ABSTRACT

Assessing Precision and Application of Marker Placement Device to Enhance Motion Capture Studies

Forrest J. Whiddon, M.S.B.M.E.

Mentor: Jonathan Rylander, Ph.D.

Motion capture has become an important clinical tool used in applications of therapy and treatment plans as well as surgical evaluations. However, due to factors such as human error, having multiple examiners, and using multiple days, there is an inherent presence of error within clinical motion capture due to marker replacement. The objective of this study was to develop and evaluate a device that increases the precision of repeatedly placing motion capture markers on a subject for between-day and between-examiner situations. Each mechanical component of the device, as well as body positioning and marker placement repeatability, was evaluated for differences that compounded throughout the process. Kinematic trials were executed to indicate the significance of the device in application. The results showed that the device performed superiorly to human marking of all levels, producing maximum difference measurements of <8.08 mm and minimal measurements resulting in significant kinematic change.

Assessing Precision and Application of a Marker Placement Device
to Enhance Motion Capture Studies

by

Forrest J. Whiddon, B.S.M.E.

A Thesis

Approved by the Department of Mechanical Engineering

Paul Ro, Ph.D., Chairperson

Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree
of
Master of Science in Biomedical Engineering

Approved by the Thesis Committee

Jonathan Rylander, Ph.D., Chairperson

Brian Garner, Ph.D.

Jaeho Shim, Ph.D.

Accepted by the Graduate School
December 2020

J. Larry Lyon, Ph.D., Dean

Page bearing signatures is kept on file in the Graduate School.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I'd like to first off thank Dr. Rylander for being my advisor and helping me work through this project from start to finish through all the curveballs COVID threw at us. I'd also like to thank my fellow Biomotion Lab Members, Bradley Nelson and Amanda Nuckols, for helping with data collections as well as keeping me sane while we all pushed to get our projects finished. Thank you to all of my human subjects who gave up their mornings, afternoons, or evenings to come and help with this project on multiple days, it really relieved some stress in getting this done to have some very willing people in my life. I'd also like to thank the rest of my panel, Dr. Garner and Dr. Shim for giving me feedback on my project and reading through my thesis.

Outside of the Baylor bubble, I'd like to thank Cristina Diaz for being my number one supporter through this all. This could not have been done without you! I'd also like to thank my family for being supportive throughout the whole process, no matter the circumstance. And finally, a quick thank you to my friends: Jonathan, Ezra, Chris, Andrew, Luke and Ben. You each played a significant role in keeping me moving forward and helping me stay motivated. Thank you all.

DEDICATION

To my parents and Cristina. Thank you for the encouragement and support. We did it.

CHAPTER ONE

Introduction

The analysis of human movement is significant in being able to fully understand the body. In order to do anything in the biomedical world, from enhancing devices to diagnosing injuries, an understanding of the body is critical. Motion capture, seen in Figure 1.1, is one of the most common tools used to understand human movement, which commonly utilizes markers or fixtures placed along the surface of the body segment being analyzed [7]. The marker placement location is typically found through palpation or using the hands of the examiner to find the anatomical landmarks on the body. Motion capture is very beneficial to the medical community but is also working and affecting the entertainment field as well.

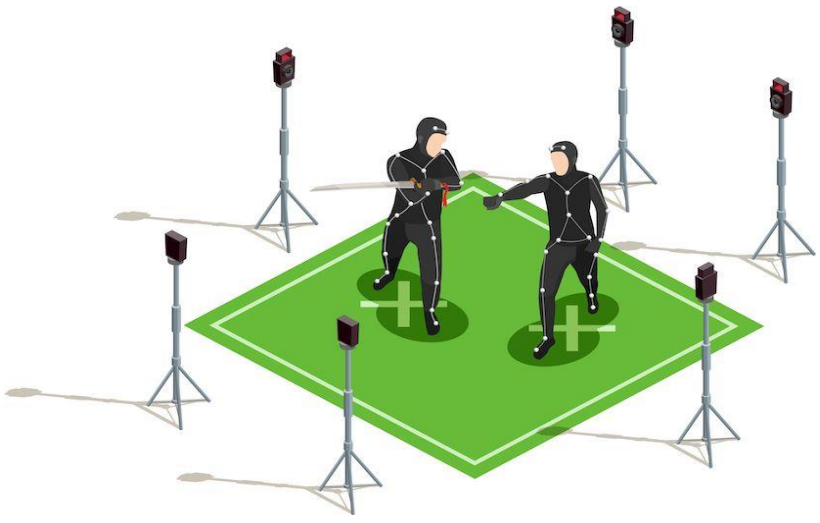

Fig 1.1. Example of motion capture system setup for entertainment [1].

In the gaming and animation world, optical motion capture is used to create replicas of people into characters in a movie or a game. These systems can even take actions done by the person in the real world and recreate this move as an in-game characteristic. These systems are also highly popular and useful in the movie industry, where CGI (computer generated images) have become a critical part of almost every movie. Major films like Avatar and Dawn of the Planet of the Apes use large amounts of motion capture so that their actors are transformed into their character. In typical medical settings, the subject has markers placed on the body in an attempt to diagnose injuries or abnormal walking patterns as well as effects of treatment. The subject then goes through sets of trials, typically walking trials where the recorded movement of the markers or fixtures is used to produce an understanding of the motion the segments and joints of the body are going through. These segments can also be used to infer the joint movement between segments, most common being the knee [7]. These are critical trials and can take place over certain increments of time (i.e. 1 month, 6 months, etc.) allowing for the doctor or therapist to see change, whether positive or negative [5].

Types of Motion Capture

Motion capture has become a valuable tool in the rehabilitation and medical world. 3-Dimensional motion analysis is commonly used to evaluate the effect of corrective therapies and interventions, the outcome of surgeries, as well as the effects of strength and gait trainings. This requires having multiple sessions of trials recorded in the motion capture system that occur between days, months, or even years. The different styles of motion capture systems include active marker setups, passive marker setups, and marker-less setups.

Active Marker Motion Capture

Active markers are characterized by LED lights and batteries that result in a system that is independent of its environment. Each marker is equipped with its own unique LED light which provides high accuracy and precision of capture, seen in Figure 1.2. Because it has its own lights, active marker systems are lighting independent, making them highly effective in areas where the lighting is not controlled [13,14].

Fig 1.2. Person marked with active motion capture setup [2].

With all the extra electronics added on, active markers tend to limit the movement of the subject, resulting in limited areas of trials and studies [13]. The needed power source for the markers is also a limiting factor as it can cause a delay or malfunction in reading if the battery is needed to be replaced. This might not be the biggest issue, but when the capture time is large and a marker goes out, this creates a larger problem. The extra space taken by the added wires and electronics results in less number of markers being allowed. There is benefit from clumps of markers being used to negate the soft tissue artifact in areas of muscle/fat and this takes away from that benefit [7,15].

Passive Marker Motion Capture

Passive markers are characterized by a reflective coating and a surface that allows itself to be attached to subject, seen in Figure 1.3. This simplicity results in a larger area of free movement and a larger viewing angle achieved [13,16]. The passive markers are power independent allowing an advantage when it comes to replacing batteries, these markers simply reflect light from the room and cameras back to the cameras in order to be found[16].

Fig 1.3. Person marked with passive motion capture [3].

These markers, however, are also more likely to be obscured and covered by clothing or body parts within the capture area, depending on the testing. This results in corrective action required to fill gaps created in the capture recording. Another issue with passive markers is the potential for cross-talk, or the software reading the markers as the incorrect location, resulting in skewed data. This is corrected in active systems by the markers having their own unique identifiers [13,14]. For a clinical setting, passive markers are a good option due to the ease of setup and application. Passive markers do

not require as long of a setup time when compared to active markers, allowing for less time needed for appointments or clinical tests. Passive markers also are less invasive by the lack of wiring. Patients can be inclined to change motion habits when they become too aware of the body attachments, so it is important to compare the wearability of markers and devices [17].

Marker-Less Motion Capture

Marker-less motion capture is characterized by the lack of markers needed to be placed on the subject. Still relatively novel and imperfect, this is the future direction of motion capture as it heavily reduces the preparation time of the subjects with the need for markers removed [13,15]. Similarly, the lack of markers has potential to prove more natural results, as the markers can cause a subject to adjust their own movement to accommodate the markers. One of the primary methods of marker-less motion capture is the visual hull method, which creates a locally convex representation that is created through volume intersection techniques, or reconstruction of a body through silhouettes, seen in Figure 1.4 [4].

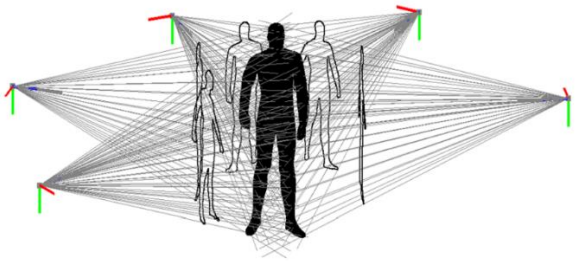

Fig 1.4. Example of visual hull reconstruction [4].

The current hurdle for this area of motion capture is the dialing in of the level of accuracy of the system in compared to marker-based systems. Previous studies that compare marker-less motion capture to marker-based motion capture have shown that some of the difficulties include ‘phantom volume’ or volume that doesn’t exist on person that the imaging software creates [15]. This tends to happen around the hip area, causing errors to be present in the readings of hip angles. There also tends to be an issue with the removal of background objects, specifically during the mid-stance and mid-swing phases of gait due to the self-shadowing [15]. These fall into the area of needs for improvement in the marker-less motion capture systems.

Clinical Use of Motion Capture

Motion capture has become a major tool in the clinical world. The systematic study of human walking is referred to as gait analysis, which uses instrumentation as well as experienced users to measure movements and mechanics of the body during walking[15]. Many gait analysis laboratories include a motion capture system, as this has become a significant application to retrieving data needed for analysis. These labs provide support in planning treatments for injuries or therapies, diagnosing pathologies, and even designing plans for surgical operations [15]. A brochure from the Nemours Gait and Analysis Lab can be seen in Figure 1.5 [5].

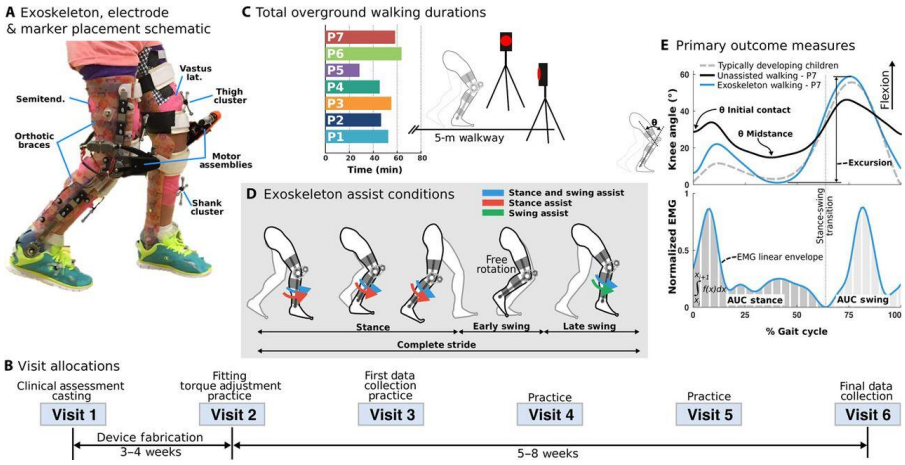

Fig 1.5: Lower-extremity exoskeleton study description[18].

One of the major usages for motion capture system in gait laboratories is when working with children that have or may have ambulatory cerebral palsy. The most common cause for physical disability in children, cerebral palsy affects 2-3 out of 1000 kids [19]. CP is a disorder of the development of posture and movement that is a result of issues occurring during brain development [19]. Children with ambulatory cerebral palsy maintain the ability to walk, although walking is done in an altered way due to the effects of the CP. In the image above, the gait analysis of an exoskeleton treatment for children with cerebral palsy is shown. This study used motion capture to analyze the effects of the treatment and how the gait changed [18]. Over the course of 12 weeks, patients returned for 6 visits where different modes of the exoskeleton used for the therapy were analyzed. They applied the individual conditions and evaluated the changes in knee angles through motion capture [18]. Another study was used to analyze upper extremity motion in children with unilateral cerebral palsy. Six daily tasks of the upper body were assessed using motion capture to evaluate correlation and timing, as well as look for trunk movement [20]. While not always the main tool of intervention, motion capture is used

primarily to assist in decision making of treatment options or therapy paths as well as evaluation of effectiveness. A study by Shurtleff and Engsberg, the trunk and head stability of children with cerebral palsy was evaluated using motion capture. This study took place over 12 weeks where a 45 minute intervention of hippotherapy was applied each week [21]. Variables of interest included translation of the head and spine and average head angles. These variables were found with the use of motion capture [21]. Ambulatory cerebral palsy patients are one of the primary demographics in gait analysis laboratories that have motion capture systems.

Many other neuromuscular conditions that affect walking (i.e. spina bifida) can also benefit from the analysis of motion capture, specifically when surgery is an option for correction or treatment [5]. Patients with a surgical option will typically visit a gait analysis lab approximately 9 months prior to surgery as well as 6 months before surgery so that the lab can process and analyze the walking pattern. From this analysis, the surgeon will then be able to make assessments and plan the surgery for the desired outcome. Clinicians can look at the data on gait, walking speed, cadence, balance, and joint angles at certain points within the walking cycle. Combining these variables with questions about pain levels, scientific correlation can be made to further assist in diagnosing treatment options [22]. This can eliminate the subjective nature of pain, allowing for it to be supported by objective data [22]. Post-surgery, the patient will return to the lab for analysis and the results will be able to be compared to the pre-surgery sessions and the improvement visibly seen in the analysis [5].

Motion capture is also used to verify treatment in patients with less severe conditions and where the improvements, while important, appear in a smaller way.

Patellofemoral pain syndrome is a disorder that causes pain in the anterior knee, most common in adults and adolescents. An example of patellofemoral pain syndrome and its effect on the knee can be seen in Figure 1.6. From a gait analysis standpoint, PFPS can be characterized by lower gait velocity, decreased cadence, and reduced knee extensor moment in the loading response and terminal stance, delayed peak rear foot eversion during gait and greater hip adduction [23]. Therapists who are applying an intervention to patients experiencing PFPS can verify improvements through gait laboratories with motion capture systems.

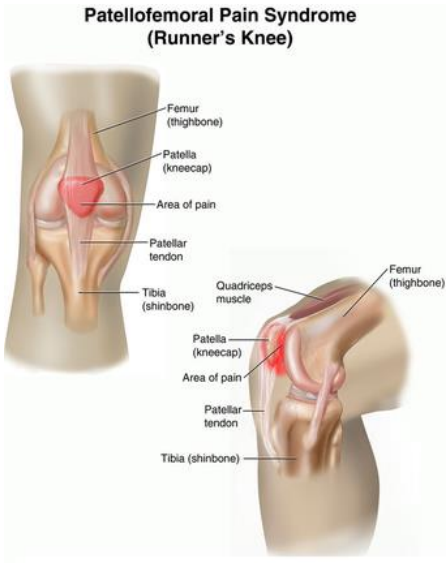

Fig 1.6 Patellofemoral Pain Syndrome Anatomy [6]

The usage for these systems has steadily increased over the past few years as the benefit of being able to diagnose conditions affecting walking more precisely has become more apparent [22]. With this increase in usage, however, it has become more imperative that this system performs with as little error as possible.

Common Sources of Error

Marker-based motion capture has been the gold standard for kinematic evaluation of the body; however the systems and processes of collecting data as a whole are not without error [15]. Attempting to place the markers in the exact same position by hand across multiple collections conducted on different days inherently produces errors in precision. Error can cause incorrect kinematic variable outcomes that can lead to an incorrect interpretation of treatment effect on a patient or injury state prior to surgery. Common sources of error stem from a single examiner, multiple examiners, multiple days, the system itself, or changes in the subject over time.

Single Examiner

In the case of a single examiner being the only person to place markers in a study, the error of precision is typically one of the lowest. Precision within a single trial done by a single examiner is typically high and does not contributing greatly to the variability as a whole [24,25]. However, while each day might have high precision with a single examiner, between days has proven to increase the variability of the study [24]. Even for a skilled user placing markers, variability can still range from 4.8 mm to 21 mm between study sessions [26]. Clearly the best possible situation for high precision and low variability occur when a single examiner does everything in one session, however that is not typically the design of most studies using motion capture. Typically, they require multiple sessions that may not occur frequently as they want to see the change over time. Having to take into account this source of variability can cause the validity of the study to decrease.

