A Thesis

entitled

Reliability of Lower Extremity Biomechanics During Functional Activity Performance

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master’s of Science Degree Exercise Science

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An Abstract of
Reliability of Lower Extremity Biomechanics During Functional Activity Performance
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Context: Three dimensional, passive motion analysis systems allow researchers to non-invasively, yet thoroughly, examine the biomechanics of patients with many different orthopedic ailments. One problem with this technology is a lack of consistency in the number and placement of retroreflective markers. This results in a difficulty comparing results from studies done in the same lab over time.

Objective: The purpose of this study is to determine the reliability of the chosen marker set when using passive motion capture to assess biomechanics during various dynamic tasks.

Design: The design is a test-retest study.

Setting: Musculoskeletal Health and Movement Science Laboratory

Participants: Fifteen participants were recruited and volunteered for this study. Fourteen participants (age: 23.9±33.56 years; height: 1.73±0.12 m; mass: 71.93±15.95 kg; body mass index [BMI]: 23.82±2.76 kg/m²) completed the study.

Intervention(s): Participants reported to motion analysis laboratory for two trials separated by seven days. The clinician placed 37 retro-reflective markers over the pre-
determined anatomical landmarks. The subject then performed self-selected walking gait, standard walking gait, stair ascent/descent, jump landing and sit-to-stand tasks.

**Main Outcome Measures:** The dependent variables include three dimensional, lower extremity biomechanics at the hip, knee, ankle, and trunk during each of the four biomechanics tasks. The independent variable is time (session 1 and session 2). The statistical analysis used to compare the measurements was independent t-tests and intraclass correlations (ICC).

**Results:** Standard gait speed yielded the best ICC values (ICC > 0.652) for kinematics and kinetics at the hip and knee in both the frontal and sagittal plane. All other tasks found varying ICC values for kinetic and kinematic data in the frontal and sagittal plane (0.970 > ICC > 0.003).

**Conclusion:** The present study showed that the chosen marker set is reliable when a novice clinician places the surface markers on the pre-determined anatomical landmarks.
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Chapter One

Introduction

Anterior cruciate ligament (ACL) injuries occur at a rate of over 250,000 injuries per year in the United States.\(^1\) Research has shown that anywhere between 45-50\% of those people will eventually develop osteoarthritis (OA) in the affected knee within 10-15 years after the injury.\(^2,3\) Changes in lower extremity biomechanics as a result of injury and/or surgery reportedly contribute to the high incidence of joint degeneration in this patient population.\(^4,5\) Specifically, patients after ACL injury/surgery have been demonstrated to walk with a “stiff knee gait”, meaning they reduce the knee flexion excursion during walking.\(^6\) This adaptive strategy arises from a need to limit the eccentric demand placed on a weakened quadriceps muscle group. However, this aberrant biomechanical pattern also increases joint contact forces, thereby overloading articular cartilage and contributing to its degeneration. The ability to detect these and other abnormal biomechanics is imperative to the development of strategies to counter them and restore normal joint motion.

Both two- and three-dimensional motion analysis systems have been developed, with three dimensional motion capture being the more commonly utilized technique. Three dimensional, passive motion analysis systems allow researchers to non-invasively, yet thoroughly, examine the biomechanics of patients with many different orthopedic ailments. Movement patterns such as walking, stair climbing, sit-to-stand, and jump landing can be investigated in a laboratory setting. Biomechanical analysis of these movements can give clinicians insight into the forces and intersegmental moments of the musculoskeletal system.\(^7\) This insight could provide clinicians information on how to
identify biomechanical alterations and how best to treat these patients. One problem, however, with this technology is a lack of consistency in the number and placement of retroreflective markers. If there is variability in marker sets and placements within one laboratory, it may ultimately result in a lack of uniform data, and present difficulty in comparing data across sessions and from different studies conducted in the same laboratory.

Among the types of markers used for passive motion capture are bone pins and surface markers. Bone pins provide the most accurate data with respect to bone movement; however, they are invasive. Bone pins require the use of a needle to be properly placed. This method of placement increases the risk of infection to the participant. Additionally, bone pins can be very painful for the participant and, therefore, can result in altered biomechanical movements due to pain. Bone pins also require a trained professional, such as a physician, to insert. This increases the time and potential cost of the study. With the increased risk of infection, pain, time and cost, along with the minimal increase in accuracy of the data, it can be argued that the risks of using bone pins outweigh the benefits.

A good alternative to bone pins is surface markers. Traditionally, there are two different ways surface markers are used for biomechanical movement analysis: clusters of markers or individual markers placed over specific bony landmarks. When using clusters of markers, researchers place 3-4 markers on a semi-rigid shell, which is then affixed to the participant. Because the markers are consistently placed equidistant to one another, cluster sets have the benefit of being reliable. Another benefit of cluster sets is the fast and easy set up the markers on the participant and the non-invasive nature of this
type of marker set. The problem that cluster sets pose is that they often slide on the participant’s skin during movement, especially during more dynamic tasks or in cases when the participants may be sweating. This movement could decrease the reliability of the data.

An alternative to cluster sets are individual surface markers placed on bony landmarks. Individual surface markers are easy to place on the participant; however, they do take more time to set up compared to cluster sets. Individual surface markers are similar to bone pins in that they provide insight into the movement of the skeletal system; however, there are several limitations to consider. Since surface markers are placed on the skin, there is a layer of muscle and adipose separating the marker from the bone. This causes surface markers to move with respect to the underlying bone. The more dynamic the movement, the greater the possibility for movement of the markers. This could reduce the reliability and raise concern over the accuracy of the data obtained. To help combat these limitations, one experienced investigator should be consistent in the placement of the individual markers. If the investigator lacks experience, the consistency of the measures may be affected.\cite{9,10} Another way to reduce error is to have the participants wear as minimal/tight clothing as possible to ensure the markers are placed directly on the skin and not over clothing. Though it is not without limitations, the non-invasive nature and ease of placement of surface markers make this type of marker set a logical choice for investigating human movement. Surface markers have been used previously to evaluate movements such as walking,\cite{11} stair ascent/descent,\cite{12} sit-to-stand,\cite{13} and jump landing.\cite{14}
Statement of Problem

Human motion analysis laboratories have used many different types of marker sets to assess movement for many different tasks. One major problem with using multiple marker sets within one laboratory is that it is difficult for these studies to be compared to one another. Additionally, biomechanics are frequently compared over time. It is important to know that the data obtained are consistent between sessions so that differences detected can be attributed to true biomechanical alterations and not errors in data collection.

It is also important for the marker set to be reliable in order for the data within the lab to be connected. Reliability is defined as a test or procedure that will provide similar results regardless of the evaluator. This study, specifically, will be looking at intra-rater reliability, which is the extent to which the same examiner can reproduce the same results on the same participant. Ensuring that there is high intra-rater reliability will ensure that the data obtained are consistent between sessions and can be compared over time.

Statement of Purpose

The purpose of this study was to determine the reliability of the chosen marker set when using passive motion capture to assess biomechanics during level walking, stair ascent/descent, sit-to-stand, and jump landing. It was theorized that the chosen marker set would provide reliable data between sessions.

