	-7.53	-44.24	-12.13	-11.36

PSW: Preferred Step Width, WSW: Wide Step Width

Table 14. Peak Vertical GRF (N) for Uphill, Downhill and Level Walking.

Participant	Uphill PSW	Downhill PSW	Uphill WSW	Downhill WSW	Level PSW	Level WSW
5	808.63	902.23	808.63	880.16	726.16	785.52
6	959.40	971.68	779.23	987.45	859.65	847.04
7	805.30	1078.89	878.26	1050.26	821.88	786.25
9	649.16	840.80	629.40	766.89	745.97	746.44
10	590.76	776.82	584.29	720.78	629.95	609.38
11	582.69	740.37	609.73	761.74	648.15	650.28
15	595.02	772.44	593.67	801.27	667.31	666.11
1	847.55	982.92	795.04	1.09	1009.05	924.96
2	1309.68	1566.67	1272.56	1490.96	1391.33	1402.20
4	741.08	1145.18	726.23	1244.96	812.39	748.27
12	1432.19	1699.76	1417.87	1615.84	1515.67	1495.02
13	1157.85	1482.73	1169.88	1521.75	1336.88	1353.11
16	952.31	1084.36	864.44	1082.07	1006.60	996.16

PSW: Preferred Step Width, WSW: Wide Step Width

Vita

Daniel Sample was born in Rochester, New York, to the Parents of Dave and Beth Sample. He attended Dobyns-Bennett High School in Kingsport, Tennessee, where he grew up from a young age. Upon graduation, he stayed local in Tennessee to attend The University of Tennessee in Knoxville. He received his Bachelor of Science degree in Kinesiology from The University of Tennessee, Knoxville in May 2016. In the summer of 2016, he decided to continue his education at The University of Tennessee, Knoxville and pursue a Master's Degree in Kinesiology with a concentration in Biomechanics under the advisement of Dr. Songning Zhang. His major interests of the research included biomechanical mechanisms of the lower extremity injury and prevention, gait analysis, knee osteoarthritis and human movement simulation using computer software to estimate joint contact and muscle forces.