Multiple Examiners

A typical motion capture lab consists of many different examiners or users who will take part in placing markers depending on the study. This is another potential source of error, where the difference in levels of experience can make it difficult to compare data from the trials [25]. Even with multiple experienced users placing markers, the variability between them can range from 11.5 mm to 24.8 mm [26]. Less experienced examiners will also typically have a lower level of precision and accuracy compared to experienced examiners [27]. One study found that the greatest source of error in motion capture analysis was the error between different examiners placing markers [28]. Gorton et al., in 2009, looked at a single subject being analyzed at 12 different labs over a course of 3 months, and focused on the variability that occurs within a multi-site study as well as multi-examiner. It was found that with standardized protocol added to the follow up examination, error between examiner dropped 20%, however it still remained as the largest source of error [28].

Between Days

Between day reliability is critical, as most clinical outcome human-movement studies look at changes over time. This can be a source of error due to simply the effects of time and the space between trials. Having a subject or patient repeat a standing posture a week later is difficult to ensure accurate placement of markers using palpation. Studies have proven that variability increases in between day trials when compared to within-day trials. One study looked at 20 runners who were evaluated for reliability of discrete 3D kinematic, kinetic, and ground reaction force variables. Prior to this study, discrete points had not compared to assess this reliability. It was found that all aspects were more

reliable within-day vs between day with varying magnitude [29]. Similarly, guaranteeing that the marker is placed in the same palpated location is harder to do between days, due to human error as well as the change in posture. Studies that occur over weeks or months are looking for changes due to therapy or treatments, however the changes that are seen have to be taken into consideration with the potential sources of error. Being able to minimize these errors would be severely beneficial to increase the confidence that any results observed in the study are from an actual change in the person's movement rather than from an error in marker placement.

System Error

While probably the smallest source of error, error from the system itself has to be taken into consideration in total error. Typically, state-of-the-art motion capture systems have a maximum error of approx. 1-2 mm [16,30]. This results in a near negligible source of error, and most studies do not even look into this as a major source of error [28].

Subject Error

A further source of error comes from the subject itself, making it a less controllable variable. Subjects repeating previous standing postures have produced poor to moderate repeatability measurements [31]. With coaching and training within a single session, the precision is held at a high amount, however this does not follow through between days [31]. Devices that will be discussed later have been created to assist in a repeated standing posture, but these devices have not been evaluated to see if they actually increase the repeatability of posture. An even less controllable variable of the subjects is the aspect of change in the human body. Depending on the length of testing and trials, the human body changes and therefore affects the ability for markers to be

placed in the same location, but even more so affects the data being comparable. Different placement methods can be used to attempt to account for the change, but overall, this is something that is unpredictable from the system and process standpoint of motion capture.

Marker Placement

There are many different marker sets that can be involved in marker based motion capture studies. Which method to use depends on the application of the set and the desired measurement that the user wants to be able to evaluate. However, all marker sets use the same general process of using the position of the marker, combined with the measurements of the body to create segments that allow for proper evaluation. Once markers are labeled or identified by the system, it is then able to connect the appropriate markers together that create the segments and then use the segment throughout the kinematic evaluation. Different marker sets include the Helen Hayes marker set, Plug-In Gait marker set, cluster marker sets, and various others. Each has pros and cons depending on simplicity and ease of placement, usually countered by the resultant values produced.

Cluster marker sets, like the Point Cluster Technique used by Andriacchi seen in Figure 1.6, are used to reduce the error induced by soft tissue artifact on the limbs with larger amounts of soft tissue [7]. The marker set accomplishes this by using the additional clusters of markers on the thigh and shank. When increased motion of the marker cluster occurs between time points, it indicates non-rigid body motion. The magnitude of the marker trajectory is then reduced to simulate rigid body motion [7].

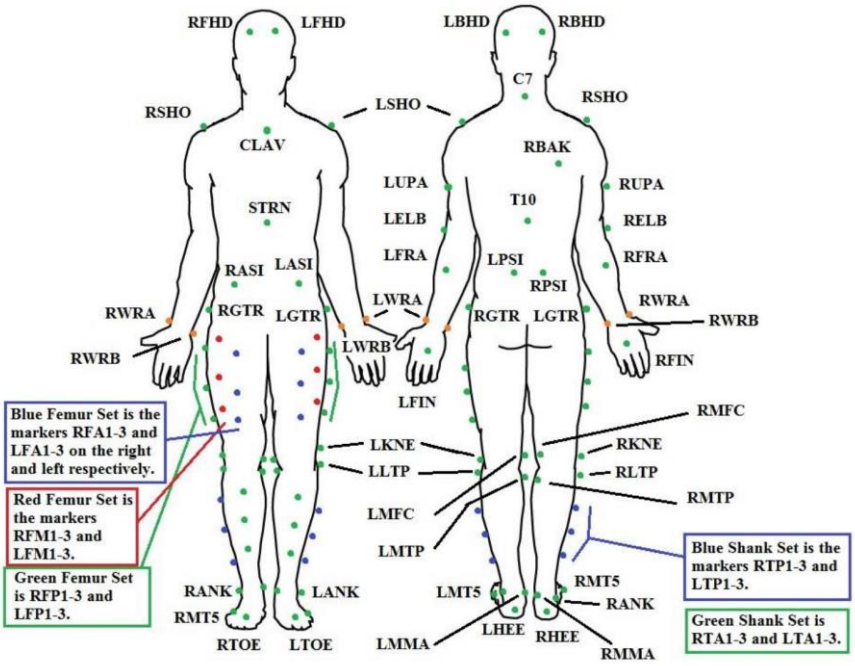

Fig 1.6. Point Cluster Technique [7].

The Helen Hayes marker set, seen in Figure 1.7, is characterized by 4-inch wands protruding from the femur and tibia. Similarly, the Modified Helen Hayes set removes these wands and replaces them with markers placed on the anterior of the leg [8]. Another difference between this and other marker sets is the single marker on the back of the pelvis, labeled the sacrum. The Helen Hayes marker set is widely used as a simple marker set within the marker-based motion capture discussion. Its limitations come from the simplicity of the marker set, specifically around the joints. As seen in the previous section, some marker sets have clusters that account for soft tissue artifact, however the Helen Hayes marker set does not. At the joints during activities of high flexion and extension in the joints, the skin on the joint can experience large magnitude of soft tissue artifact, up to 40 mm [9].

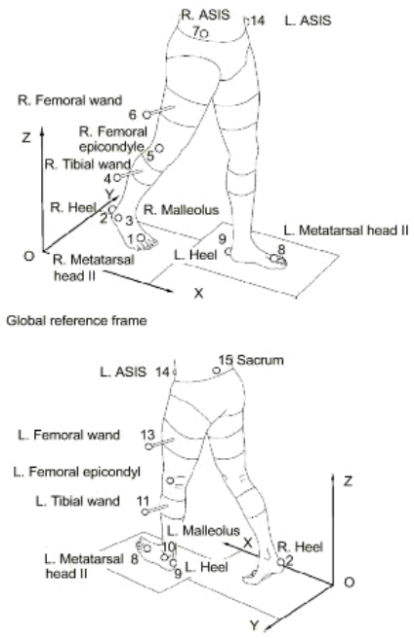

Fig 1.7. Helen Hayes Marker Set [8]

The research contained in this thesis is focused on the Plug-In Gait marker set, displayed in Figure 1.8.

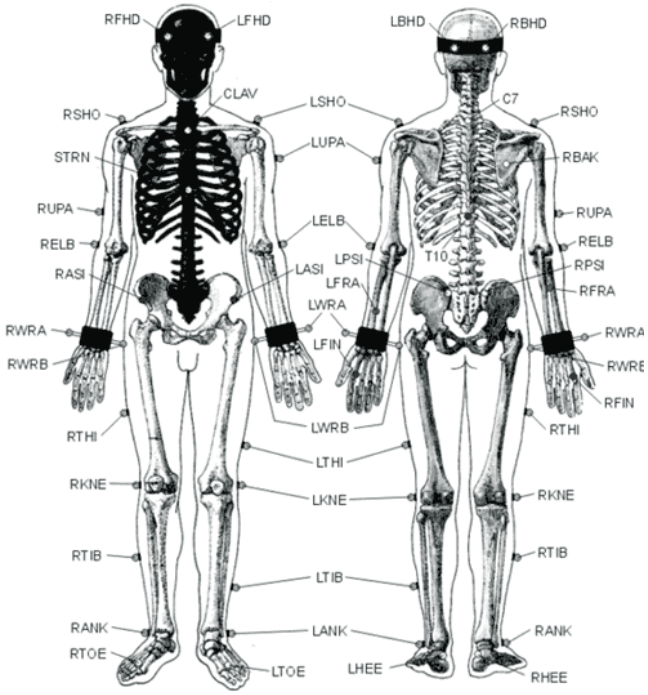

Fig 1.8: Plug-In Gait Marker Set [9].

Due to the focus of this study, the markers needed were cut down to strictly lower body. Different than the HH marker set, Plug-In Gait has two back pelvic markers, RPSI and LPSI, and no wands protruding from the limbs. Within Plug-in-Gait, the markers carry more weight in calculations because of the minimal markers on the body, much like the Helen Hayes set. The knee marker is valuable in creating the knee joint center and identifying the connection between the femur and the tibia [10]. The knee joint center is found through Vicon by input of the knee width from when the subject is initially measured. This measurement allows for Vicon to take where the knee marker is placed and calculate where that joint center is located. Similarly, the location of the knee marker defines one end of the femur segment and the tibia joint segment. Misplacement of this marker affects both segments and can cause skewed results in the aspect of knee angles in kinematic trials. The orientation of the coordinate system based on the markers placed can be seen in Figures 1.9-1.11 below for the pelvis, knee, and ankle, which are the three joint centers of focus in this study.

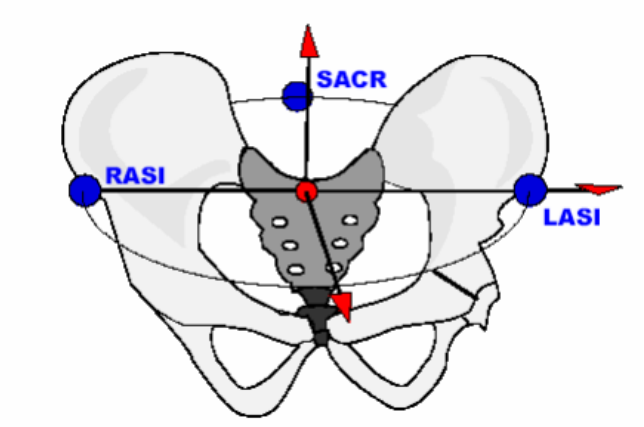

Fig. 1.9: Pelvic coordinate system based off marker placement [10].

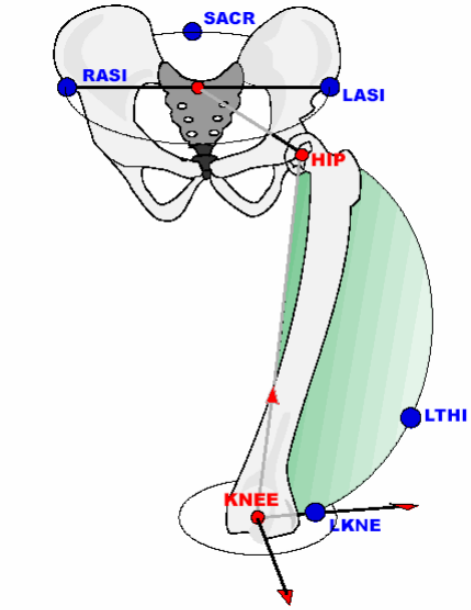

Fig. 1.10: Knee coordinate system based off marker placement on lower body [10]

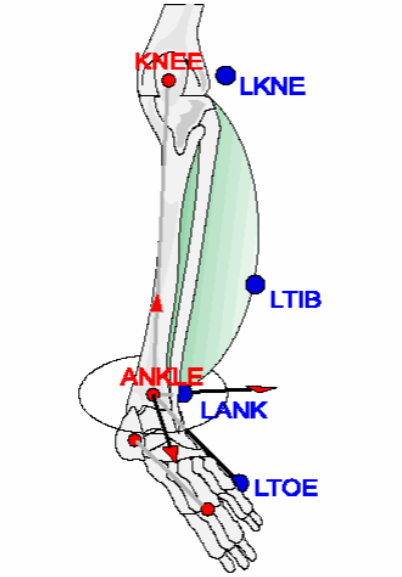

Fig. 1.11: Ankle coordinate system based off marker placement on lower body [10]

Vicon Nexus

The software used in the Baylor Biomotion Lab is from the company Vicon based out of Oxford, United Kingdom. Vicon has been around for 36 years, officially being founded as Oxford Metrics in 1984 [32]. The earliest systems went to universities in Australia, West Virgina and Strathclyde, and also to a rehabilitation center in Japan. These locations began pushing the limits of the Vicon software driving the initial research for the company [32]. In the 90s, the entertainment industry began rapidly developing the usage of motion capture in movies and video games. Due to the demand, Vicon launched the first motion capture system dedicated to the entertainment market in 1996 [32]. Vicon has continued to experience success and growth throughout the years following, expanding their line of cameras and motion capture software to better suit the needs of the industries as they arise.

Similar Studies

There are two devices that have been previously described in the literature that served as inspiration and comparison for the device that is detailed in this thesis. Noehren created the first of these devices in 2010, and was the inspiration for the creation of the device at Baylor [11]. Hutchinson created a second iteration of this device in 2018, the most recent found device created to improve accuracy of marker placement [12]. However, both of the studies came up with shortcomings that this device hopes to alleviate and improve upon.

In 2010, Noehren et al. created the first iteration of the marker placement device. The device consisted of a back support to maintain trunk positioning, upper and lower laser pointer arms for marker placement, and foot guides to assist in stance consistency.

The upper arms helped in marking on the hip and pelvis, the lower set of arms helped in marking the medial and lateral markers for the knee. The device can be seen in Figure 1.12 below [11].

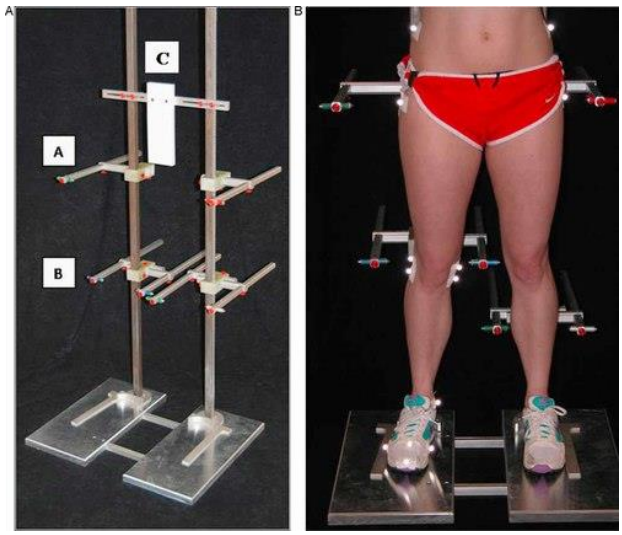

Fig 1.12: Marker Placement Device by Noehren [11]

Peak angles of the lower body joints were compared between the manual placement of markers and the use of the marker placement device. In this study, the subject came in for three sessions over the course of seven days. On the first session, the subject was marked and was asked to run on the treadmill while being recorded on Vicon. On the second session, the subject was again marked by hand and asked to run on the treadmill. During this session, the subject was placed in the marker placement device and the device alignment was recorded. On the third and final visit, the subject was marked by the device instead of by hand. The study then compared ICC values of the two methods, with 7 out of 9 ICC values of the marker placement device being >0.9 while for the manual placement, only 3 out of 9 were in that range [11]. This study proved that the marker placement device was beneficial in increasing precision in marker placement, and

was especially useful in studies looking at small changes in kinematics. However, the limitations of this study included the lack of body positioning support in the device and the limited variables analyzed in their evaluation. This device lacks the proper supports to assist in standing repeatability, only having a minimalist trunk support and the foot guides, the knees are allowed to flex and extend and rely solely on the ability of the subject to stand still in the same position for extended amounts of time. Another issue is that this study only looked at between-day repeatability of a single user instead of multiple users. As stated before, multi-user has been found to be the area that produces the greatest percentage of error in marker placement repeatability [28]. Overlooking this aspect does not allow for the device to be fully evaluated and proven beneficial in all circumstances.