Research Hypothesis

The chosen marker set will provide reliable data in a test-retest design for level walking, stair ascent/descent, sit-to-stand, and jump landing tasks.
**Limitations of the Study**

It is recognized that the surface markers provide only relative movement and do not represent the exact movement of the underlying bones. Surface markers also have the potential of falling off during the trial and being placed in a slightly different spot than they were originally located. Additionally, this study was performed only on healthy individuals, with a specific set of physical demographics, which may limit the generalizability of our findings.

**Significance of the Study**

Biomechanical analyses have proven essential for understanding and treating a variety of pathological and injured patient populations. These analyses enhance our understanding of how these diseases and injuries impact both short and long-term patient health. This knowledge allows researchers and clinicians to work together to change treatment strategies to improve quality of life. This study was one important step in that process.

**Operational Definitions**

- ACL............................Anterior Cruciate Ligament
- AMTI ............................Advanced Mechanical Technology, Inc.
- BMI ............................Body Mass Index
- MRI ............................Magnetic Resonance Imaging
- OA..............................Osteoarthritis
- vGRF.............................Vertical Ground Reaction Force
Chapter Two

Literature Review

Motion analysis is an effective tool used by clinicians to evaluate human movement patterns. The purpose of this literature review is to: 1) investigate the importance of movement analysis; 2) examine the varying types of motion analysis; and 3) show the importance of intra-rater reliability when assessing movement.

Importance of Studying Human Movement

Anterior cruciate ligament injuries occur at a rate of over 250,000 injuries per year in the United States.\(^1\) Research has shown that up to 50% of those who suffer an ACL injury will eventually develop OA in the affected knee within 10-15 years after the injury.\(^2,3\) An increased number of patients after ACL injury experience symptoms of OA as early as their 30s and 40s, likely due to the young age at which their initial injury occurred.\(^3\) The early development of this disease means that these people will potentially be living with this debilitating condition for a long period of their lives.

Individuals living with OA often experience neuromuscular changes and or pain. These factors are believed to be caused by the initial ACL injury, the surgery to reconstruct the injury, or arise during the post-traumatic development of OA. Any one of these factors can cause biomechanical changes to the lower extremity during functional movement tasks such as walking, stair ascent/descent, sit-to-stand or landing from a jump. For example, Butler \textit{et al.}\(^3\) reported that patients following ACL reconstruction showed an increase in peak knee abduction moment during walking compared to healthy control participants.\(^3\) Excessive tibial rotation during walking in ACL-reconstructed participants causes excessive loading in areas of cartilage that are not commonly
stressed. The areas of the cartilage that are not normally stressed are not able to withstand the new forces and eventually begin to wear down, contributing to the development of OA.

Due to this growing problem of the early development of knee OA after ACL reconstruction, research has begun to investigate differences in movement patterns with gait analysis for patients following ACL injury and those with OA through the use of human movement analysis. Human movement analysis is assessing joint kinematics, which is the description of relative movement between two bony segments, the proximal and distal. The description of joint kinematics must be repeatable, especially in human motion analysis. It has been argued that the main goal of biomechanics in regards to human motion analysis is to produce anatomically valid and reliable measurements.

The purpose of these analyses is to gather quantitative information about the biomechanics of the musculoskeletal system during specific movements or tasks. There has been a wide range of methods used to gather motion analysis data, including single plane fluoroscopic techniques, magnetic resonance imaging (MRI), and stereoradiography. Each method has benefits and drawbacks when collecting motion analysis data.

**Types of Motion Analysis**

*Fluoroscopic Techniques*

One of the newer techniques used to assess skeletal movements involves fluoroscopic evaluation and, more specifically, biplane radiographic techniques. This technique involves the use of two radiographic imaging devices, and two image intensifiers. One approach to fluoroscopic techniques is x-ray fluoroscopy, which
uses a pulsed fluoroscopic sequence in conjunction with a feedback loop in a camera. This allows the current and voltage to be adjusted to ensure optimal clarity with minimal radiation.\textsuperscript{23} One example of biplane fluoroscopic techniques in dynamic trials is the use of a treadmill centered between two fluoroscopic imaging machines.\textsuperscript{24} Another common application of biplane fluoroscopic motion analysis is placing the x-ray sources lateral to the treadmill with the image intensifiers on the opposite side of the treadmill. This approach is used in order to provide sufficient space for treadmill walking or running.\textsuperscript{21}

The major benefit with the use of these forms of imaging is that the clinician can assess the position of the underlying bone directly.\textsuperscript{22} It also allows the participants to move freely while capturing the motion of the underlying surface.\textsuperscript{25} Tashman \textit{et al.}\textsuperscript{21} reported that radiographic imaging has been shown to depict static bone positioning to within a range of $\pm 10 – 250 \ \mu m$. Radiographic exams utilize ionizing radiation to penetrate the body, and the images result from the absorption and dispersion of radiation by both bone and soft tissue to create an image.\textsuperscript{16,22}

There are some major drawbacks to this form of motion analysis that make it a less than ideal choice for motion capture. One major downside to this technique is the exposure of radiation that is not justifiable for a healthy participant.\textsuperscript{7,23} The accuracy of this technique is also a potential downside. Studies have shown it to be accurate in determining location of the skeletal system during a static trial; however, conflicting results have been shown during movement tasks, such as gait.\textsuperscript{20,21,23} Ultimately, this is a very costly method for human movement analysis, especially for a technique that can only accurately depict static trials.\textsuperscript{23}
**Magnetic Resonance Imaging**

Magnetic resonance imaging (MRI) is also a technique that is used in human motion analysis. This technique has been recommended as the new “gold standard.”\(^\text{25,26}\) This technique requires the participant to lie in an MRI machine. While in the machine the participant will do static trials or perform small dynamic movements.

The contraindications of MRI include metal implants, pacemakers, tattoos, pregnancy, and/or participants who have increased anxiety due to claustrophobia create limitations to this method.\(^\text{16}\) Also, there is minimal space for movement within the MRI machine, which will only permit small dynamic movements, and not allow for large dynamic trials. The limited amount of movement will not allow for the motion needed to perform trials such as walking gait, stair ascent and descent, sit to stand, and jump landing. Additionally, participants are in a non-weight bearing position during testing. This limits the applicability of these studies to diseases such as knee OA, which results from abnormal joint loading during weight bearing activities.