In 2018, Hutchinson took the Noehren device and the study, looking to improve upon the results found and further evaluate their own device, seen in Figure 1.13. The major difference between the two devices is that this device does not have the laser pointers used for marker placement, and instead places them by virtually recreating the initial placements that are recorded from the first visit [12]. The device consists of a support below the gluteal cleft that helps position the pelvis and thighs, and one posterior to the calves that that positions the shanks. It also has adjustable foot guides that help in positioning the stance from the original visit [12].

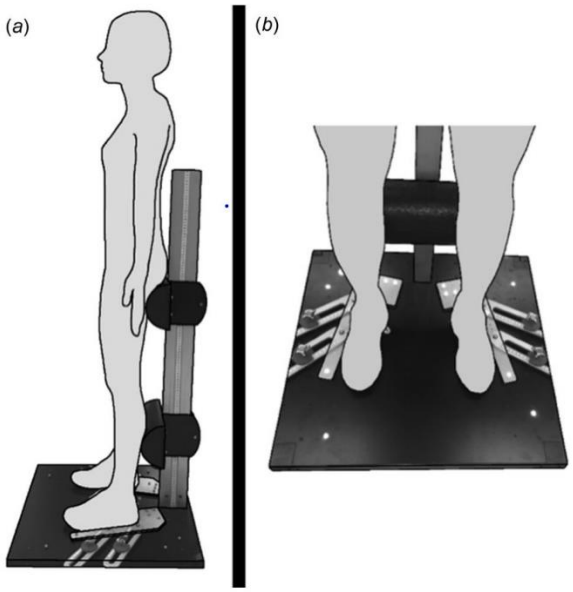

Fig 1.13: Marker Placement Device by Hutchinson [12]

When using this device at the first session, anatomical markers and tracking markers are placed on the subject. The anatomical markers are registered with respect to reference markers located on the base of the device. The tracking markers are placed on the thigh and shank and the footplates are also registered to the base of the device. The registered positions are then input into a unique matlab operation that then reconstructs the markers virtually on following visits. When the subject returns, they will only have the tracking marker placed back on their body as the anatomical markers are then only used virtually [12]. The kinematic angles were then evaluated and compared between multiple users and the results when the device was not used. The device proved to be beneficial in eliminating the need for manual palpation for the hip and knee markers and increased the precision found using the device [12]. However, the limitations of this study included the lack of between day testing and the requirements for long-term standing of subjects [12]. The study looked at multiple examiners and the difference

between them as well as the device, this was an area of weakness of the Noehren study [11]. However, unlike Noehren, Hutchinson did not look at between day decreases in precision. Taking all of the data on one single day, this study allowed for the subject to get more comfortable and remember the physical cues of the device, potentially skewing the data on repeatability [12]. Also, the device requires the subject to stand in the appropriate position for a much longer period of time than the Noehren device, as it aligns the posture virtually prior to placing the markers. This causes an additional requirement that subjects are able to stand for a long period of time [12].

Between the two studies, there are still areas of improvement for the design and evaluation of a similar device. Both studies operated on different research plans, Noehren using a single examiner over multiple days, and Hutchinson using multiple examiners over a single day [11,12]. A fully complete study would include multiple examiners over multiple days to provide the most complete look at evaluating this device. Both studies also verified the device by angles, and not directly by marker placement itself. Verifying the device by the actual positioning of the replaced markers would directly align with the intention of the device since kinematics are a combination of the marker placement as well as the marker set + kinematic model that is used by the research study. Finally, while Hutchinson did improve on the positioning supports of the device, both devices still relied on the subject's ability to hold their own positioning relative to the physical cues. An ideal device would eliminate the need for the subject to infer their own positioning and allow for them to base their posture solely on the cues of the device and take pressure of the stance.

Objective

The purpose of this study is to develop and evaluate a device that increases the precision of repeatedly placing motion capture markers on a subject for between-day and between-examiner situations. In order to achieve this purpose, we focused on a device that increases the subject positioning precision and ability to maintain that position while rigid-body sliding linkages are used to align lasers with the desired locations on the person's body. This study will look at the mechanics of the device itself and analyze the mechanical error of the different components included in the device. Similarly, the study will look at the process of using the device itself and the error associated with this aspect. Another key aspect of this study will be to look at numerically defining the repeatability of the posture, based on the location of the markers while the subject is placed on the device. In Figure 1.14, the process by which the device is to be tested and assessed can be seen. By the end of the study, the device and process will have been analyzed component by component. Following this process, kinematics trials will be run to add application to the device's performance in the preceding trials.

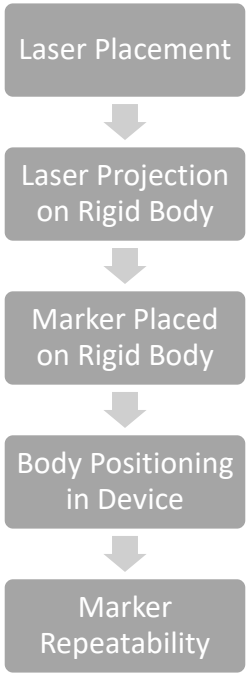

Fig. 1.14: Testing process for the device in this study.

This study creates a road map, as seen in Fig 1.14 that allows for component by component breakdown of error and difference occurrence within the device. The different sections of the trials can be broken down into the aims and the hypothesis that go along with these aims.

Aim – 1: To evaluate the device components directly by investigating the marker placement precision on a static rigid body. The laser placement, laser projection, and marker placement on a rigid body are the focus of this Aim. The intention is to evaluate if the device itself operates mechanically without creating error beyond the system threshold of 2 mm. This can be quantified based off of the system error that is inherent in Vicon Nexus, found to be less than 2 mm based on the study by Merriaux. [30]. This threshold applies to the first three aspects of testing, laser placement, laser projection, and marker placement on a rigid body. We hypothesize that the amount of difference will

increase as the components are compounded upon each other, prior to having a human added.

Aim – 2: To evaluate the subject body positioning repeatability of the device by measuring change in location of markers in relation to local reference points. Previous studies have not produced an effective way to quantify their body positioning, so a value to compare to from previous studies is unavailable. However, in a study by Croce, the amount of difference in marking can be found to be up to 25 mm [11,12,33]. Because of this, it is hypothesized that body positioning will have a larger step of increase in the amount of difference produced, due to the addition of a human subject.

Aim – 3: To evaluate the repeatability of marker placement within the device as well as comparatively to a novice and experienced examiner. The values from Croce's study are also used in hypothesizing for the marker repeatability section of the study [33]. The hypothesis is that the difference will increase the most for this aspect of the study since all the previous measured components (laser, slider, and subject positioning in the device) will be compounded together and then repeated for multiple sessions.

Aim – 4: To evaluate the significance of the device by systematically altering the location of markers on the knee and observing the changes in kinematics that result. Through this process, an association between marker position and kinematic shift was obtained and can be used to help understand the potential benefits of using a marker-placement device. We hypothesize that the device will significantly reduce marker placement error which will in-turn reduce kinematic error.

Different than previous studies, this study will look at the precision error between day and between examiners. This stands out compared to Hutchinson's and Noehren's

study as the combination of variables that have not been studied in comparison. Figure 1.15 shows this relationship.

	Single Examiner	Multiple Examiner
One Day Collection	N/A	Hutchinson et al
Multiple Day Collection	Noehren et al	*Thesis Study*

Fig 1.15: Examiner and Day Breakdown of Studies [11,12].

CHAPTER TWO

Marker Placement Device Upgrades

Backboard

The device acquired at the beginning of the study was created in 2016 by Baylor Senior Design students, based off a similar device used by Noehren et al in 2010 [11]. The device, referred to as the "Markerena", improved the ability for users to replace markers, however did not overcome the shortcomings experienced by Noehren. The biggest shortcoming seen in both situations revolved around the positioning of the human body. While getting a subject or patient to stand still can be difficult in its own right, trying to have a subject or patient repeat a standing position a day, week, month, or year later would produce poor to moderate results [31]. These devices are helpful in influencing the standing patient's posture, however with majority of the influences occurring in the upper body, the joints in the lower body are free to move about while still maintaining a standing position. To take the next step with the device and address the lack of control in postural stance, a backboard was added to the device, tilted backward at an angle to allow the subject to lean against it, see in Figure 2.1. The backboard itself rested on the upper railing of the frame surrounding the device and was attached with adapted hose brackets. A support was also added behind the backboard to reduce the amount of flexion occurring in the device as the subject placed their weight against it. The lean of the backboard allows for the patient to have multiple points of contact with

the backboard to influence stance without adding stress. As well, it reduces the need for any restraint that may benefit repeated standing posture, but cause issues with safety. Any restraint to the lower body of a patient on a device like this requires restraint to the upper body as well. The backboard voids the need for restraint and thus saves time and stress that applying restraints could bring about to the patient.

Fig 2.1: Baylor Biomotion Lab Marker Placement Device

Body Positioning Components

Foot Guides

While the backboard is a major step toward creating a device that influences postural repeatability, more additions were added to the device to hopefully further advance the success. Starting inferiorly, foot positioning guides were screwed tightly to the base of the device stand at a slightly outward angle, seen in Figure 2.2. These guides

were on the device when initially created; however, they were left loose to allow for adjustments. While having the adjustments is beneficial in being able to accommodate patients with different foot stances, it also allowed for movements in the guides that would result in less accurate foot placement. While the more permanent placement of the guides might not be able to accommodate all patients in their most comfortable stance, it should accommodate for a majority of people or at least be within a reasonable range for the patient to be able to stand appropriately for a short time. The angle applied to the foot guides also influences the knee placement. With the slightly outward rotation of the lower leg, the knee loses some of the natural inclination to bend to accommodate weight that occurs with a straight-forward stance.

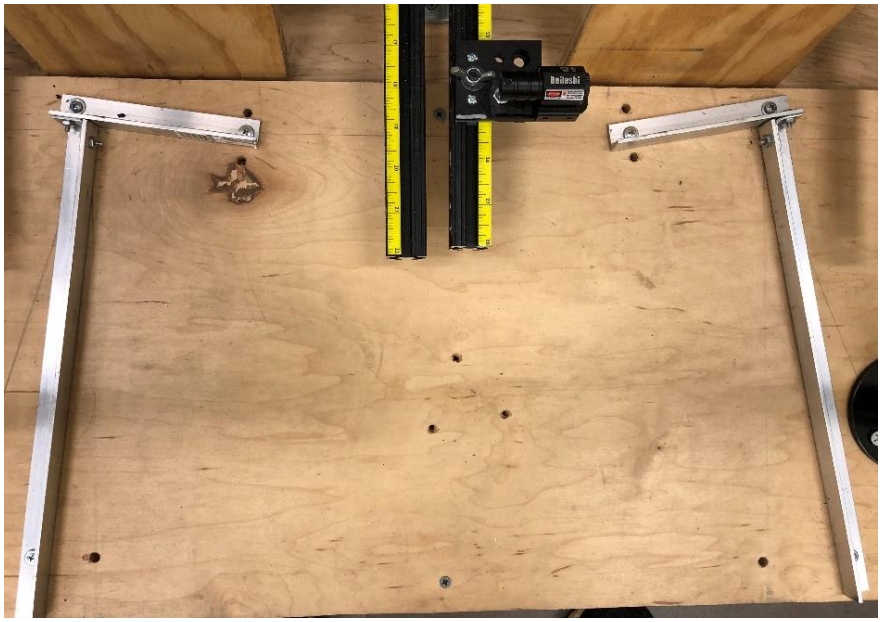

Fig 2.2: Foot guides on device.

Knee Guides

Continuing with the knee adjustments, two independent knee guides were added, one for each leg. The knee guides were made from a high density half-round foam roller, commonly used for physical therapy and stretching. The roller was 12 inches long and cut in half so that each knee received a 6-inch-wide guide. Along the backboard and the guides, Velcro strips were applied to allow for continuous adjustable attachment. The initial design used hooks and a rail with 12 specific openings for the hook, however this idea was abandoned largely due to the gaps between the placements not being accounted for when placed. The initial design can be seen in Figure 2.3.

Fig 2.3: Preliminary knee guides on device.

Also, the initial design pushed the knee too far forward, causing strain in the legs and requiring the patient to stand in a way that isn't sustainable for longer than 1-2 minutes. The guides are not meant to be full supports of the knee, but mainly touchpoints

to help the patient repeat the standing position. An adhesive measuring tape was applied to both sides so that the guides themselves could be adjusted and positioning recorded. The final design can be seen in Figure 2.4.

Fig 2.4: Final knee guides on device.

Lower Back Support

Moving up the body, a lower back support was added to the middle of the backboard, seen in Figure 2.5. When the backboard was first added, the lack of support to the lower back made it uncomfortable to stand on. The influence of the lower body setup causes a slight arch to the lower back that can become uncomfortable if held over a long period of time. The lower back support is generally a comfort addition to the device,

prolonging the amount of time a subject can hold their position. The padding used was previously the head support of the initial iteration of the device with the brackets and attachments removed. Similar to the knee guides, the lower back support had two strips of Velcro applied to its outer edges, and two strips also applied to the backboard allowing for continuous adjustment. An adhesive measuring tape was applied to allow for the placement of the device to be measured and recorded.

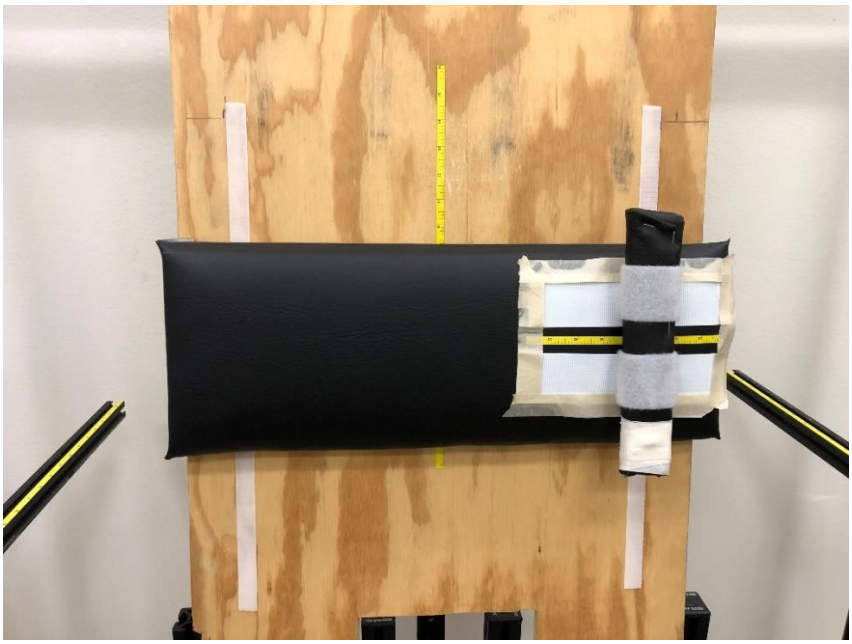

Fig 2.5: Lower back support on device.

Hip Guide

After initial marker placement testing, it was found that a hip guide was needed. Analysis of initial data showed that the highest source of posture repeatability error came from side-to-side changes between trials (in the Biomotion Lab, the y-axis). Specifically, the hip markers experienced high changes in relative location in this axis and skewed results. This proved to remain consistent across multiple subjects, so a hip guide was

added to the device. The hip guide is a small pad that was previously used for arm supports on the initial iteration of the device, seen in Figure 2.6. It is attached to the lower back support on the left side of the body, intended to be a touch point for the side/hip to assist the subject in realigning in the same position as previous appointments. Similar to previous additions, the hip guide has two Velcro strips applied to the top and bottom and two strips were added to the left side of the lower back support. An adhesive measuring tape was also added so the placement of the hip guide could be measured and recorded.

Fig 2.6: Hip guide on device.

Head Support

The final support/guide added to the device was a head support, seen in Figure 2.7. At the top of the backboard a cut was made to allow for the backboard to rest on the frame. However, it resulted in an area that is uncomfortable for a patient to rest their head. While not the most critical component to enhancing posture repeatability, the head support adds comfort to the positioning of the patient and allows for them to maintain

position longer. Also, it removes the natural forward lean the subject may have in order to avoid resting their head on the backboard. This forward lean could influence the body as a whole as it adapts to an adjustment in weight distribution. The head support is a smaller version of the lower back support, previously used as the back support on the initial iteration of the device. It has two Velcro strips applied to the back of the cushion, and two strips applied to the backboard to allow for continuous adjustments. An adhesive measuring tape was applied next to the backboard next to the device to allow for the placement to be measured and recorded.

Fig 2.7: Head support on device.

Miscellaneous

Additional to all the supports and guides added to the device with the backboard, there were only a couple of other minor changes to the device itself. The measuring tape was replaced on all (10) laser positioning arms for consistency, as well as for basic upkeep. The previous measuring tape was frayed and the width of the tape was larger than the width of the location of application, so there was hangover that interfered with

the laser sliding. Also, the laser positioning arms specific to the outer ankle were moved forward as far as possible to accommodate for the more forward positioning of the feet.

CHAPTER THREE

Device Testing Methods and Results

Device Evaluation

With the new construction of the device and the added components, it is necessary to re-evaluate the device. Proving that the device works and does so with accuracy and precision is crucial to being able to use the device to prove or disprove things later on. Similarly, this device will remain in the Baylor Biomotion Lab for the foreseeable future, evaluating the device and proving its worth will benefit the lab itself by providing a device that is proven to be improved from previous methods. Previously, a Baylor student has done device evaluation for an honor's thesis, including finding laser placement error and the laser pointing error of the device, however it was advised that these steps should be completed with more rigor and further steps be taken to evaluate. A similar process was done to evaluate the device in this case, taking each level of possible error and calculating the resultant error.

Laser Placement

The first set of device evaluation trials consisted of verifying the replacement of the laser pointers on the laser positioning arms of the device. To accomplish this, a marker was placed on the laser being tested, while another marker was placed on the base of the device, shown in Figure 3.1.

Fig 3.1: Markers placed for laser placement trials.

The user set the positioning of the laser pointer to an original position, recorded the placement of the laser pointer (both vertical and horizontal measurements) and took a baseline capture of the positioning in the Vicon Nexus software. The laser was then moved away from its original positioning down the length of the support arms in both the vertical and horizontal directions, and then repositioned at the original recorded measurements. Another capture was taken of the positioning in the Vicon Nexus software. This continued for 20 trials of the laser positioning and then repeated for each

of the 10 laser positioning arms on the device. In order to account for creator bias with the device, a second user was brought in to verify the results. Said user had zero experience with the device, having only seen it in the lab itself but never positioned lasers in any fashion. The second user completed 20 trials of positioning and re-positioning the laser pointers on two separate laser pointers that were randomly selected, seen in Figure 3.2.

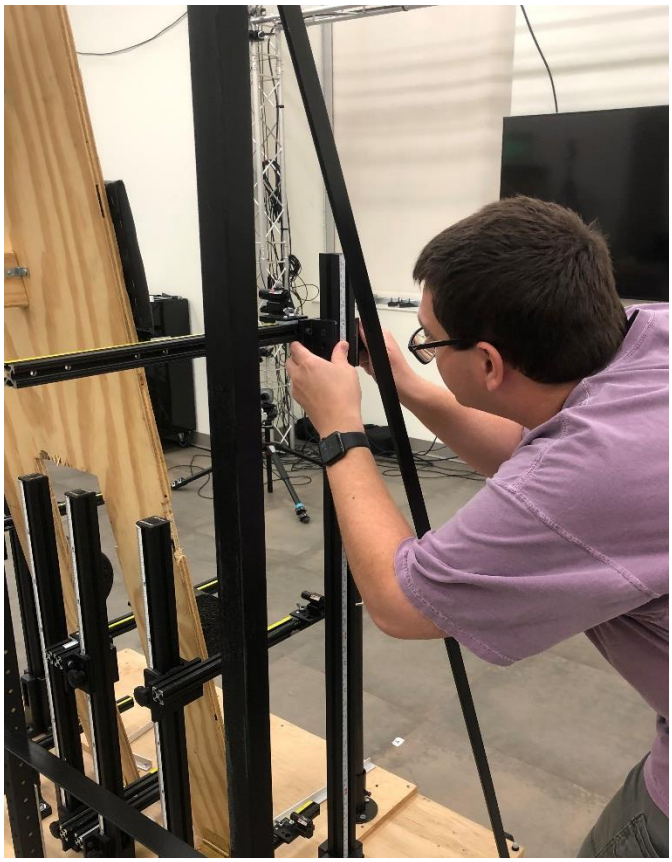

Fig 3.2: Second user testing laser placement on device.

The captured positioning images were then processed by finding the coordinates of the baseline marker on the laser and the device itself in space, and calculating the distance between in the x-, y-, and z-axis. The 20 following trials were then processed in

the same way and compared to the baseline distances to find the difference that was produced.

Laser Placement Results

From the 20 trials, the average absolute difference between the trials and the baseline trial were found along with their standard deviation. The values for each laser placement can be seen in Table 3.1.

Table 3.1. Laser Placement Absolute Difference Results

Laser	Avg. Difference (mm)	Std. Dev. (mm)	SEM
Right Hip	0.44	0.28	0.06
Right Outer Knee	0.64	0.60	0.13
Right Outer Ankle	0.51	0.52	0.12
Right Inner Knee	0.42	0.26	0.06
Right Inner Ankle	0.65	0.23	0.05
Left Hip	0.41	0.30	0.07
Left Outer Knee	0.32	0.41	0.09
Left Outer Ankle	0.37	0.37	0.08
Left Inner Knee	0.12	0.20	0.04
Left Inner Ankle	1.02	0.44	0.10

The average absolute difference between the second user trials were also found and can be seen in Table 3.2.

Table 3.2. Second User Laser Placement Absolute Difference Results

Laser	Avg. Diff. (mm)	Std. Dev. (mm)	SEM
Right Hip	0.36	0.25	0.06
Left Outer Knee	0.36	0.25	0.06

As stated previously, the inherent system error found in the Vicon Nexus system is less than or equal to 2 mm found through a study by Merriaux et al focused on assessing Vicon performance [16,30]. From this section of testing, the maximum difference value is 1.02 mm with a standard deviation of 0.44. Of the 10 markers tested, 6 of them are below 0.5 mm of difference. The results can be seen displayed visually in Fig 3.3.

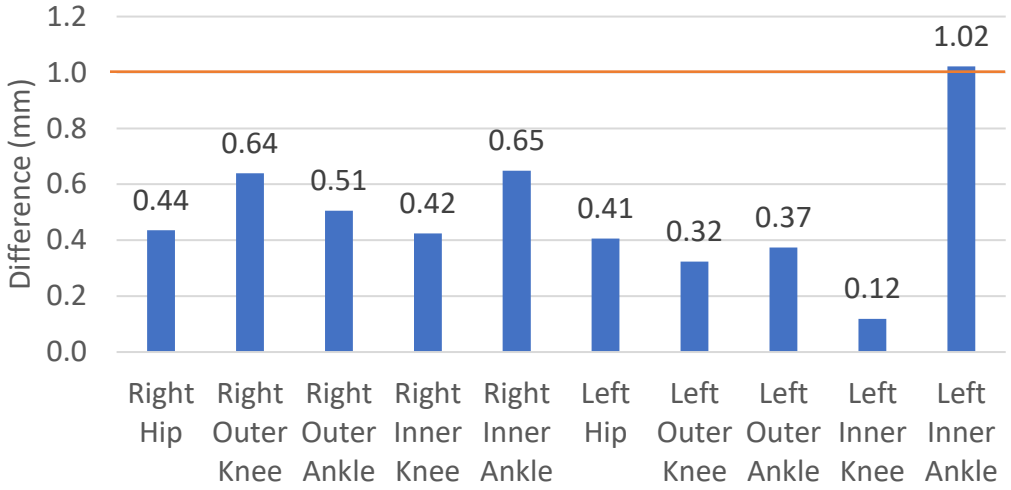

Fig. 3.3: Average Absolute Difference in Laser Placement for All Laser Pointers

These results are acceptable and fall below 2 mm, meaning that the results cannot be distinguished as additional error added to the system due to the device. Between users, the differences are negligible and support the precision of laser placement on this device between users. The positive results from this section resulted in narrowing down the lasers used for trials in the further steps in this study due to the consistency of results across lasers. The right hip, right outer knee, right inner knee, and right outer ankle lasers were used going forward and the results can be applied to the device as a whole.

Laser Point

The next set of device evaluation trials consisted of verifying the resultant point of the laser pointers on a rigid body. To accomplish this, a piece of wood was attached to the backboard by use of Velcro and straps to hold it in place, seen in Figure 3.4. It was imperative that the wood did not move or results could be skewed.

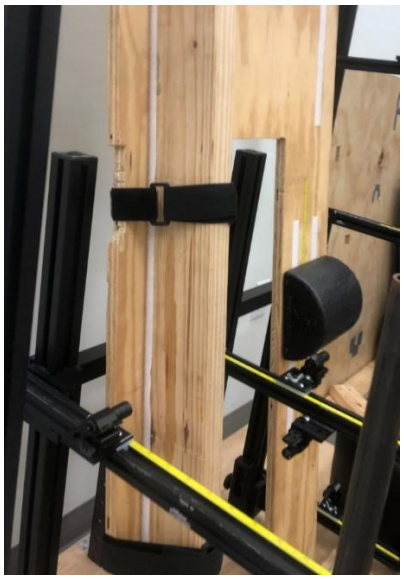

Fig 3.4: Rigid body attachment for laser projection trial.

The laser pointers were positioned at an original location on the laser positioning arms, the measurements recorded, and then the laser pointer was turned on. The resultant point on the piece of wood was marked using a pen to display where the original point was located. The laser pointer was then moved from its positioning down the length of the support arms in both the horizontal and vertical directions, and then repositioned at the recorded original measurements. The laser pointer was then turned back on and the resultant laser pointer was compared to the initial baseline marker, with the distance between measured and recorded using a caliper for high accuracy. This methodology can be seen in Figure 3.5 below.

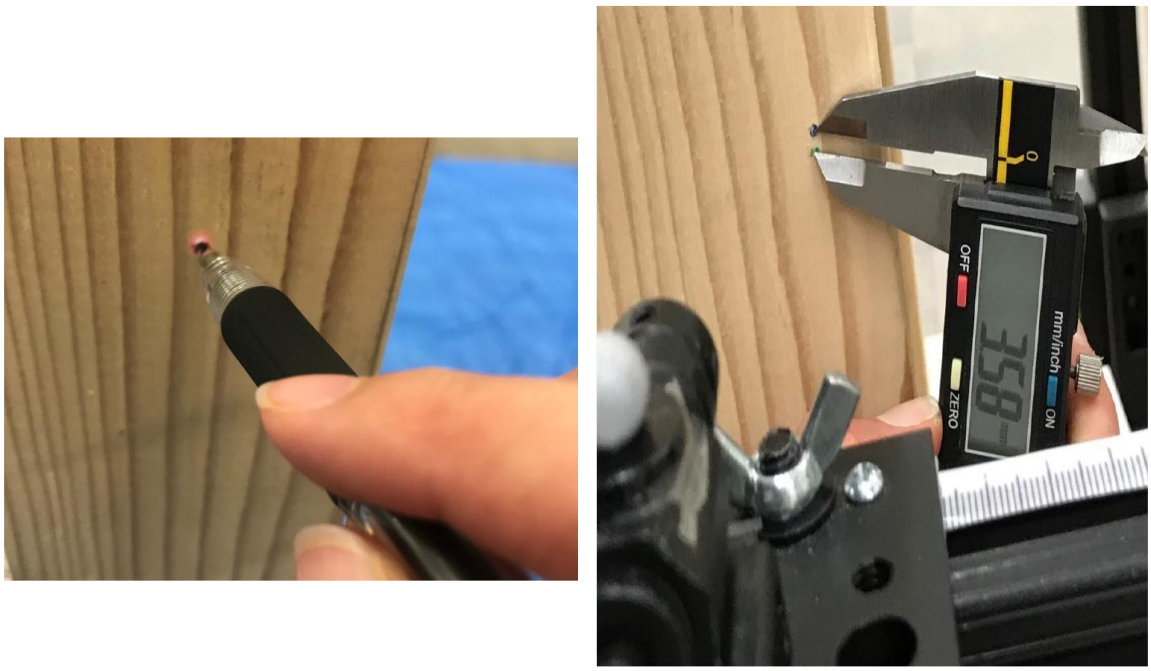

Fig 3.5: Laser Projection Difference Methodology

This was repeated 20 times more with the differences between the resultant laser point and the original baseline recorded, and then the whole verification was done for 3 other lasers on the device. Only 4 laser pointers were tested on this trial based on the results from the original step of device evaluation. The precision of each laser was within acceptable range so that the results of some laser pointers could be assumed for all the laser pointers going forward.

Laser Point Results

The results from the 20 trials from this section were used to find the absolute difference between the laser point on the wood of each trial and the mark of the initial trial point. These values look at the repeatability of the laser point that is shown on the piece of wood. The results from these trials can be seen in Table 3.3.

Table 3.3. Laser Pointer Absolute Average Difference Results

Laser	Abs. Avg. Difference (mm)	Std. Dev. (mm)	SEM
Right Hip	0.93	0.88	0.20
Right Outer Knee	0.17	0.19	0.04
Right Outer Ankle	0.90	0.40	0.09
Right Inner Knee	0.91	0.79	0.18

From the table, the largest value of absolute average difference occurred at the right hip and was 0.93 mm with a standard deviation of 0.88. All the average values fall below 1 mm which falls below the value of 2 mm previously mentioned as an value that can be applied to the Vicon system itself [16,30]. Because of this, the difference found cannot be specifically applied to the laser point or the laser point placement itself as a major source of error. These results are acceptable and cumulative of the last two sections as the laser was replaced every trial.

Marker Placement-Rigid Body

The final step of device evaluation, prior to introduction of a human for further testing, was the verification of the placement of markers on the rigid body. The piece of wood attached to the backboard from the previous setup was used again for actual placing of the markers. To accomplish the testing, the laser pointer was positioned along the laser positioning arms, with its position recorded both horizontally and vertically. The laser pointer was then turned on and a marker was placed at the site of the resultant laser point. Another marker was placed at another location on the piece of wood to simulate multiple markers on a single segment. This additional marker would be the reference marker and would remain in place for all the trials of the single laser pointer. Once the markers were in place, a capture was taken using the Vicon Nexus software. The laser was then moved

out of position by at least 10 mm in both the horizontal and vertical directions and the placed laser was also removed from the block of wood, leaving only the reference marker to remain on the wood. The laser pointer was then repositioned in the originally recorded position, the laser turned on, and a marker was placed at the resultant laser point. This can be seen in Figure 3.6. A capture was taken of the positioning of the lasers that would later be compared to the original baseline. This was repeated 20 times for the same 4 lasers from the previous trials.

Fig 3.6: Markers placed and laser projection on rigid body.

In order to account for creator bias in this step of the evaluation process, another second user was brought in to verify results. Said user was a different second user from previous trials and also had no experience with the device. This user also had no experience placing markers on either a rigid body or a person. The second user performed 20 trials of positioning the laser and placing a marker on one of the lasers tested, chosen at random.

In order to process the marker placement evaluation, the captures were opened up in Vicon Nexus software. Positioning of the baseline capture were initially found, finding the location of the reference marker as well as the applied marker on the wood. The distance between the two markers was calculated in the x-, y-, and z-axis and recorded. The following trials were then brought into the software and processed in the same pattern. The resultant distances of the trials were compared to that of the baseline values to find the precision error of this evaluation.

Marker Placement Rigid Body Results

The resultant vector lengths between the baseline and the following trials were compared and the average absolute difference was recorded. The results for each laser tested can be seen in Table 3.4.

Table 3.4. Marker Placement on Rigid Body Absolute Difference Results

Laser	Avg. Difference (mm)	Std. Dev. (mm)	SEM
Right Hip	0.82	0.83	0.19
Right Outer Knee	0.46	0.30	0.07
Right Outer Ankle	0.80	0.47	0.10
Right Inner Knee	0.90	0.68	0.15

The results from the second user, who tested the right hip marker which was chosen at random, can be seen in Table 3.5.