**Stereoradiography**

Stereoradiography is the reconstruction of three dimensional landmarks coordinates from photographs and video imaging.\(^\text{19}\) This technique is widely used, due in large part to the reduction in time and monetary cost when compared to other forms of motion analysis.\(^\text{19}\) This system works by placing retroreflective markers on specific anatomical landmarks.\(^\text{7}\) The markers are placed over anatomical landmarks that are not directly observable. These markers form a kinematic chain which represents a portion of the human body called a body segment. Each segment consists of a bony part and soft tissue.\(^\text{18}\)
Markers can be placed in a cluster frame or anatomical frame, and will be discussed later in this review. These markers work in conjunction with infrared stroboscopic illumination produced by light-emitting diodes around the lens of the motion capture cameras. The markers reflect the light back toward the cameras, which will recognize the position of the markers either through pattern recognition software or hardware circuits.\textsuperscript{19} A three dimensional coordinate system of each marker is then calculated based on the two dimensional data from at least two of the cameras.\textsuperscript{19} It is suggested that each marker should be seen by more than two in order to prevent factors such as arm swing, rotation of the body, or objects (\textit{i.e.} the railing of the stairs) from blocking the markers from the view of the cameras.\textsuperscript{19} This investigation will utilize a twelve camera motion capture system to increase the chance that each of the retro-reflective markers is being tracked by at least two of the cameras at any given time. The markers must also be seen simultaneously by at least two cameras in order to reconstruct a three dimensional model.\textsuperscript{18,19} A major advantage to three dimensional human models is the ability to gain more complete data when compared to a two dimensional model. It also provides a more accurate model for more complex human movements.\textsuperscript{27}

Human motion analysis can be performed with the use fluoroscopic techniques or stereoradiography. It is important to recognize the benefits and drawbacks to both techniques. Dual plane fluoroscopic human motion analysis allows for direct imaging of the bone by omitting the superficial surface of the skin. However the limitations of exposure to radiation, conflicting data on the accuracy, and the limited participant movement allowed by the technology make this technology a poor choice for this study. The twelve camera system ultimately will make it easier to create a three dimensional
model. A major advantage to three dimensional human models is the ability to gain more complete data when compared to a two dimensional model. It also provides a more accurate model for more complex human movements.27

**Marker Sets**

*Active Marker Sets*

There are two main forms of markers used in human motion analysis: active and passive. Active markers are light-emitting markers that are pulsed sequentially with diodes mounted around the camera. This enables the system to automatically and accurately track the markers during human motion analysis.19

*Passive Marker Sets*

Passive markers, or retroreflective markers, are used with infrared stroboscopic illumination produced by the light emitting diodes around the motion analysis cameras.19 The markers are recognized through either recognition software or hardware circuits.19 Although active markers are potentially more accurate than passive markers, the absence of wires, batteries, and pulsing circuits on the participant’s body make the passive marker set a better choice for this study.

Among the types of markers used for passive motion capture are bone pins and surface makers.8

*Bone Pins*

Bone pins are placed under local anesthesia directly into bony landmarks of the participants. These bone pins are placed directly through the skin and soft tissue into the underlying bone.8,25 Bone pins provide the most accurate data with respect to bone movement, and are considered to be the “gold standard” for human motion analysis.25
There are several limitations to these types of marker sets that ultimately limit the amount of accurate data that is obtained. Bone pins can be painful and are very invasive, which can create an antalgic gait for the participant. This will inhibit the natural movements of the participant, which in turn will affect the accuracy of the data collected. Bone pins require the use of a needle to insert the pin, which increase the risk of possible infection and require a physician be present for placement of the markers. The bone pins are also exposed to extreme bending and shearing forces in areas such as the hip. These forces can cause the pins to bend in the muscle, which will yield inaccurate data to the clinician.

**Surface Markers**

More commonly utilized are surface markers. This involves placing markers directly onto the skin over relative landmarks. The movement of the markers represents an estimation of the underlying segments. There are two main types of surface markers; cluster sets and anatomical frame. Cluster marker sets describe the relative movement of a bony segment by using the instantaneous position of at least three, non-aligned superficial markers. Cluster sets are reliable because the markers are equidistant from each other, but they often slide on the participant’s skin during movement. The ease of placement of the clusters decreases the amount of set-up time and the invasive nature of the experiment; however, the clinician will sacrifice the reliability of the data because of the amount of movement of the cluster set on the skin of the participant.

The anatomical frame is composed of individual surface marker sets placed over bony landmarks. These markers are placed over specific landmarks, as opposed to cluster sets which are placed over relative segments of the body.
frames meet the requirements of intra- and inter-participant repeatability. The anatomical frame ultimately allows the clinician to create a model specific to the participant because the markers are placed over exact anatomical landmarks, whereas in a cluster set the marker(s) may not be over the desired anatomical landmark.\textsuperscript{18}

The individual markers are easy to place on the participant; however, they do take more time compared to cluster sets. These surface markers also provide insight into the movement of the skeletal system, much like the bone pins. However, in contrast to the bone pins, the surface markers provide relative movement of the underlying surface. Due to these factors, this study will use surface markers placed over bony landmarks because it provides reliable data with the least risk and most comfort for the participant.

Determining which marker set to use and precise placement of the markers are two important factors to consider when using surface markers\textsuperscript{19}. It is imperative for a marker set to accurately determine the joint center of the desired segment(s).\textsuperscript{29} Some general rules that have been proposed by Cappozzo et al.\textsuperscript{18} for finding these placements include: each marker should be within the field of view of at least two cameras at any given time\textsuperscript{18}; the markers attached to the same segment should be adequately distributed to minimize position error propagation to bone orientation; the movement between markers and underlying bones should be minimal; there should be minimal marker disturbance to the subject under analysis; and the placement of the markers on the subject should be overall a fast, easy and safe procedure.\textsuperscript{18,19,27}

Considering all of the above-mentioned factors, the present investigation will utilize surface markers placed directly over specific anatomic landmarks. This will allow
for a non-invasive method by which to capture the relative movement of the trunk and lower extremities while participants complete a series of daily and athletic tasks.

**Reliability**

Reliability is defined as a test or procedure that will provide similar results regardless of the evaluator. Reliability can be broken down further into two different categories: intra-rater, and inter-rater reliability. Intra-rater reliability is the extent to which the same examiner can reproduce the same results on the same participant. Interrater reliability is the extent to which different examiners can produce the same results for the same participant. For the purpose of this study we will be looking at the intra-rater reliability of the clinician to effectively obtain similar biomechanics data on the same participant in a test-retest design. This is important as it will show that with the proper training in this laboratory setting, the chosen marker set and associated data collection and processing methods will have high intra-rater reliability; which will provide consistent data that can be compared overtime.
Chapter Three

Methods

Participants

Fifteen participants were recruited and volunteered for this study. Kinematic and kinetic data were collected and processed on fourteen participants (age: 23.9±3.56 years; height: 1.73±0.12 m; mass: 71.93±15.95 kg; body mass index [BMI]: 23.82±2.76 kg/m²) who completed the study. Due to complications with equipment during the retest session for one participant, stair descent data were not collected, thus only data on 13 total participants were collected and processed for the stair descent task.

The participants were required to be physically active, which was defined as a minimum of 30 minutes of activity per day for at least three days per week. Participants were excluded if they had a history of lower extremity or back fracture or surgery or if they sustained any lower extremity injury within the previous 6 months. Also, any participant with any cardiovascular disease or medical condition that precludes safe participation in exercise was excluded from this study.

With a predetermined alpha level of 0.05 and 1-β of 0.8, an a priori power analysis using previously reported knee extension moments during stair descent revealed a need for 12 participants to generate no more than a 10% difference between sessions.

Study Design

The current study was a reliability study. Participants reported to the University of Toledo Musculoskeletal Health and Movement Science lab a total of two times, with seven days between each session. At each session, participants performed a series of four
biomechanical tasks: over-ground walking, stair ascent and descent, sit-to-stand, and jump landing. The same clinician collected all data at each session.

**Kinematic and Kinetic Data Collection and Analysis**

The kinematic data were gathered using a 12-camera, high speed (200 Hz) motion capture system (Motion Analysis Corporation, Santa Rosa, CA) and associated Cortex 3.6.0.1312 software. Following the calibration of the cameras, the participant was outfitted with 37 retroreflective markers (Figure 1). A static trial was taken of the participant from which a kinematic model was built in Visual 3D software (C-Motion, Rockville, MD, USA). This model consisted of six degrees of freedom per joint.