Table 3.5. Second User Marker Placement on Rigid Body Absolute Difference Results

Laser	Avg. Difference (mm)	Std. Dev. (mm)	SEM
Right Hip	1.71	0.86	0.19

From the first table, all the absolute average difference distances fall below 1 mm, with the largest occurring at the right inner knee with a value of 0.90 mm and a standard deviation of 0.68. The second user doubled the value of the marker placement difference to 1.71 mm for the right hip with a standard deviation of 0.86. While this is a large increase, it still falls below the threshold previously mentioned of 2 mm of error unable to be fully separated from the system itself. The increase is evidence that the placing of the marker itself has human bias between marker placers, while the previous second user testing held the device usage itself to a negligible difference.

Conclusion and Discussion

Throughout the device evaluation process, the aim has been to keep the difference occurring in the data to below 2 mm. Merriaux et al performed a study that resulted in the previously mentioned value of error that is indistinguishable from the system error [30]. Because of this, the source of error or difference occurring below 2 mm, while potentially resultant from user or device, is unidentifiable. The final trials of the testing combined the previously tested components of the user and device interface. The lasers were moved and replaced to a certain location, the lasers turned on, and a marker placed on a rigid body. The step-by-step process through the components allows for a specific look at the

origins of error and difference in trials from this device. In the final stage, the largest value of difference was 1.71 mm with standard deviation of 0.86. This was a result of a second user using the device who had never used the device before the trials. This resultant difference falls below the 2 mm threshold and therefore supports the device in its precision and lack of increased error of marker placing. Because of this, the device is approved to go forward and include the factors of a human body into the experimentation. The following trials will look more closely at the device in relation to future subjects and future data collections.

CHAPTER FOUR

Data Collections

Human Sessions

Following the trials focusing on evaluating the device, data collections were run to further analyze the benefit of the device in use. An application was submitted and approved which made this study human subject exempt by the IRB board. This indicates that the data being found from the data collections would not be used for generalizations about the human population, rather it would be used specifically for proving the device. Human subject exemption also limited the number of subjects that could be involved in order to help prove the device to 5. We had 5 subjects come in for two separate occasions to complete data collection process and acquire data that looked at marker placement repeatability, body position repeatability, and kinematics.

Marker Placement Repeatability

Marker placement repeatability is the key factor of this study, as it is the crucial point of error in the optical motion capture world. Any source of improvement adds major value to the data found in a study. To test for marker placement repeatability, a trial was setup to directly compare the precision of the device to human placement. There

were two human examiners who palpated for location: one experienced (n = 250+data collections) and one novice (n = 10 data collections). This gave the results two demographics of markers to compare against the device precision. To begin the trials, a subject was brought in and marked with the lower body plug-in-gait marker set. Additionally, markers were added to the greater trochanter and the inner knee, as these were two of the laser positions evaluated throughout the study. The subject then went through calibration in the Vicon Nexus software, so the segments and lower body shape would be recognized. The subject then stepped into the marker placement device to allow for the user to adjust the laser positioning arms as well as the body positioning arms to fit the subject. The positions of all aspects of the device were measured and recorded to be used later in the study. Following the calibration, additional reference markers were added to the segments of interest on the right leg. These reference markers would be used to create a local coordinate system to better compare the precision of marker placement on that segment. The femur, tibia, and foot all received these three additional reference markers, allowing for the reference coordinates to measure markers placed above the reference. The configuration for these markers can be seen in Fig 4.1.

Fig 4.1: Reference markers placed on tibial segment.

The four markers that the study is looking at are the same four form the device evaluation trials, the hip (RHIP), outer knee (RKNE), outer ankle (RANK), and inner knee (RIKNE) markers. The femur reference markers would be for the hip, the tibia for both the knee markers, and the foot for the ankle. Following the calibration and addition of reference markers, the subject was ready to go through the repeatability study.

To collect the data necessary for the marker placement repeatability trials, the subject rotated through the 3 different marker placement methods. The three included the novice examiner, the experienced examiner, and the marker placement device. At each station in the rotation, the subject would have the 4 markers mentioned previously replaced on the subject's right leg. Once the markers were in position, the subject then would position themselves in the middle of the capture area and a capture was taken using the Vicon Nexus software. Once the capture was taken, the subject then removed the four markers, the previous marker placer checked the locations for any signs that may remain from the application and removal process, and then the subject moved to the next method of placement. The subject was marked three times by each method, for a total of nine marker placements during the visit. This was done for 5 subjects, and the subjects completed this twice on two separate days. This allowed for the precision on same day to be compared, as well as the precision between days.

Body Position Repeatability

During these same trials, data for body positioning was also collected for processing. This aspect is to look at the change in the body stance on the device when being repositioned after a certain amount of time. This is a critical source of error, as a person can stand in a slightly different stance, and cause major errors in the placement of

the markers [31]. In order to collect the data necessary for the body positioning repeatability, captures were taken immediately following the placement of markers on the device each time while the subject remained on the device. Three reference markers were added to the base of the device that will be used in processing to accurately look at the ability for a person to reenter the exact same standing posture as previously recorded. The references markers will be used in relation to the reference markers placed on the separate segments of the body in order to see the changes in the different directions for posture repeatability. These markers included RASI, RTHI, RTIB, and RTOE, and were placed in the initial palpated marking of the body and then not removed until the session came to a close. These markers can be seen indicated in the Fig 4.2 using the plug in gait image from earlier.

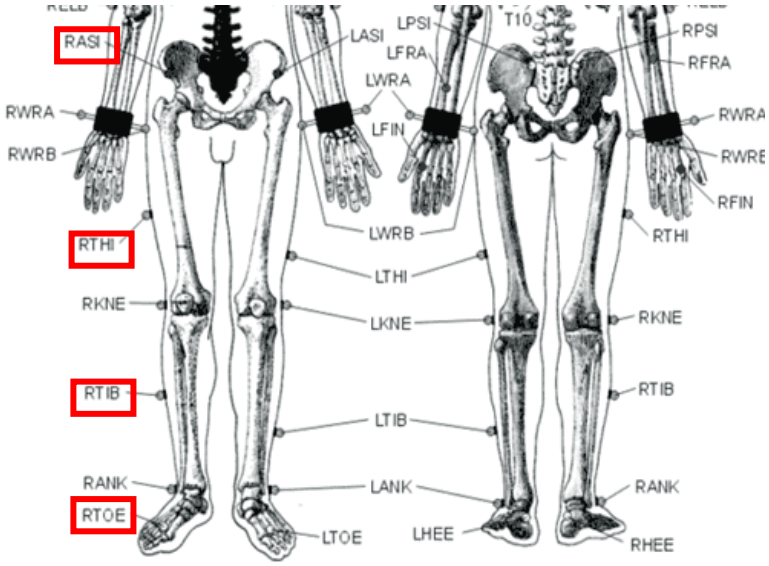

Fig 4.2: Body positioning markers of interest

The RASI marker is on the pelvis, the RTHI is on the femur, the RTIB is on the tibia, and the RTOE is on the foot. Since each subject was remarked 3 times on the

marker placement device, there will be 10 sessions of body positioning repeatability available for processing.

Kinematics

Each subject also went through kinematic trials at the end of one of their sessions. Kinematics in motion capture are directly based on the locations and placements of the reflective markers along the body. These trials looked at many different kinematic activities and were aimed to see the difference in measurements when a marker is misplaced. Specifically, the outer knee marker placement was the area of interest for this study as with most similar studies [27]. Surrounding the normal RKNE marker placed on the outer knee, 4 more markers were added, one superiorly, one posteriorly, one inferiorly, and one anteriorly in relation to the RKNE marker, and will be referenced accordingly going forward. The configuration for these knee markers can be seen in Figure 4.3. The knee marker is an important one in allowing for Vicon to identify joint centers by creating segments that meet at the knee marker. This marker combines with thigh and pelvic markers to create the femur segment, and combines with the tibia and ankle markers to create the tibia segment. Where these segments intersect at the marker is considered the joint center for the knee joint.

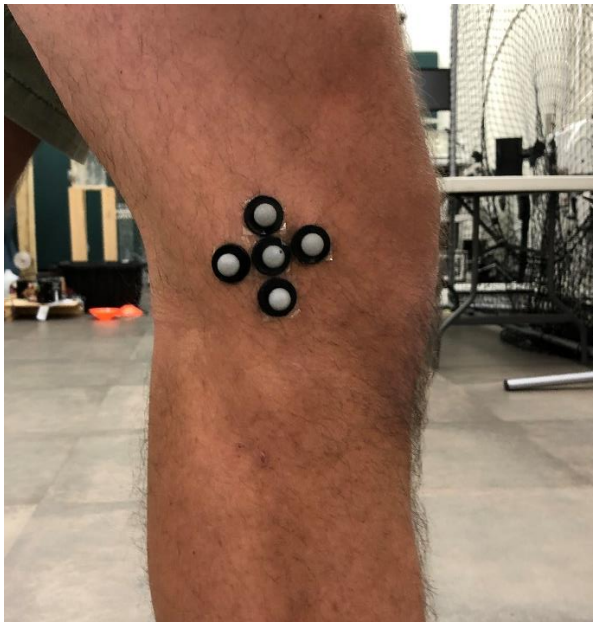

Fig 4.3: Kinematic trials knee marker configuration.

These different markers will be used to display the difference in kinematic results based on placing a marker in the wrong location. All 4 of the markers were placed with the outer edge touching that of the RKNE, so indicative of a misplacement of one whole marker (approx. 15-20 mm). These incorrect placements would cause the segments of the leg to be shorter or longer depending on which direction, and would likely cause the angle to change. The results of incorrect placement are likely to cause angles that are incorrect or don't fully represent the angle occurring, producing results that might seem like the knee is hyperextended or some other variation of knee angle diagnostics [27]. Other than this area, the subject remained in the normal plug-in-gait marker set. Once marked and ready, the subject was asked to perform 6 different types of kinematic movement to allow for appropriate analysis, 3 of which were then processed and analyzed in this study. These 6 different kinematic movements included walking, running, stepping up onto a stool, jumping down from the stool and landing on one leg,

run-to-cut, and squatting. The three analyzed in the study were walking, running, and run-to-cut.

CHAPTER FIVE

Results

Data Collection Results

The results of this study were collected in three separate categories, however they are all significant to each other and the success of the device. Body position repeatability and marker placement repeatability continue the evaluation of the device while adding the human element. Kinematics results are to add significance to the results from previous study by applying it to real world scenario.

Body Position Repeatability

Body position repeatability is a topic that seems to be difficult to quantify based off of previous studies. Both Noehren and Hutchinson listed body positioning and postural repeatability as limitations due to the inability to accurately differentiate the body positioning error from marker replacement error [11,12]. Their devices from these previously mentioned studies influenced posture to stand straight, however they were not able to identify if it was able to enhance repeatability of the posture. The device in this study aimed to take the control of posture out of the subject's hands and influence them in a way that allows for a high level of repeatability without increasing the amount of work or time required. This study looked at the position of 4 markers that were not removed from the body during testing (RASI, RTHI, RTIB, and RTOE) and the

positioning of the marker related to a local reference on the device. Each marker resides on a separate segment from the others so a full visualization of the segmental positioning was able to be found through these trials. Using Vicon Nexus, the mean difference between the markers in the x-, y-, and z- directions were pulled from the static pose and recorded. Difference between trials was pulled from trials in sequence (Trial 2-Trial 1, Trial 3-Trial 2, etc.) and then averaged for the subject. The results of the four markers and their absolute differences in the x-, y-, and z- direction were then averaged for each marker and can be seen in Table 5.1.

Table 5.1. Combined Body Positioning Absolute Average Difference of Marker

Marker	X (mm)	Std.Dev	Y (mm)	Std. Dev	Z (mm)	Std. Dev
RASI	1.81	0.76	6.12	2.00	1.61	0.73
RTHI	1.84	0.83	4.71	1.20	1.06	0.42
RTIB	2.27	1.19	3.08	1.27	0.79	0.28
RTOE	1.18	0.81	0.81	0.35	0.40	0.13

From the table, the largest value occurred for the RASI marker in the y-direction. In this section of testing, the y-direction refers to side-to-side motion of the subject in the device. The largest value was 6.12 mm with a standard deviation of 2.00. The body positioning in the x-direction (front-to-back) and z-direction (up-and-down) did not exceed 2.27 mm with a standard deviation of 1.19. The data from the table above can be better visualized in Fig. 5.1.

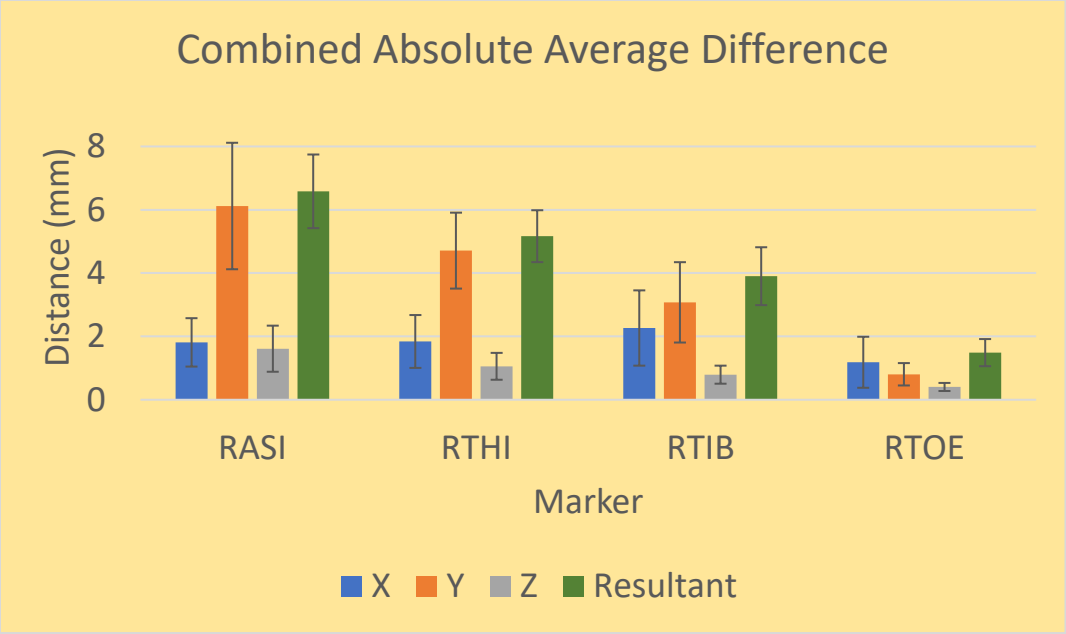

Fig 5.1: Combined absolute average difference for body position repeatability.

The resultant vector length from these results was also found and can be seen in Table 5.2 and graphed in Fig 5.1. These values represent the actual average distance the marker would have moved away from the original placement of the body within the device.

Table 5.2. Body Positioning Resultant Vectors for Absolute Average Difference

	Resultant Vector (mm)
RASI	6.58
RTHI	5.17
RTIB	3.90
RTOE	1.49

The largest resultant vector occurred in the RASI, where the average resultant vector of difference was 6.58 mm. From the Figure 5.1 and Table 5.2, it can be seen that the difference decreases as it moves from most superior marker on the body to most inferior. This is expected as the feet are on the base of the device and have little room for

movement, while the RASI, or the pelvis, has the least amount of restriction and is a resultant positioning based on the rest of the lower body.

In order to look at a more common aspect of correlation, interclass correlation coefficients (ICC) were calculated for the data of each subject. An ANOVA two-factor statistics analysis was run for the sets of data and from that the ICC value was calculated. These values are expected to be high, due to the nature of the testing and the small differences. The coordinate location values of all the trials from both sessions for each subject were correlated with the resultant value seen in the Table 5.3.

Table 5.3. ICC Values for Coordinates for Each Subject

Subject	X	Y	Z
1	0.996	0.996	0.995
2	0.998	0.993	0.999
3	0.998	0.981	0.998
4	0.998	0.992	0.999
5	0.999	0.995	0.997

From this table, the only value lower than 0.99 occurred in the y-direction of subject 3 with a value of 0.9813. This is still an acceptable value and occurs in the axis that is also expected to result in the lower ICC based on previous results. The combined ICC values were also compared and can be seen in the Table 5.4.

Table 5.4. Combined ICC Values for Each Subject

Subject	Comb. ICC
1	0.998
2	0.999
3	0.999
4	0.999
5	0.999

The lowest ICC value occurring is 0.998 with subject one. These ICC values represent a high correlation between the positioning in all coordinate directions and imply that the device results in high repeatability when it comes to posture.

Marker Placement Repeatability

Marker placement repeatability is the critical point in this study, and is the aspect that has been attempted to improve by many studies mentioned in earlier sections [11,12]. The testing done in the sessions of this study looked at the precision of a novice examiner placing the markers, an experienced examiner placing the marker and the device. The way this precision was measured was based off the largest absolute difference method. The center of the three marker coordinates was found and the furthest marker from the center dictated the value. An example of the measurement method can be seen in Fig 5.2. Matlab code was written that calculated the center of the three markers and then found which of the three was furthest from the center. It then plotted the circle encapsulating all of the markers and produced the repeatability value (R Value) for that circle. The Matlab code can be found in Appendix A.

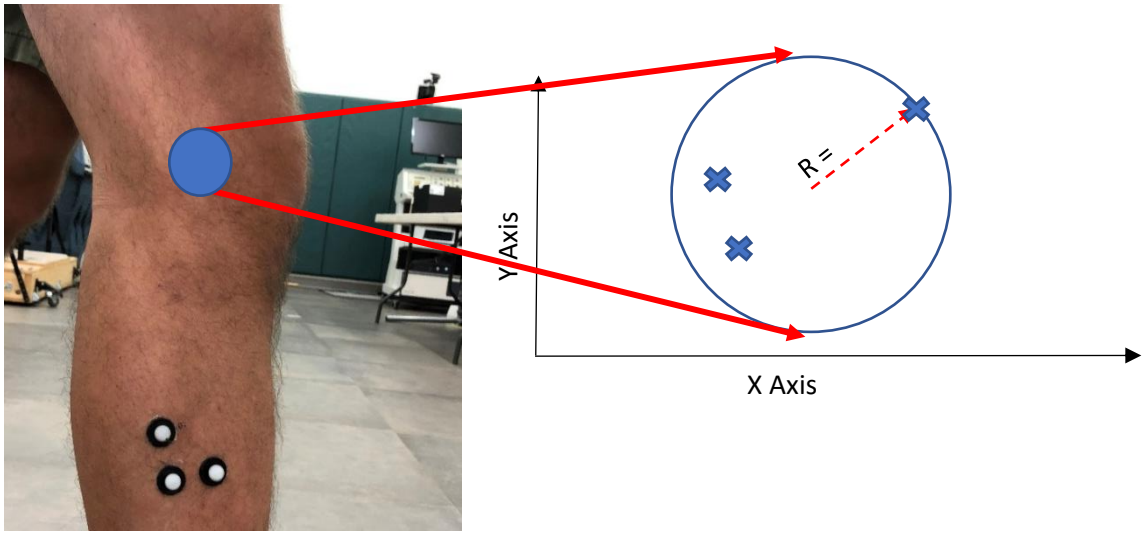

Fig 5.2: Repeatability or ‘R’ Value process of measurement.

The value produced from this method, referred to from here on out as “the R-Value” or repeatability value, is the radius of the circle produced. From this method, an assumption can be made that all three markers fall within a circle of diameter 2*R. Three circles are produced on the graphs of this study, each one representing either the experienced examiner, the novice examiner, or the device. For every subject and session, a graph was produced for all four of the markers replaced on the body throughout the session. The three circles can be seen in Figures 5.3 and 5.4 below. In Figure 5.3, the circles appear warped, that is only due to the limitations of the range on the axes.

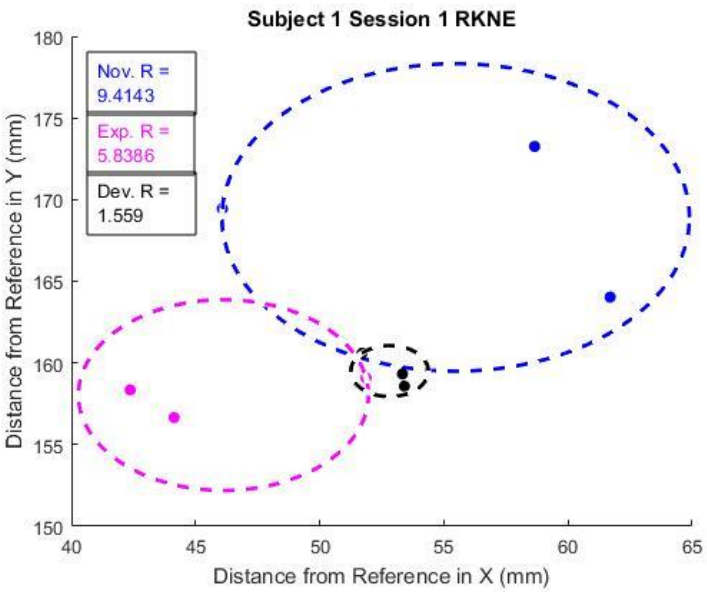

Fig 5.3: Subject 1 Session 1 RKNE marker circles

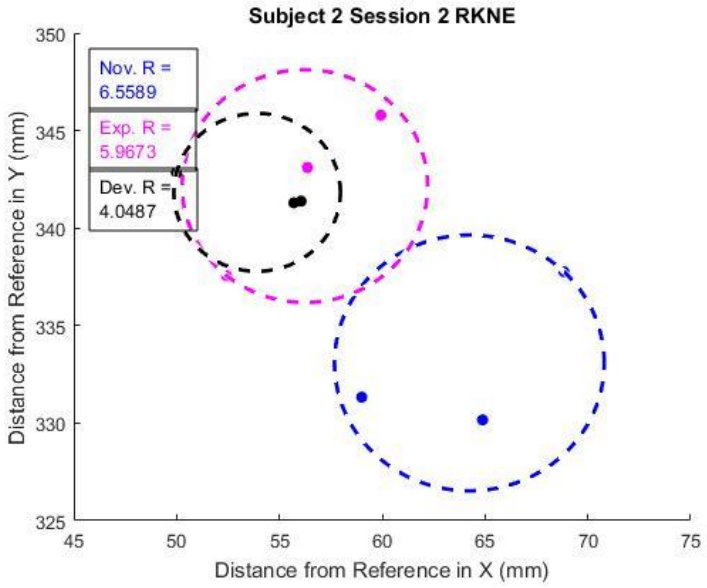

Fig 5.4: Subject 2 Session 2 RKNE marker circles

These example graphs look at the RKNE marker, which is a critical joint marker for gait analysis and tends to be a difficult one to mark precisely. Blue circle represents the novice examiner, pink circle represents the experienced examiner, and the black circle

represents the device. In the legend located in the upper left hand corner of the graph, the R values for this specific graph can be seen. This is where the R value from the resultant tables was pulled from.

From these graphs, the R values were pulled and compared between the different marking methods (experienced, novice, device). All of these values can be seen in the appendix, but the average across subjects for each location was found and can be seen in Table 5.5.

Table 5.5. Averaged Repeatability ('R') Value for each Marker

Marker	Novice	SD	Experienced	SD	Device	SD
RHIP	12.63	7.82	10.27	3.15	3.72	1.58
RKNE	6.74	3.02	7.37	3.74	3.52	2.09
RINKNE	13.73	6.30	7.13	3.84	6.47	3.91
RANK	4.10	2.29	4.48	6.13	2.46	0.85
Average	**9.30**		**7.31**		**4.04**	

The bold numbers in the bottom row display the overall average r-value for each marker over all subjects, sessions, and markers. The device had an overall average of 4.04 mm, the experienced examiner had an overall average of 7.31 mm, and the novice examiner had an overall average of 9.30 mm.

In order to compare between day precision, the difference in R-value between-day for each marker was found and can be seen in Table 5.6. This looks at how the precision values between each day looks and puts a value to consistency.

Table 5.6. Between Day Difference in Repeatability ('R') Value for each Marker and Subject

Subject	Marker	Novice	Exp.	Device
1	RHIP	17.39	1.88	0.31
	RKNE	5.47	0.87	5.65
	RIKNE	11.07	0.66	4.14
	RANK	7.50	1.72	2.19
2	RHIP	9.73	8.85	0.003
	RKNE	0.72	2.20	0.93
	RIKNE	1.93	1.43	0.26
	RANK	2.95	0.74	0.94
3	RHIP	5.76	4.00	0.93
	RKNE	3.66	4.25	1.02
	RIKNE	18.22	4.25	0.75
	RANK	5.19	2.01	0.05
4	RHIP	2.65	1.25	1.94
	RKNE	7.02	7.41	3.52
	RIKNE	6.21	0.75	14.61
	RANK	0.47	1.23	1.08
5	RHIP	1.46	8.02	2.02
	RKNE	4.04	7.45	0.99
	RIKNE	11.40	5.58	1.46
	RANK	0.56	21.12	1.36
	Average	6.17	4.28	2.21

The red cells in the table represent the high values of difference in the r value between day and the green cells represent the low values. The average for all the differences can be seen in the bottom row of the table where the values have been found. For the novice examiner, the average difference between day r values was 6.17 mm, the experienced examiner had a value of 4.28 mm, and the device had a value of 2.21 mm.

From these coordinates, correlation is observed through Interclass Correlation Coefficient. This study looked at correlation in two different scenarios, within a single marker placement method, and between different methods (methods being experienced,

novice, and device). In Table 5.7, the ICC values for the markers placed by a single rater are compared.

Table 5.7. ICC Values for each Subject compared WITHIN the Method

	Session 1			Session 2		
Subject	Novice	Exp.	Device	Novice	Exp.	Device
1	0.969	0.996	0.999	0.997	0.999	0.999
2	0.999	0.999	0.999	0.999	0.999	0.999
3	0.999	0.998	0.999	0.996	0.999	0.999
4	0.997	0.999	0.998	0.997	0.999	0.999
5	0.997	0.997	0.999	0.997	0.999	0.999

In Table 5.7, the red cells are the 10 lowest ICC values from within rater, while the green cells are the highest 10 ICC values, indicating high correlation. In Table 5.8 below, the ICC values of the coordinate points between the different marking methods as well as the coordinates overall.

Table 5.8. ICC Values for each Subject compared BETWEEN the Method

	Session 1				Session 2			
Subjects	Nov/Exp	Exp/Dev	Nov/Dev	All	Nov/Exp	Exp/Dev	Nov/Dev	All
1	0.979	0.995	0.972	0.982	0.995	0.998	0.997	0.997
2	0.997	0.999	0.999	0.998	0.995	0.999	0.994	0.996
3	0.996	0.996	0.999	0.997	0.995	0.999	0.994	0.996
4	0.996	0.999	0.997	0.997	0.994	0.999	0.994	0.996
5	0.991	0.999	0.992	0.994	0.995	0.998	0.995	0.996

Another aspect of the precision that was looked at was the Inner Quartile Range value for each session and marker per subject. This value displays the middle 50% of the coordinates, taking the weight of the outliers out of the calculations. In Table 5.9 below, the x- and y- IQR values are shown for the coordinate location for each marker for each session.

Table 5.9. IQR Values for X- and Y- Coordinates for each Subject and Method

	Novice				Experienced				Device			
Marker	Session1		Session2		Session1		Session2		Session1		Session2	
	XIQR	YIQR	XIQR	YIQR	XIQR	YIQR	XIQR	YIQR	XIQR	YIQR	XIQR	YIQR
1 - RHIP	2.91	24.28	5.63	8.16	1.10	7.77	4.03	5.76	1.43	1.01	2.33	0.60
RKNE	7.81	4.61	2.61	2.58	4.75	1.21	0.60	3.72	0.85	1.01	5.55	0.08
RIKNE	4.95	16.79	6.58	7.98	6.05	3.10	6.78	3.72	1.91	3.85	8.25	2.71
RANK	0.79	0.43	6.75	3.18	0.38	1.40	2.75	1.39	1.29	1.70	4.22	2.26
2 - RHIP	12.36	6.51	4.76	3.55	11.32	2.57	4.37	3.12	1.47	1.11	1.86	0.89
RKNE	5.49	2.57	4.92	3.80	2.33	1.69	3.75	4.11	4.58	1.76	3.03	0.77
RIKNE	6.48	6.13	8.49	2.04	1.06	1.94	4.04	1.48	6.69	1.12	6.22	0.30
RANK	1.47	1.12	4.38	2.92	0.84	0.60	1.10	1.39	1.03	0.65	1.80	1.00
3 - RHIP	3.90	2.66	6.14	8.31	9.26	3.76	5.67	4.84	2.81	0.60	3.01	2.32
RKNE	2.07	2.49	5.51	3.66	10.53	3.31	8.73	1.91	0.64	0.38	1.69	0.95
RIKNE	6.08	2.32	19.02	6.16	13.34	6.96	8.70	4.77	4.37	1.07	3.84	1.38
RANK	2.19	2.09	5.96	3.24	3.33	2.40	1.24	2.11	0.92	1.39	1.26	0.97
4 - RHIP	9.58	12.89	9.01	18.23	4.25	7.14	8.56	2.82	6.14	0.85	4.70	1.14
RKNE	13.38	2.33	5.21	3.03	10.16	3.12	6.04	1.49	6.09	0.91	2.41	0.93
RIKNE	4.05	13.86	3.43	7.81	3.05	2.47	1.53	2.52	16.19	2.72	1.36	0.88
RANK	2.06	1.33	2.72	1.53	1.28	1.30	1.80	2.46	0.78	1.60	2.64	1.20
5 - RHIP	3.64	1.05	0.22	3.37	7.26	2.55	3.65	13.75	2.38	0.19	2.24	3.96
RKNE	4.23	4.90	6.81	6.48	6.60	4.67	7.32	5.94	2.28	2.15	3.06	1.01
RIKNE	2.97	19.74	7.52	16.64	1.70	3.34	4.63	4.27	4.55	1.45	8.05	2.60
RANK	0.36	2.94	1.18	2.47	16.67	6.29	0.82	1.19	3.16	0.63	1.76	0.37

The red cells indicate IQR greater than 3 mm, while the green cells indicate an IQR less than 1 mm. These values were then compared between day to look at the precision and consistency of this range. These between day comparisons can be seen below in Table 5.10.

Table 5.10. Difference in IQR Values Between Day for each Subject and Method

	Between Day Compared					
	Novice		Experienced		Device	
Markers	X	Y	X	Y	X	Y
1 - RHIP	2.71	16.12	2.93	2.00	0.91	0.41
RKNE	5.20	2.03	4.15	2.50	4.70	0.93
RIKNE	1.63	8.80	0.73	0.62	6.34	1.13
RANK	5.96	2.75	2.38	0.01	2.93	0.55
2 - RHIP	7.60	2.96	6.94	0.55	0.39	0.22
RKNE	0.57	1.23	1.43	2.42	1.55	1.00
RIKNE	2.01	4.09	2.97	0.46	0.48	0.82
RANK	2.91	1.80	0.26	0.78	0.77	0.34
3 - RHIP	2.24	5.65	3.59	1.09	0.20	1.72
RKNE	3.45	1.17	1.81	1.40	1.04	0.57
RIKNE	12.93	3.85	4.64	2.20	0.53	0.31
RANK	3.77	1.15	2.09	0.29	0.34	0.43
4 - RHIP	0.57	5.34	4.32	4.32	1.45	0.28
RKNE	8.17	0.70	4.13	1.63	3.68	0.02
RIKNE	0.61	6.05	1.52	0.05	14.83	1.83
RANK	0.66	0.20	0.52	1.16	1.86	0.40
5 - RHIP	3.42	2.32	3.61	11.19	0.14	3.77
RKNE	2.57	1.57	0.72	1.27	0.78	1.14
RIKNE	4.55	3.10	2.93	0.93	3.49	1.15
RANK	0.81	0.48	15.85	5.11	1.41	0.25

The previous sections all took part in proving the usefulness and validity of using the marker placement device. As the study went on, the trials compounded the difference from the previous trials. In the chart seen in Fig. 5.5, the absolute average difference for each section was graphed, including laser placement, laser pointer, marker placement, body positioning, and marker repeatability, from left to right. The first three bars are the device only, while the last two introduce the human body to the study bringing about less controllable sources of error. The marker repeatability trials encapsulated all the elements of the previous trials.