Ground reaction force data were recorded as participants contacted two AMTI OR 7 force platforms (Advanced Mechanical Technology, Inc., Watertown, MA, USA) centrally located in the camera capture volume, sampling at 1000 Hz, and synchronized with the motion capture system. The participants were instructed to contact the force platform(s) during all trials for this study.

Data were extracted in the following ways for each procedure. For the gait and stair trials, data were extracted as the peak sagittal, frontal and transverse plane angles and moments for the hip, knee, ankle and trunk over the first half of the stance phase. These temporal markers were chosen for the over ground walking gait and stair gait because from the clinical perspective, problems arise within the first half of stance when angles and moments tend to peak. For the jumping and sit-to-stand trials, data were extracted at the instant of peak vertical ground reaction force (vGRF). This was chosen because there is no on/off of the stance phase and peak vGRF represents one time when injury has been postulated to occur. Thus, looking at that time point could lend insight
into injury mechanics. These data were averaged across trials and then used for statistical analysis.

**Data Processing**

Joint rotations were calculated using a Cardan rotation sequence based on the three dimensional marker trajectories during each trial and expressed relative to the participant’s neutral position. After collecting the data from each participant’s trials, the data were averaged across trials. The averaged data were then used for statistical analysis. All data were filtered using a fourth-order, zero-lag Butterworth filter with a 12 Hz cut-off frequency. Data were analyzed with standard inverse dynamics analysis in Visual 3D.

**Procedures**

As previously mentioned, the participants reported for testing a total of two times, with seven days between each session. Prior to the initial session, each participant was given an explanation of the study and completed a consent form and all the necessary paperwork. Upon inclusion in the study, 37 retro-reflective markers were placed on the participant with double-sided tape. The same clinician placed the markers for each of the two sessions.

Hip, knee, ankle and trunk biomechanics were recorded while participants completed the movement tasks below. The tasks were randomized for each participant; however, the order was kept the same between sessions for the same participant. The participant was allowed as many practice trials as he or she needed in order to feel comfortable completing the individual tasks correctly.
Retro-reflective markers were placed over the predetermined anatomical landmarks, and can be found in Appendix A.

**Over-Ground Walking**

Participants walked a distance of approximately 4m along the floor, contacting the force platforms embedded in the floor as they walked. Two walking speeds were tested. First, participants walked at their normal, comfortable walking pace (±5%). Next, participants walked at a speed equivalent to normal, human walking speed (approximately 1.4 m/s ±5%). Gait speed was determined by a stopwatch synchronized with two photoelectric sensors (Cutler-Hammer SMPR3-HD, Eaton Corporation, Cleveland, OH, USA). Participants completed five successful trials at each speed for each limb. Success was determined as the desired limb landing entirely within the center of the force platform without normal gait being disrupted.

**Stair Ascent and Descent**

The stair climbing task was completed using a custom built staircase designed to fit over the force platform that is embedded into the floor. Each participant completed a total of ten successful trials (five ascending and five descending) per session for each limb.

**Sit-to-stand**

The participants performed a sit-to-stand exercise in which the participant was seated in a chair with his/her arms crossed over the chest. The chair was adjusted so that the participant’s knee was flexed to 90° in the starting position. Participants were instructed to rise from the chair to a standing position with one foot on each of the two force platforms. Five trials will be collected.
**Drop Landing**

To perform the jump landing task, the participant stood on top of a 30 cm platform placed at a distance equal to 50% of the participant’s height away from the edge of the force platform. The participant was instructed to jump down off of the box toward the force platform. The participants landed with one foot on each of the force platforms. The participant was instructed to stick the landing, with no rebound jump. Five trials were collected.

**Statistical Analysis**

The dependent variables include three dimensional, lower extremity biomechanics at the hip and knee during each of the four biomechanics tasks. The independent variable was time (session 1 and session 2). The statistical analyses used to evaluate differences between measurements from each session were dependent t-tests and intraclass correlation coefficients (ICCs) for absolute agreement. ICCs for absolute agreement cutoff values were defined as strong (ICC > 0.8), moderate (ICC 0.5 – 0.8), and weak (ICC < 0.5). All statistical analyses were performed using IBM SPSS (SPSS: version 19. IBM Corporation, Armonk, NY, USA).
Chapter 4

Results

Gait

All kinetic data can be found in Table 1. No differences presented in joint moment data obtained between sessions for any joint moment or rotation during walking ($P>0.05$; Table 1 and Table 2). During self-selected walking, sagittal plane hip joint moments demonstrated strong reliability between sessions. Moderate reliability was observed for the knee sagittal plane measures while weak reliability was observed in the frontal plane at the hip and knee joints. During walking at a standard gait speed, strong reliability was noted for hip joint moments in the frontal plane and knee joint moments in the sagittal plane. Moderate reliability was noted for sagittal plane hip and frontal plane knee joint moments. Peak vGRF yielded moderate reliability between sessions regardless of walking speed. Self-selected walking speed was available for six participants. Those data suggest that participants walked at a similar speed between session 1 and 2 ($P=0.13$).

All kinematic data are located in Table 2. Self-selected walking yielded strong reliability for measuring joint rotations in the hip sagittal and knee sagittal and frontal planes. Moderate reliability was noted for the frontal plane at the hip. Walking at a standard speed yielded strong reliability for all measured joint rotations.

Stairs

Hip sagittal plane torque was significantly greater during session 1 than session 2 for stair ascent ($P=0.043$). Similarly, peak vGRF was greater during session 2 for stair descent compared to session 1 ($P=0.009$). No other differences presented in joint moment or rotation data during stair ascent/descent ($P>0.05$). During stair descent, strong
reliability was noted between sessions for joint moments in the hip frontal plane. Moderate reliability was measured for joint moments in the hip sagittal and knee frontal planes. Finally, weak reliability was observed when measuring torque in the knee sagittal plane and peak vGRF. During stair ascent, strong reliability was observed when measuring joint moments in the hip frontal plane. Moderate reliability was observed for the hip sagittal and knee sagittal and frontal plane joint moments as well as peak vGRF between sessions.

Joint rotation measurements during stair descent yielded strong reliability in the hip sagittal and frontal planes, while moderate reliability was noted for the knee sagittal and frontal planes. During stair ascent, strong reliability was observed for joint rotations in the sagittal plane at the hip and knee. Moderate reliability was noted in the hip frontal plane and weak reliability presented for knee frontal plane joint rotations.

**Jump Landing**

There were no differences in jump landing kinetics or kinematics between sessions 1 and 2 ($P>0.05$). Jump landing presented with strong reliability when measuring torque in the hip sagittal and frontal plane. Peak vGRF also yielded strong reliability. Moderate reliability was observed for knee frontal plane moments, with weak reliability observed for knee sagittal plane moments.

Joint rotation reliability during jump landing was strong for the hip frontal and knee sagittal planes. Moderate reliability presented in the hip sagittal plane rotations, while knee frontal rotations yielded weak reliability.
**Sit-to-Stand**

There were no differences in STS kinetics or kinematics between sessions 1 and 2 ($P>0.05$). Performance of the STS task yielded strong reliability in the hip frontal and knee sagittal and frontal plane torque measurements. Moderate reliability presented for the hip sagittal joint moments and peak vGRF.