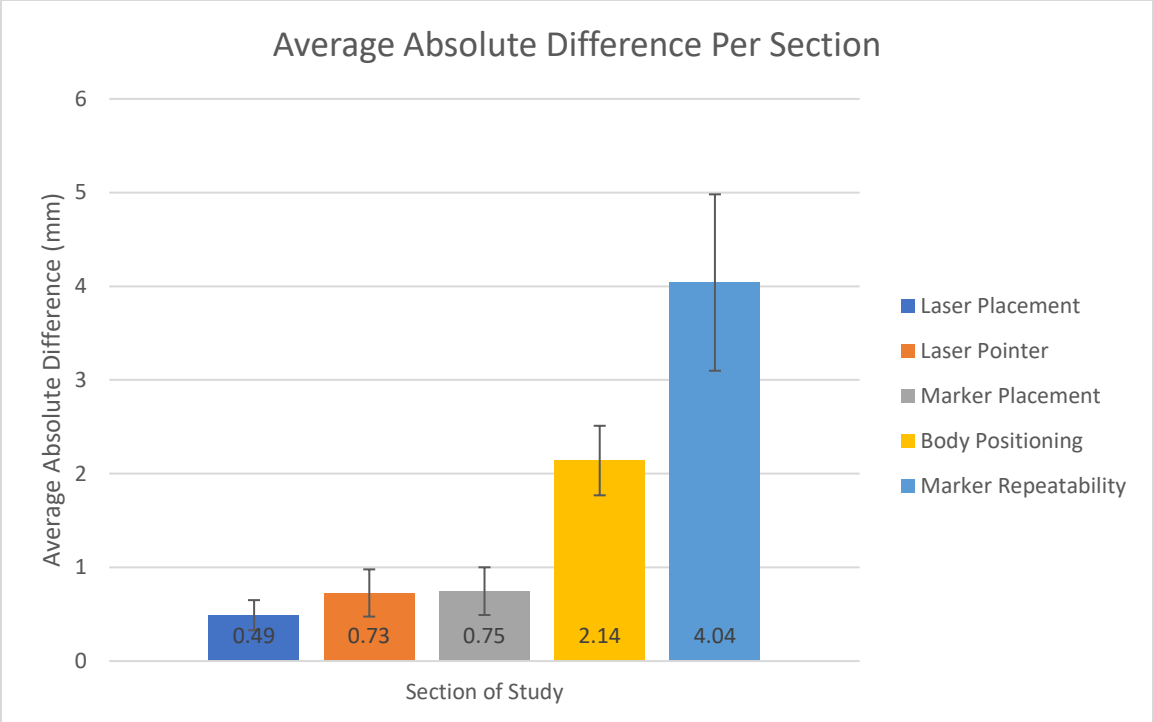

Fig 5.5: Average absolute difference per section of study with SEM.

As expected, the absolute average difference increases as the different sections go forward, compounding the error as the components combine. When the absolute average difference of the first four sections is added together, it results in 4.10 mm. This value is only .06 mm away from the resulted absolute average difference from the marker repeatability section, supporting the expectation of compounded difference of all sections.

Kinematics

The kinematics trials aimed to numerically be able to define the degree of change that occurs due to the change in marker placement. As seen in the previous section, the five markers are placed in a plus sign pattern on the knee, with the middle marker being the common location for the RKNE marker. The distances between the markers were

found using Vicon and the average distance between the markers can be seen in Figure 5.6.

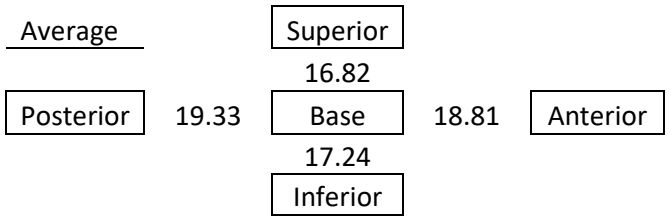

Fig 5.6: Average distances (mm) between markers on the knee.

The maximum and minimum flexion/extension angles were found along with the knee angle at heel strike and toe off. All of the markers indicated in Fig 5.6 were present for each data trial, so differences comparing the kinematics calculated using these markers represent an actual difference between the marker placement and not a difference between different motion trials. The same trial of data was re-processed 5 times to accommodate the 5 different knee markers (Base, Anterior, Superior, Inferior, Posterior) and these values were compared. An example graph of the different marker-kinematics for the same trial can be seen in Figures 5.7-9 below. The maximum angle, which is the most obvious point of difference, is boxed in Figure 5.7. All of these values are from the same person for the five different markers and the resultant angles for each of the three major variables of interest: knee flexion angle, hip flexion angle, and ankle flexion angle.

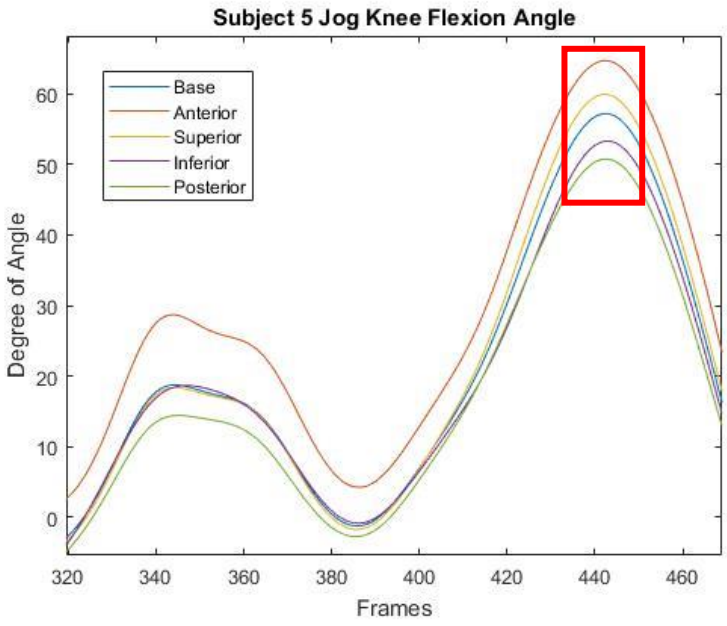

Fig 5.7: Knee Flexion Graph

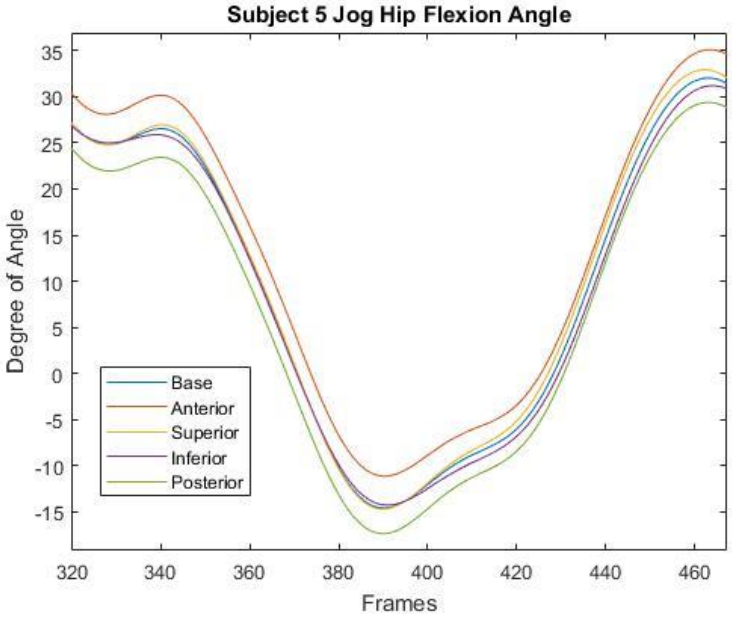

Fig 5.8: Hip Flexion Graph

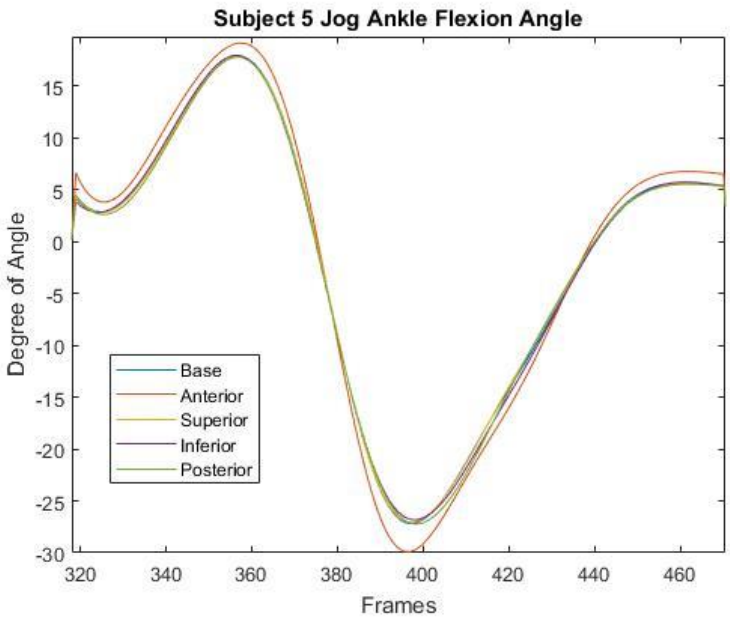

Fig 5.9: Ankle Flexion Graph

The values in the tables below represent the difference between the angles measured using the marker listed on the right, and the angles from the base or center marker. The values are positive if the resultant angle is greater than the base angle, and negative if the angle is less. Table 5.11 represents the values described above for all of the walking trials and subjects. The subjects were combined to find the average difference in kinematics when using the different knee marker placements.

Table 5.11. Walking Trials Average Angle Difference (in degrees) Between Markers

Walk	Knee Flex				Ankle Flex		Hip Flex	
Marker	Max	Min	HS	TO	Max	Min	Max	Min
Anterior	8.90	5.88	6.26	8.91	2.42	-1.60	3.19	3.31
Superior	2.42	-0.33	-0.13	0.52	-0.02	0.40	0.42	-0.06
Inferior	-3.53	0.18	0.51	-6.35	0.03	-0.39	-0.44	-0.04
Posterior	-5.71	-3.07	-3.20	-7.28	-0.64	0.55	-3.01	-3.18

The table shows the highest difference in angle values occurring in the knee flexion angles. A difference ranging from 5.88 to 8.91 degrees can be seen from the anterior marker, while a difference ranging from -3.07 to -7.28 can be seen from the posterior marker. Table 5.12 looks at the same values but for the jogging trials for all subjects.

Table 5.12. Running Trials Average Angle Difference (in degrees) Between Markers

Jog	Knee Flex				Ankle Flex		Hip Flex	
Marker	Max	Min	HS	TO	Max	Min	Max	Min
Anterior	6.17	4.33	6.17	6.94	1.29	-1.88	3.16	2.29
Superior	2.15	-0.30	-0.17	0.10	-0.02	0.10	0.87	0.01
Inferior	-4.15	-0.31	-0.39	-0.10	0.05	-0.05	-0.89	-0.20
Posterior	-7.26	-2.66	-2.94	-2.82	-0.12	0.34	-2.94	-2.29

The table shows the highest differences in angle values occurs in the knee flexion angles, although the values change slightly compared to the walking. A difference ranging from 4.33 to 6.94 degrees can be seen from the anterior marker, while a difference ranging from -3.66 to -7.26 can be seen from the posterior marker. The final ROM exercise assessed was the run-to-cut movement. Table 5.13 shows the values from these trials for all subjects.

Table 5.13. Run-to-Cut Trials Average Angle Difference (in degrees) Between Markers

R2C	KneeFlex				AnkleFlex		HipFlex	
Marker	Max	Min	HS	TO	Max	Min	Max	Min
Anterior	8.76	3.72	6.50	6.84	2.06	-1.80	2.94	0.06
Superior	2.40	-0.21	-0.16	-0.38	-0.06	0.01	0.78	0.03
Inferior	-2.86	0.30	0.22	-0.42	0.11	0.18	-1.04	-0.16
Posterior	-6.71	-2.70	-2.32	-3.58	-0.34	0.24	-3.06	-0.67

This table shows the same trend that has been seen in the previous table, with the highest differences in the angle occurring in the knee flexion. A difference range of 3.72 to 8.76 degrees can be seen from the Anterior marker, and a difference range of -2.70 to -6.71 can be seen from the Posterior marker.

All of these values were combined and averaged to produce Table 5.13 below. Based on this study, the values in the table below show the angle difference of range of motion trials when a marker is replaced incorrectly.

Table 5.14. Combined Trials Average Angle Difference (in degrees) Between Markers

Combined	Knee Flex				Ankle Flex		Hip Flex	
Marker	Max	Min	HS	TO	Max	Min	Max	Min
Anterior	7.95	4.64	6.31	7.56	1.92	-1.76	3.10	1.89
Superior	2.33	-0.28	-0.15	0.08	-0.03	0.17	0.69	-0.01
Inferior	-3.52	0.06	0.11	-2.29	0.06	-0.09	-0.79	-0.14
Posterior	-6.56	-2.81	-2.82	-4.56	-0.36	0.38	-3.01	-2.04

From Table 5.14, we can see that the largest differences overall occurred in the knee flexion category of the trials. An average difference range of 4.64 to 7.95 can be seen in the anterior marker, while an average difference range of -2.81 to -6.56 degrees can be seen in the posterior marker.

In order to quantify the change in degrees based on the millimeters of difference, it is assumed that the correlation between distance and degrees is linear. Looking at the worst case scenarios of degree change, occurring in the anterior and posterior knee flexion max angle, the incremental degree change per millimeter can be calculated. That is found to be 0.42 mm. In physical therapy, there are many studies that answer the question of what a typical significant incremental change would be. Many studies indicate that a significant increment in knee angle change is 5-10 degrees [34,35].

Physical therapy offices also typically use devices with an error of 6 degrees, which also falls into that range [36]. Using this value and applying the incremental degree change per millimeter, the potential error from the repeatability values found earlier can be found. The r-value that results in 5 degree difference is found to be 6.6 mm, the r value that results in 10 degree change is found to be 13.2 mm. Using these values, the r values from the previous section are analyzed and the number of times the novice, expert, and device had an r value greater than the values mentioned for the RKNE marker were counted. The count of occurrences in RKNE R values can be seen in Table 5.15. All of the repeatability graphs for the RKNE marker can be seen in Appendix B.

Table 5.15. Count of Repeatability Values Above 5 or 10 Degree Threshold

5 degree Values > 6.6mm		10 degree Values > 13.2mm	
Novice	6	Novice	1
Expert	5	Expert	1
Device	2	Device	0

As seen in the table, the novice examiner had 6 occurrences potentially causing 5 degree change in knee angle and 1 occurrences potentially causing 10 degree change in knee angle. The experienced examiner had 5 occurrences potentially causing 5 degree change in knee angle and 1 occurrences potentially causing 10 degree change in knee angle. The device had 2 occurrences potentially causing 5 degree change in knee angle and 0 occurrence potentially causing 10 degree change in knee angle. It is clear from the data that the device is valuable in decreasing the significant angle change in kinematics trials.

CHAPTER SIX

Discussion and Conclusion

The goal of this study was to determine and quantify the improved precision that occurs when the marker placement device from this study is used compared to traditional marking by hand. The device itself had to first be proven through testing and comparative analysis, looking at the differences and errors produced compared to standard metrics and other studies. Following the device being proven, the ability for the device to enhance body posture repeatability was studied, looking at non-removed markers from the body between trials as the subject was repositioned in the device. The aspect of precision and marker repeatability was then studied, comparing a novice and experienced marker placer to the device itself. In order to quantify and fully see the affect errors in precision make on knee angles, kinematic testing was done using added knee markers to provide results. These kinematics results were then compared to the repeatability results to further support the device and the need for improved precision in marking.

Overview

Marker replacement is a key piece of clinical motion capture. Maintaining consistent placement allows for measurements that are beneficial in seeing treatment improvements and diagnosing walking pathologies. However, there is inherent error in marker replacement, even up through experienced examiners due to the areas of system

error, between day error, between person error, and subject error. All of these contribute to a certain degree of uncertainty in results from clinical motion capture trials.

The marker placement device in this study proved to be a benefit to marker placement repeatability. The initial trials of device testing proved that the device does not bring inherent error above that found in the motion capture system itself. Mechanically, the device only helps and does not hurt the process of clinical motion capture. When a second user was brought in, having never used the device before, the difference was negligible or increased, but not above the threshold of system error (2mm). Because of this the device proved itself to be a viable and useful device that does not increase the error or difference.