Joint rotations during the STS yielded strong reliability in the hip frontal and knee sagittal planes. Moderate reliability was noted for hip sagittal plane joint angles. Finally, joint rotation measurement in the knee frontal plane yielded weak reliability.
<table>
<thead>
<tr>
<th>Task</th>
<th>Session 1 (mean±sd)</th>
<th>Session 2 (mean±sd)</th>
<th>P-value (t-test)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Sagittal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>0.04 ± 0.06</td>
<td>0.02 ± 0.05</td>
<td>0.129</td>
<td>0.840</td>
</tr>
<tr>
<td>Standard</td>
<td>0.02 ± 0.05</td>
<td>0.002 ± 0.03</td>
<td>0.106</td>
<td>0.652</td>
</tr>
<tr>
<td>Down</td>
<td>0.14 ± 0.04</td>
<td>0.13 ± 0.06</td>
<td>0.409</td>
<td>0.636</td>
</tr>
<tr>
<td>Up</td>
<td>0.06 ± 0.06</td>
<td>0.03 ± 0.07</td>
<td>0.043</td>
<td>0.751</td>
</tr>
<tr>
<td>Jump</td>
<td>-0.16 ± 0.20</td>
<td>-0.19 ± 0.21</td>
<td>0.305</td>
<td>0.883</td>
</tr>
<tr>
<td>STS</td>
<td>-0.37 ± 0.12</td>
<td>-0.34 ± 0.07</td>
<td>0.344</td>
<td>0.438</td>
</tr>
<tr>
<td><strong>Hip Frontal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>-0.54 ± 0.07</td>
<td>-0.50 ± 0.17</td>
<td>0.357</td>
<td>0.379</td>
</tr>
<tr>
<td>Standard</td>
<td>-0.55 ± 0.07</td>
<td>-0.54 ± 0.07</td>
<td>0.371</td>
<td>0.937</td>
</tr>
<tr>
<td>Down</td>
<td>-0.54 ± 0.10</td>
<td>-0.54 ± 0.11</td>
<td>0.786</td>
<td>0.908</td>
</tr>
<tr>
<td>Up</td>
<td>-0.48 ± 0.08</td>
<td>-0.48 ± 0.09</td>
<td>0.942</td>
<td>0.954</td>
</tr>
<tr>
<td>Jump</td>
<td>-0.16 ± 0.14</td>
<td>-0.18 ± 0.16</td>
<td>0.204</td>
<td>0.930</td>
</tr>
<tr>
<td>STS</td>
<td>-0.02 ± 0.08</td>
<td>-0.03 ± 0.07</td>
<td>0.254</td>
<td>0.970</td>
</tr>
<tr>
<td><strong>Knee Sagittal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>-0.23 ± 0.33</td>
<td>-0.11 ± 0.10</td>
<td>0.255</td>
<td>0.702</td>
</tr>
<tr>
<td>Standard</td>
<td>-0.15 ± 0.03</td>
<td>-0.15 ± 0.03</td>
<td>0.624</td>
<td>0.851</td>
</tr>
<tr>
<td>Down</td>
<td>-0.06 ± 0.03</td>
<td>-0.09 ± 0.04</td>
<td>0.079</td>
<td>0.156</td>
</tr>
<tr>
<td>Up</td>
<td>1.98 ± 3.31</td>
<td>2.52 ± 3.05</td>
<td>0.508</td>
<td>0.714</td>
</tr>
<tr>
<td>Jump</td>
<td>1.09 ± 0.18</td>
<td>1.08 ± 0.14</td>
<td>0.845</td>
<td>0.210</td>
</tr>
<tr>
<td>STS</td>
<td>0.51 ± 0.10</td>
<td>0.53 ± 0.07</td>
<td>0.386</td>
<td>0.862</td>
</tr>
<tr>
<td><strong>Knee Frontal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>0.05 ± 0.02</td>
<td>0.15 ± 0.38</td>
<td>0.351</td>
<td>0.006</td>
</tr>
<tr>
<td>Standard</td>
<td>0.04 ± 0.02</td>
<td>0.05 ± 0.02</td>
<td>0.435</td>
<td>0.742</td>
</tr>
<tr>
<td>Down</td>
<td>0.04 ± 0.04</td>
<td>0.04 ± 0.02</td>
<td>0.650</td>
<td>0.447</td>
</tr>
<tr>
<td>Up</td>
<td>-0.12 ± 0.02</td>
<td>-0.14 ± 0.02</td>
<td>0.066</td>
<td>0.474</td>
</tr>
<tr>
<td>Jump</td>
<td>0.04 ± 0.10</td>
<td>0.03 ± 0.11</td>
<td>0.651</td>
<td>0.581</td>
</tr>
<tr>
<td>STS</td>
<td>-0.002 ± 0.06</td>
<td>-0.003 ± 0.06</td>
<td>0.849</td>
<td>0.934</td>
</tr>
<tr>
<td><strong>Max vGRF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>1.14 ± 0.07</td>
<td>1.13 ± 0.02</td>
<td>0.664</td>
<td>0.795</td>
</tr>
<tr>
<td>Standard</td>
<td>1.13 ± 0.07</td>
<td>1.13 ± 0.06</td>
<td>0.930</td>
<td>0.736</td>
</tr>
<tr>
<td>Down</td>
<td>1.23 ± 0.14</td>
<td>1.30 ± 0.13</td>
<td>0.009</td>
<td>0.003</td>
</tr>
<tr>
<td>Up</td>
<td>1.09 ± 0.05</td>
<td>1.10 ± 0.08</td>
<td>0.663</td>
<td>0.795</td>
</tr>
<tr>
<td>Jump</td>
<td>1.86 ± 0.36</td>
<td>1.85 ± 0.41</td>
<td>0.906</td>
<td>0.809</td>
</tr>
<tr>
<td>STS</td>
<td>0.56 ± 0.05</td>
<td>0.55 ± 0.05</td>
<td>0.526</td>
<td>0.502</td>
</tr>
</tbody>
</table>

Joint moments Nm/kg*m.

vGRF = vertical ground reaction force (N/kg)

STS = sit-to-stand
Table 2. Joint kinematic data at the hip and knee for all tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>Session 1 (mean±sd)</th>
<th>Session 2 (mean±sd)</th>
<th>P-value (t-test)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Sagittal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>12.5 ± 6.4</td>
<td>11.4 ± 6.6</td>
<td>0.363</td>
<td>0.868</td>
</tr>
<tr>
<td>Standard</td>
<td>14.2 ± 4.7</td>
<td>13.0 ± 6.0</td>
<td>0.310</td>
<td>0.821</td>
</tr>
<tr>
<td>Down</td>
<td>2.9 ± 5.3</td>
<td>0.1 ± 6.9</td>
<td>0.052</td>
<td>0.855</td>
</tr>
<tr>
<td>Up</td>
<td>39.3 ± 6.5</td>
<td>37.2 ± 7.6</td>
<td>0.151</td>
<td>0.844</td>
</tr>
<tr>
<td>Jump</td>
<td>25.3 ± 6.2</td>
<td>24.4 ± 9.9</td>
<td>0.706</td>
<td>0.597</td>
</tr>
<tr>
<td>STS</td>
<td>69.1 ± 8.3</td>
<td>66.5 ± 7.3</td>
<td>0.176</td>
<td>0.777</td>
</tr>
<tr>
<td>Hip Frontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>-1.0 ± 4.1</td>
<td>-0.2 ± 6.3</td>
<td>0.452</td>
<td>0.627</td>
</tr>
<tr>
<td>Standard</td>
<td>-0.8 ± 4.0</td>
<td>-0.9 ± 3.7</td>
<td>0.826</td>
<td>0.901</td>
</tr>
<tr>
<td>Down</td>
<td>-1.8 ± 3.2</td>
<td>-2.2 ± 3.4</td>
<td>0.497</td>
<td>0.840</td>
</tr>
<tr>
<td>Up</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.568</td>
<td>0.589</td>
</tr>
<tr>
<td>Jump</td>
<td>-6.0 ± 3.3</td>
<td>-6.3 ± 3.5</td>
<td>0.534</td>
<td>0.891</td>
</tr>
<tr>
<td>STS</td>
<td>-5.7 ± -5.1</td>
<td>-5.1 ± 6.2</td>
<td>0.601</td>
<td>0.876</td>
</tr>
<tr>
<td>Knee Sagittal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>-16.8 ± 7.8</td>
<td>-15.2 ± 6.8</td>
<td>0.157</td>
<td>0.912</td>
</tr>
<tr>
<td>Standard</td>
<td>-18.9 ± 4.8</td>
<td>-17.6 ± 3.5</td>
<td>0.063</td>
<td>0.913</td>
</tr>
<tr>
<td>Down</td>
<td>-30.5 ± 5.7</td>
<td>-29.5 ± 5.7</td>
<td>0.177</td>
<td>0.499</td>
</tr>
<tr>
<td>Up</td>
<td>-73.7 ± 3.5</td>
<td>-73.7 ± 3.7</td>
<td>0.590</td>
<td>0.821</td>
</tr>
<tr>
<td>Jump</td>
<td>-47.2 ± 10.2</td>
<td>-48.2 ± 11.9</td>
<td>0.713</td>
<td>0.828</td>
</tr>
<tr>
<td>STS</td>
<td>-78.3 ± 6.0</td>
<td>-79.0 ± 5.6</td>
<td>0.484</td>
<td>0.912</td>
</tr>
<tr>
<td>Knee Frontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self</td>
<td>-0.2 ± 2.5</td>
<td>-0.2 ± 2.4</td>
<td>0.379</td>
<td>0.917</td>
</tr>
<tr>
<td>Standard</td>
<td>-0.1 ± 2.4</td>
<td>0.3 ± 2.3</td>
<td>0.319</td>
<td>0.890</td>
</tr>
<tr>
<td>Down</td>
<td>-0.9 ± 2.9</td>
<td>-0.5 ± 2.8</td>
<td>0.726</td>
<td>0.499</td>
</tr>
<tr>
<td>Up</td>
<td>-1.3 ± 3.1</td>
<td>-0.5 ± 3.3</td>
<td>0.531</td>
<td>0.129</td>
</tr>
<tr>
<td>Jump</td>
<td>-4.3 ± 4.2</td>
<td>-4.7 ± 3.5</td>
<td>0.762</td>
<td>0.267</td>
</tr>
<tr>
<td>STS</td>
<td>-5.5 ± 4.1</td>
<td>-5.3 ± 4.2</td>
<td>0.936</td>
<td>0.112</td>
</tr>
</tbody>
</table>

Joint rotations are in degrees (°)
STS= sit-to-stand
Chapter 5

Discussion

A reliable marker set allows the researcher and clinician to conclude that differences obtained between sessions or separate studies are present due to biomechanical changes and not marker placement. Specifically, intra-rater reliability is crucial for a marker set because this will show the examiner is able to reproduce the same results on the same participant across multiple sessions. This study sought to determine the intra-rater reliability of the chosen marker set when using passive motion capture to assess biomechanics during level walking, stair ascent/descent, sit-to-stand, and jump landing.

Gait

Moderate to strong reliability was obtained for all gait variables except frontal plane moments at the hip and knee during self-selected walking trials ($r^2 = 0.652 – 0.917$). During previous studies it was found that joint kinematics in the frontal and sagittal plane were highly repeatable at the hip ($r^2 > 0.85$) and moderately repeatable for the knee ($r^2 = 0.54 – 0.74$). Joint moments also had high reliability for the anatomical landmark model at the hip and knee. This previous study performed the test-retest on the same day with a minimum of four hours between sessions. Separate researchers also performed a gait analysis during the morning trials (inter-rater reliability), while one of the 2 researchers from the morning session performed the afternoon session (intra-rater reliability). Differences in the amount of time between sessions may help account for differences in reliability between our study and that of Besier et al. The previous study tested participants on the same day with only hours between, which could have allowed
for familiarity of the clinician with the marker placement from the first to the second session. In our study, there was a seven day gap between the first and the second session.

Previous studies have also suggested in a test-retest that pelvic movements exhibited lower reliability (ICC < 0.7), which has been suggested to be a result of the clinician having more difficulty locating and identifying anatomical landmarks in the hip and pelvis.\textsuperscript{36} The same study also discussed that lower reliability of knee movement in the frontal plane may be because of the small ROM of the knee in the frontal plane.\textsuperscript{36}

The present study found similar results as the previous studies in that frontal and sagittal plane kinematics and kinetics at the hip yielded moderate to strong reliability for both standard and self-selected gait with the exception of hip moments in the frontal plane during self-selected gait. The BMI cutoff helped increase the clinician’s ability to find the desired anatomical landmarks. The present study also found moderate to strong reliability in the frontal plane at the knee for both gait speeds is similar to the results found by Lacroche \textit{et al.}\textsuperscript{36}

A study by Laroche \textit{et al.}\textsuperscript{36} enrolled participants with unilateral hip osteoarthritis and had them walk at a comfortable speed across a 4 m platform. The previous study compared the affected to the unaffected limb and found that all lower limb variables had ICC values ranging from good (ICC > 0.7) to excellent (ICC > 0.9).\textsuperscript{36} That study differs from the current study in that Laroche and colleagues utilized patients with hip OA who ranged in age from 45-75, whereas we enrolled healthy college-aged individuals. There has been conflicting evidence that describes changes in variability of gait as individuals get older, and several studies suggesting variability increases in older adults while others indicate variability does not increase with age. The previous study used an experienced
clinician to place the markers over the designated anatomical landmarks, whereas the clinician in the present study had minimal experience with marker placement. This could help explain the differences in ICC values, as well as suggest that having more experience with marker placement potentially leads to increased reliability between sessions.

As noted above, the self-selected walking speed was similar between sessions. However, the higher ICC values for standard gait compared to self-selected walking gait suggest that standardized walking speeds may yield more reliable kinetic and kinematic data during gait analyses.

**Stairs**

Stair descent produced moderate to strong reliability for all variables except knee sagittal plane moments and peak vGRF. Stair ascent resulted in moderate to strong reliability for all variables except knee abduction angles. Statistically significant results were observed for stair ascent moments, as well as vGRF during stair descent trials. Limited data are available on biomechanical reliability during stair ascent and descent. However, a study conducted by Leitner et al.\(^3\)\(^7\) demonstrated good reliability of vGRF detection in older adults ascending and descending stairs (ICC: 0.537-0.836). It is not clear why differences in vGRF reliability exist between the Leitner et al.\(^3\)\(^7\) investigation and the present study; however, differences in the participants utilized may contribute to the differences in ICC values. The previous study utilized older adults (mean age 80.1 years) while the present investigation utilized younger adults. As mentioned previously, the influence of age on reliability in biomechanical analyses is unclear. Future
investigations seem necessary to conclusively determine the reliability of vGRF measurements during stair ascent and descent.

**Jump landing**

Biomechanical data obtained during jump landing were reliable, with the exception of knee flexion moments and abduction angles. Several studies have examined reliability of lower extremity biomechanics during jumping tasks. Milner *et al.*\(^3^8\) utilized a stop-jump task and found good reliability in knee kinetics and kinematics as well as vGRF (ICC: 0.685-0.959) between sessions. Ford *et al.*\(^3^9\) examined reliability during a drop vertical jump. These authors reported good reliability for sagittal and frontal plane biomechanics at the hip and knee (ICC: 0.592-0.922).\(^3^9\) Both of these studies demonstrated their lowest reliability for knee abduction moments. Differences in the jumping task performed across these studies may help account for the varying results. It is likely that a drop vertical jump would yield more consistent results than a jump landing, because the jump landing is a more dynamic task, as it requires participants to push off rather than drop from a box. The Milner *et al.*\(^3^8\) study utilized a stop-jump, though biomechanics were assessed upon landing from the vertical jump portion of the task. Thus, it is logical the previous studies would yield similar reliability. That our data differed indicates that the more horizontal approach of the jump landing may yield less reliable biomechanics than a vertical approach.

**Sit-to-Stand**

The sit-to-stand task produced moderate to strong reliability for all variables except knee abduction angles. Previous sit-to-stand motion analysis reliability studies showed that ICC values of trunk and knee joint angles had high reliability (ICC > 0.8)
between trials 1 and 2. A more likely reason is that Suh et al. used three different time points to determine joint angles, which was done by using a video recording and goniometric measurements. The present study used 33 passive markers placed over anatomical landmarks, and utilized 12 motion capture cameras to analyze all movements. Although the results from the present study and previous studies have similar ICC values, the weak reliability for knee abduction angles could be attributed to the small range of motion that occurs in the frontal plane at the knee.

**Conclusion**

The present study showed that the chosen marker set is reliable when a novice clinician places the surface markers on the pre-determined anatomical landmarks. In order to increase the reliability of the chosen marker set, we suggest that there should be an experienced clinician helping with the placement of the markers as well as the creation of a standardized set of directions that the clinician must read to the participant before every task. This will ensure that the clinician has performed the same actions between sessions.
References


Appendix A

Approved Consent Form

ADULT RESEARCH SUBJECT INFORMATION AND CONSENT FORM

Reliability of Lower Extremity Biomechanics During Functional Activity Performance

Principal Investigator: Abbey Thomas, PhD, ATC

Other Staff (identified by role): Brian Pietrosimone, PhD, ATC (Co-investigator)
Hayley Ericson, MS, ATC (Coordinator)
Michael Alfonsi, ATC (Coordinator)

Contact Phone number(s): (419) -530-4501

What you should know about this research study:

- We give you this consent/authorization form so that you may read about the purpose, risks, and benefits of this research study. All information in this form will be communicated to you verbally by the research staff as well.
- Routine clinical care is based upon the best-known treatment and is provided with the main goal of helping the individual patient. The main goal of research studies is to gain knowledge that may help future patients.
- We cannot promise that this research will benefit you. Just like routine care, this research can have side effects that can be serious or minor.
- You have the right to refuse to take part in this research, or agree to take part now and change your mind later.
- If you decide to take part in this research or not, or if you decide to take part now but change your mind later, your decision will not affect your routine care.
- Please review this form carefully. Ask any questions before you make a decision about whether or not you want to take part in this research. If you decide to take part in this research, you may ask any additional questions at any time.
- Your participation in this research is voluntary.

PURPOSE (WHY THIS RESEARCH IS BEING DONE)

You are being asked to take part in a research study of functional activity performance in healthy adults. The purpose of the study is to determine the reliability of leg biomechanics during activities of daily living. This information will help the researchers determine the best methods to use when assessing leg biomechanics.

You were selected as someone who may want to take part in this study because you are a healthy adult. Up to 30 people from the University of Toledo and surrounding community will participate in this study.
DESCRIPTION OF THE RESEARCH PROCEDURES AND DURATION OF YOUR INVOLVEMENT

If you decide to take part in this study, you will be asked to report to the Musculoskeletal Health and Movement Sciences Laboratory on up to 3 occasions (once per week for 3 weeks). Each session will last approximately 2 hours. Your participation in this study will last 3 weeks.

At each session, you will be asked to perform a series of functional activities. Prior to performing these tasks, a series of joint markers will be placed on your legs and trunk. Joint markers are Styrofoam balls covered in tape. They allow researchers to recreate your joint motion on a computer. You may also have electrodes (stickers) placed on the skin over your thigh muscles so that the researchers can record your muscle activity while you complete the tasks. Functional activities you may be asked to perform include:

1) Walking
2) Stair ascent/descent
3) Sit-to-stand
4) Jump landing

Walking
You will be asked to walk approximately 30 ft on a level floor. As you walk, you will step on a force plate (scale). A force plate allows researchers to understand the loads being placed on your joints as you walk. You will be asked to perform this task at two different speeds, your comfortable walking pace and a speed equivalent to normal, human walking speed. This task should take approximately 15 minutes to complete.

Stair Ascent/Descent
You will be asked to go up and down a custom-made staircase. This stair case has four steps. You will be asked to go up at a comfortable pace. You will pause briefly at the top and then be asked to go down the stairs at a comfortable pace. This task will take approximately 15 minutes to complete.

Sit-to-Stand
You will be asked to perform a five times sit-to-stand task. For this task, you will be seated in a chair with each foot placed on a force plate. You will be instructed to rise from and return to the chair 5 times in a row. You will be asked to perform this task first at a comfortable pace and then as quickly and safely as possible. This task will take approximately 15 minutes to complete.

Jump Landing
You will be asked to jump forward a short distance off of a 1 foot high box and land on a force plate. Immediately upon landing, we may ask you to jump as high as you can straight up in the air. This task may take approximately 15 minutes to complete.

RISKS AND DISCOMFORTS YOU MAY EXPERIENCE IF YOU TAKE PART IN THIS RESEARCH

Potential Risks
- Muscle soreness or injury
- Allergic skin reaction to adhesives used to attach joint markers or electrodes
- There may be risks that are unknown to the researchers at this time

Unlikely Risks
- Loss of confidentiality
There is no known additional risk to pregnant women for participating in this study.

**POSSIBLE BENEFIT TO YOU IF YOU DECIDE TO TAKE PART IN THIS RESEARCH**
There are no direct benefits to you for participating in this study. This study is designed so that researchers may learn the best methods to use when examining leg biomechanics.

**COST TO YOU FOR TAKING PART IN THIS STUDY**
There is no cost to you for taking part in this study.

**PAYMENT OR OTHER COMPENSATION TO YOU FOR TAKING PART IN THIS RESEARCH**
You will not receive financial compensation for participating in this study.

**ALTERNATIVE(S) TO TAKING PART IN THIS RESEARCH**
Your alternative to participating in this study is not to participate.

**CONFIDENTIALITY - (USE AND DISCLOSURE OF YOUR PROTECTED HEALTH INFORMATION)**
By agreeing to take part in this research study, you give to The University of Toledo (UT), the Principal Investigator and all personnel associated with this research study your permission to use or disclose health information that can be identified with you that we obtain in connection with this study. We will use this information for the purpose of contacting you and conducting the research study as described in the research consent/authorization form.

Under some circumstances, the Institutional Review Board, or the Research and Sponsored Programs of the University of Toledo may review your information for compliance audits. If you receive any payments for taking part in this study, your personal information and limited information about this study will be given to The University of Toledo’s accounts payable department as necessary to process payment to you. We may also disclose your protected health information when required by law, such as in response to judicial orders.

The University of Toledo is required by law to protect the privacy of your health information, and to use or disclose the information we obtain about you in connection with this research study only as authorized by you in this form. There is a possibility that the information we disclose may be re-disclosed by the persons we give it to, and no longer protected. However, we will encourage any person who receives your information from us to continue to protect and not re-disclose the information.

Your permission for us to use or disclose your protected health information as described in this section is voluntary. However, you will not be allowed to participate in the research study unless you give us your permission to use or disclose your protected health information by signing this document.

You have the right to revoke (cancel) the permission you have given to us to use or disclose your protected health information at any time by giving written notice to Brian Pietrocinque, PhD, ATC. However, a cancellation will not apply if we have acted with your permission, for example, information that already has been used or disclosed prior to the cancellation. Also, a cancellation will not prevent us from continuing to use and disclose information that was obtained prior to the cancellation as necessary to maintain the integrity of the research study.

Except as noted in the above paragraph, your permission for us to use and disclose your protected health information will stop at the end of the research study.
IRB #

ICF Version Date:

A more complete statement of University of Toledo’s Privacy Practices is set forth in its Joint Notice of Privacy Practices. If you have not already received this Notice, a member of the research team will provide this to you. If you have any further questions concerning privacy, you may contact the University of Toledo’s Privacy Officer at 419-383-8933.

A description of this clinical trial will be available on http://www.ClinicalTrials.gov, as required by U.S. Law. This Web site will not include information that can identify you. At most, the Web site will include a summary of the results. You can search this Web site at any time.

IN THE EVENT OF A RESEARCH-RELATED INJURY

In the event of injury resulting from your taking part in this study, treatment can be obtained at a health care facility of your choice. You should understand that the costs of such treatment will be your responsibility. Financial compensation is not available through The University of Toledo or The University of Toledo Medical Center.

By signing this form you are not giving up any of your legal rights as a research subject. In the event of an injury, contact the principle investigator for this study: Abbey Thomas, PhD, ATC at 419-530-4501.

VOLUNTARY PARTICIPATION

Taking part in this study is voluntary. You may refuse to participate or discontinue participation at any time without penalty or a loss of benefits to which you are otherwise entitled. If you decide not to participate or to discontinue participation, your decision will not affect your future relations with the University of Toledo or The University of Toledo Medical Center.

NEW FINDINGS

You will be notified of new information that might change your decision to be in this study if any becomes available.

OFFER TO ANSWER QUESTIONS

Before you sign this form, please ask any questions on any aspect of this study that is unclear to you. You may take as much time as necessary to think it over. If you have questions regarding the research at any time before, during or after the study, you may contact the principle investigator for this study, Abbey Thomas, PhD, ATC at 419-530-4501.

If you have questions beyond those answered by the research team or your rights as a research subject or research-related injuries, please feel free to contact the Chairperson of the University of Toledo Biomedical Institutional Review Board at 419-383-8790.

SIGNATURE SECTION (Please read carefully)

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED ABOVE, YOU HAVE HAD ALL YOUR QUESTIONS ANSWERED, AND YOU HAVE DECIDED TO TAKE PART IN THIS RESEARCH.

BY SIGNING THIS DOCUMENT YOU AUTHORIZE US TO USE OR DISCLOSE YOUR PROTECTED HEALTH INFORMATION AS DESCRIBED IN THIS FORM.
The date you sign this document to enroll in this study, that is, today’s date, MUST fall between the dates indicated on the approval stamp affixed to the bottom of each page. These dates indicate that this form is valid when you enroll in the study but do not reflect how long you may participate in the study. Each page of this Consent/Authorization Form is stamped to indicate the form’s validity as approved by the UT Biomedical Institutional Review Board (IRB).

Name of Subject (please print)          Signature of Subject or Person Authorized to Consent          Date

Relationship to the Subject (Healthcare Power of Attorney authority or Legal Guardian)          a.m.          Time          p.m.

Name of Person Obtaining Consent (please print)          Signature of Person Obtaining Consent          Date

Name of Witness to Consent Process (when required by ICH Guidelines) (please print)          Signature of Witness to Consent Process (when required by ICH Guidelines)          Date

YOU WILL BE GIVEN A SIGNED COPY OF THIS FORM TO KEEP.
Marker Placement for All Sessions

Markers were placed over the right and left acromioclavicular joint, the sternal notch, and C7 to track the trunk, right off-set marker, right and left anterior superior iliac spine, iliac crests, posterior superior iliac spine, right and left greater trochanters, medial and lateral femoral epicondyles, distal thigh, tibial tuberosity, lateral shank, distal shank, medial and lateral malleoli, posterior calcaneus, base of the 5\textsuperscript{th} metatarsal, head of the 2\textsuperscript{nd} metatarsal, and dorsal navicular.
Appendix C

Scatter Plots for all Biomechanical Data Between Sessions 1 and 2

**Hip Sagittal Torque Self-Selected Gait**

**Hip Sagittal Rotation Self-Selected Gait**
Knee Sagittal Rotation Self-Selected Gait

Knee Frontal Torque Self-Selected Gait

Knee Frontal Rotation Self-Selected Gait
Hip Sagittal Torque Standard Gait

Hip Sagittal Rotation Standard Gait

Hip Frontal Torque Standard Gait
Hip Frontal Rotation Standard Gait

Knee Sagittal Torque Standard Gait

Knee Sagittal Rotation Standard Gait
Hip Frontal Rotation Stair Descent

Knee Frontal Torque Stair Descent

Knee Frontal Rotation Stair Descent
Hip Sagittal Torque Ascent

Hip Sagittal Rotation Ascent

Hip Frontal Torque Ascent
Hip Sagittal Torque Jump Landing

Hip Sagittal Rotation Jump Landing

Hip Frontal Torque Jump Landing
Hip Frontal Rotation Jump Landing

Knee Sagittal Torque Jump Landing

Knee Sagittal Rotation Jump Landing
Hip Sagittal Torque STS

Hip Sagittal Rotation STS

Hip Frontal Torque STS
Hip Frontal Rotation STS

Knee Sagittal Torque STS

Knee Sagittal Rotation STS