In the body positioning section of this study, the results were able to display the ability to influence posture precisely. This device had a maximum resultant difference of less than 7 mm of difference out of the four markers tested. This component of marker placement devices has not been explored in previous studies directly. Both Hutchinson and Noehren, the two other studies who looked at these devices, related the resultant angle to the body positioning effectiveness [11,12]. The error with their method is that it isn't able to locate where exactly the difference comes from, and instead puts the error on the marker replacement while the inability to quantify positioning becomes a limitation. The results from this device supported the aim of creating a device that limits the amount of error produced through posture, specifically in the lower body. One key joint in the lower body is the knee, and in looking at the posture repeatability results, we can see that the two segments that make the knee, tibia and thigh, had resultant difference vectors of 3.9 mm and 5.2 mm respectively. This is significant in that in means the knee is being

repositioned within the device with only a 3.9 mm and 5.2 mm average difference vector. Previous studies have quantified that up to 25 mm of error can occur in the area of marker placement, so having the ability and results to quantify the amount produced by body positioning allows for the components of the overall error to be addressed individually [12,26].

The device performed as expected in the marker repeatability section of the study, allowing for the results to be quantified and easily compared between the device, a novice examiner and an experienced examiner placing markers. The overall average marker absolute difference from center for the device came out to be 4.04 mm, this was 3.27 mm better than the experienced examiner and 5.26 mm better than the novice examiner. This method of quantifying marker placement was not used in this fashion in previous studies, as the method of angle differences was used. The results produced from this study, however, are more focused and specific to the component being looked at and allows for the error and difference of the marker placement difference to be understood. They allow for a systematic evaluation of the device which allows for a more in depth look into the operation precision. The device was significantly more precise in repeatedly placed markers, and also showed more precise values between-day as well.

Time is another key area of importance when running multiple human trials. The amount of time it takes to mark a subject by hand using palpation can cause the session to run longer than necessary. Shortening that time down allows for more trials to be complete and for more subjects who may be short on time to be inclined to take part in the testing. This device allows for the majority of the setup to take place prior to a subject showing up for the session. Upon arrival, the subject simply has to step into the device,

the laser pointers are turned on, and the markers placed. For 10 laser pointers, this should take less than 1-2 minutes to do. This greatly shortens the amount of setup time that has to occur while the subject is present, a benefit of the device.

The kinematic portion of the study provided context to how the device marker placement precision results could extend to actual kinematic measurement benefits. Four extra markers placed on the knee were there to account for directions of error when placing markers. When it comes to creating the model of the leg in Vicon, the knee joint center is critical as it is the connection between the two major segments, the femur and the tibia. Where the marker is placed along the side of the knee directly effects the resultant joint center as well as the resultant knee angles, and the results confirmed this point. The kinematic differences that were observed by calculating the kinematics via the various knee markers were compiled into tables. Applying these differences to the distances between markers, a unitary measure of .41 degree/mm was found and used to calculate the millimeters that would result in significant incremental changes. In literature, it was found that between 5-10 degrees of change is considered significant, so the results looked at both endpoints, 5 and 10 degrees. Out of 10 measurements, the device had 2 that could result in 5 degree change and 0 that could result in 10.This was significantly better than both the human marker placers who both had more than 5 occurrences potentially resulting in 5 degree change and 1 occurrence resulting in 10 degree change.

Significance and Limitations

While motion capture is commonly found in the entertainment industry, it is still becoming increasingly valuable in the medical community as well. The device used in

this study is one that will assist in studies or therapies that use motion capture to assess progress or to diagnose issues related to movement deficits. Unlike other devices that are similar, this device lets those using it have a better understanding of how precise this device is in all components. Having the confidence in the device will allow for medical professionals or researches to use this device to evaluate studies or diagnose patients. As seen in the kinematics trials, small degrees of difference in makers can result in significant changes in how the knee angle is interpreted. Pre- and post- surgery tests as well as ambulatory cerebral palsy gait analysis are specific areas that will benefit from this device. In each of these scenarios, the size of the changes being looked at are small, therefore any kind of small error in marking can cause skewed results or ones that do not support what is actually occurring.

While this study made a lot of progress towards systematically evaluating this device and extended what had been previously completed on similar products, the results of this study should still be considered through the lens of a few known limitations. One limitation that has been an area of limit for all similar devices is that this device should not be used in studies where the patient will go through significant physical change. Whether that be from aging (children) or posture altering surgery, this device does not have the capabilities of intuitively knowing how the body has changed. This should be recognizable from the scope of a study and researcher should be aware that this device will not be applicable. Another limitation to note is that the device does require a subject to be marked by hand prior to the device coming into play. In order to set the lasers in the proper placement, the subject has to be marked by palpation on their first visit and then the lasers are placed accordingly. The human factor does not fully get removed while

using this device and is still subject to human error in the first stages. Therefore, this device is aimed at precision relative to this first placement and not accuracy with regard to the physical target anatomical landmark. A final limitation to discuss is the use of only one experienced examiner and one novice examiner. In order to have the best results for generalizations on experience level marking, a larger amount of examiners at each level of experience would increase the significance of the results. However this was not able to be done as this study took place during COVID-19 and the number of people allowed into the lab was limited.

Future Directions

In order to improve this device in the future, the human element should continue to be removed. Initial palpation might still have to be completed, but the maker placement itself has major potential to be removed from human responsibility. A device or add-on to this marker placement device that places the markers on the skin would allow for another significant reduction in potential error and an increase in consistency. Another direction for this to go is further increasing the body position repeatability. While this device does have positive results in increasing the repeatability of the subject's posture, it still required the person to be able to stand. Adding a seated option or permanent addition that lets the subject sit in a posture repeatable with marker locations still able to be found and placed could benefit a demographic of subject population that this device does not have the capabilities of accommodating. Specifically, this could benefit children with ambulatory cerebral palsy, mentioned previously in this paper. Having a harness that hangs from the top or supports in the front for the upper body to hold on to could also greatly benefit this population of subjects.

Conclusion

Through this study, the Baylor marker placement device was assessed and was shown to be more precise than palpation on repeated studies. Mechanically, the process to place markers was broken down by components. From placing the laser along the laser arm, shining the laser, and then placing a marker using the laser, the device proved to bring about a low amount of difference within trials. The threshold for system error with Vicon Nexus has been found to be less than 2 mm [16,30]. This is an older metric from a 2004 paper. However, it is a reasonable target that is actually based on a Vicon motion capture system. 2 mm can be used as our worst case scenario threshold. From these initial trials aimed at the mechanics of the device, the difference did not exceed 1.71 mm with a standard deviation of 0.86. This indicated that the device was effective in working without increasing error or difference in an excessive amount. Once the device was proven to work mechanically, the human element was added, placing subjects into the device and doing further testing. Throughout the sessions, body position repeatability, marker placement repeatability and kinematics were tested in order to help support the effectiveness of the device. Body positioning produced favorable results, with the maximum resultant vector of difference occurring at the RASI marker on the pelvis with a value of 6.58 mm. In marker placement repeatability, the device was able to continue supporting its effectiveness, performing more precisely than both the novice examiner and the experienced examiner in all categories. The device produced an average repeatability value of 4.04 mm while the experienced and novice examiner produced 7.31 mm and 9.30 mm respectively. Kinematics were then able to allow for the real world picture of what error and difference in marker placement can produce. An increment of

0.41 degrees/mm was found from the trials to be the amount of degree change per mm of difference in placement. Using this, the repeatability trials were assessed to see the amount of times each method of placement had an occurrence that could result in significant change of 5 and 10 degrees. The device had 2 out of 10 tests that could result in 5 degrees of change in knee angle, and 0 out of 10 that could result in 10 degrees of change. This was significantly better than the novice and experienced examiners and further supported the effectiveness of the device in repeating marker placement. Ultimately, this device proved to be a benefit in the replacement of markers on a human subject, while also not increasing the difficulty of usage. Through multiple stages of trials, the process components were broken down and assessed to support the fact that this device is beneficial to the motion capture community and clinical gait analysis.

APPENDICES

APPENDIX A

Original MATLAB Repeatability Code

```
M = csvread('I:\R_Subjects\1_1.csv',48,0);

figure(1)
scatter(M(1:3,1),M(1:3,2),'filled','b');
hold on
x = mean(M(1:3,1));
y = mean(M(1:3,2));
C = [x,y];
j = [(x - M(1:3,1)),(y-M(1:3,2))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','b');
hold on
scatter(M(1:3,3),M(1:3,4),'filled','m');
str = {'Nov. R = ' num2str(R)};
a = annotation('textbox',[.15 .8 .1 .1],'String',str);
a.Color = 'blue';
hold on
x = mean(M(1:3,3));
y = mean(M(1:3,4));
C = [x,y];
j = [(x - M(1:3,3)),(y-M(1:3,4))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','m');
str = {'Exp. R = ' num2str(R)};
a = annotation('textbox',[.15 .7 .1 .1],'String',str);
a.Color = 'm';
hold on
scatter(M(1:3,5),M(1:3,6),'filled','k');
hold on
x = mean(M(1:3,5));
y = mean(M(1:3,6));
C = [x,y];
j = [(x - M(1:3,5)),(y-M(1:3,6))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','k');
str = {'Dev. R = ' num2str(R)};
a = annotation('textbox',[.15 .6 .1 .1],'String',str);
```

```
a.Color = 'k';
hold on

figure(2)
scatter(M(4:6,1),M(4:6,2),'filled','b');
hold on
x = mean(M(4:6,1));
y = mean(M(4:6,2));
C = [x,y];
j = [(x - M(4:6,1)),(y-M(4:6,2))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','b');
str = {'Nov. R = ' num2str(R)};
a = annotation('textbox',[.15 .8 .1 .1],'String',str);
a.Color = 'blue';
hold on

scatter(M(4:6,3),M(4:6,4),'filled','m');
hold on
x = mean(M(4:6,3));
y = mean(M(4:6,4));
C = [x,y];
j = [(x - M(4:6,3)),(y-M(4:6,4))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','m');
str = {'Exp. R = ' num2str(R)};
a = annotation('textbox',[.15 .7 .1 .1],'String',str);
a.Color = 'm';
hold on

scatter(M(4:6,5),M(4:6,6),'filled','k');
hold on
x = mean(M(4:6,5));
y = mean(M(4:6,6));
C = [x,y];
j = [(x - M(4:6,5)),(y-M(4:6,6))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','k');
str = {'Dev. R = ' num2str(R)};
a = annotation('textbox',[.15 .6 .1 .1],'String',str);
a.Color = 'k';
hold on

figure(3)
scatter(M(7:9,1),M(7:9,2),'filled','b');
hold on
x = mean(M(7:9,1));
```

```
y = mean(M(7:9,2));
C = [x,y];
j = [(x - M(7:9,1)),(y-M(7:9,2))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','b');
str = {'Nov. R = ' num2str(R)};
a = annotation('textbox',[.15 .8 .1 .1],'String',str);
a.Color = 'blue';
hold on

scatter(M(7:9,3),M(7:9,4),'filled','m');
hold on
x = mean(M(7:9,3));
y = mean(M(7:9,4));
C = [x,y];
j = [(x - M(7:9,3)),(y-M(7:9,4))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','m');
str = {'Exp. R = ' num2str(R)};
a = annotation('textbox',[.15 .7 .1 .1],'String',str);
a.Color = 'm';
hold on

scatter(M(7:9,5),M(7:9,6),'filled','k');
hold on
x = mean(M(7:9,5));
y = mean(M(7:9,6));
C = [x,y];
j = [(x - M(7:9,5)),(y-M(7:9,6))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','k');
str = {'Dev. R = ' num2str(R)};
a = annotation('textbox',[.15 .6 .1 .1],'String',str);
a.Color = 'k';
hold on

figure(4)
scatter(M(10:12,1),M(10:12,2),'filled','b');
hold on
x = mean(M(10:12,1));
y = mean(M(10:12,2));
C = [x,y];
j = [(x - M(10:12,1)),(y-M(10:12,2))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','b');
str = {'Nov. R = ' num2str(R)};
a = annotation('textbox',[.15 .8 .1 .1],'String',str);
```

```
a.Color = 'blue';
hold on

scatter(M(10:12,3),M(10:12,4),'filled','m');
hold on
x = mean(M(10:12,3));
y = mean(M(10:12,4));
C = [x,y];
j = [(x - M(10:12,3)),(y-M(10:12,4))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','m');
str = {'Exp. R = ' num2str(R)};
a = annotation('textbox',[.15 .7 .1 .1],'String',str);
a.Color = 'm';
hold on

scatter(M(10:12,5),M(10:12,6),'filled','k');
hold on
x = mean(M(10:12,5));
y = mean(M(10:12,6));
C = [x,y];
j = [(x - M(10:12,5)),(y-M(10:12,6))];
R = max(sqrt((j(1:3,1)).^2+(j(1:3,2)).^2));
viscircles(C,R,'Linestyle','--','EdgeColor','k');
str = {'Dev. R = ' num2str(R)};
a = annotation('textbox',[.15 .6 .1 .1],'String',str);
a.Color = 'k';
hold on
```

APPENDIX B

All Right Knee Marker Repeatability Graphs

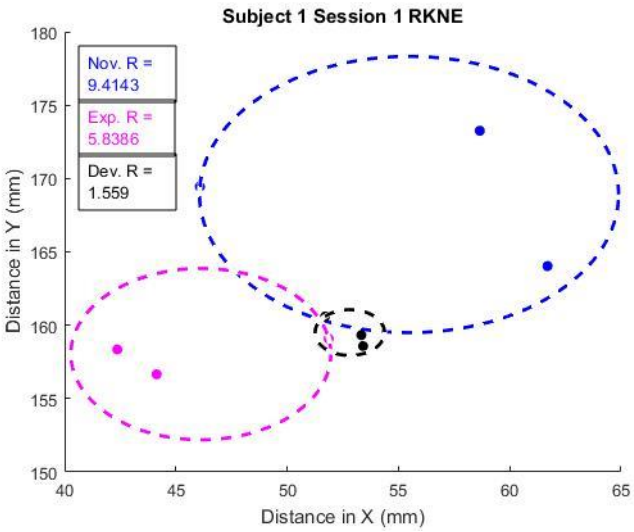

Fig. B.1: Subject 1 Session 1 Right Knee Marker Repeatability Graph

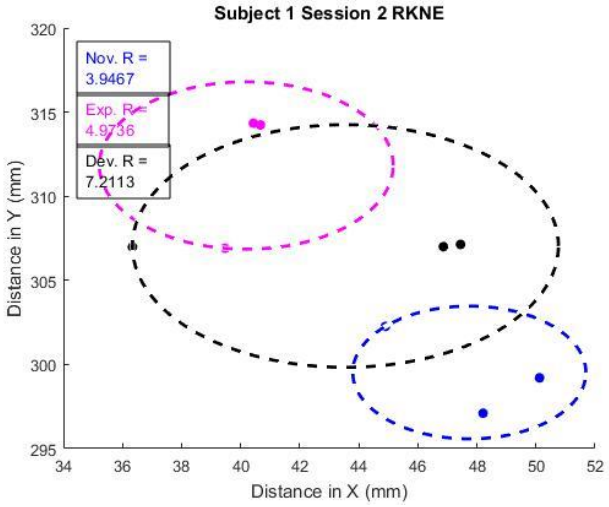

Fig. B.2: Subject 1 Session 2 Right Knee Marker Repeatability Graph

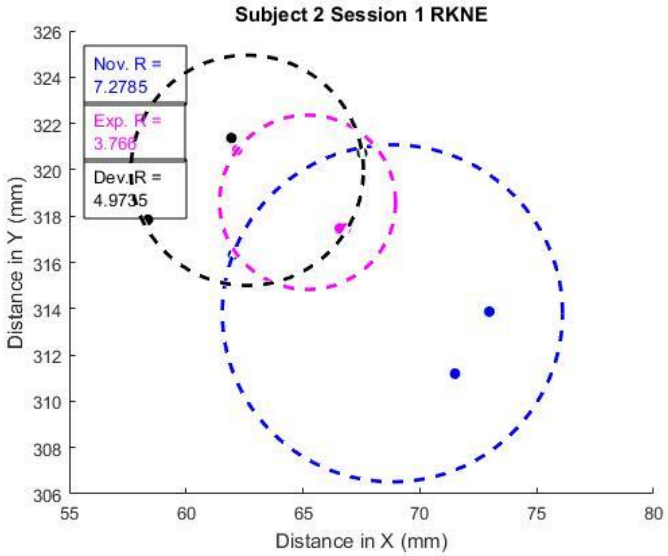

Fig. B.3: Subject 2 Session 1 Right Knee Marker Repeatability Graph

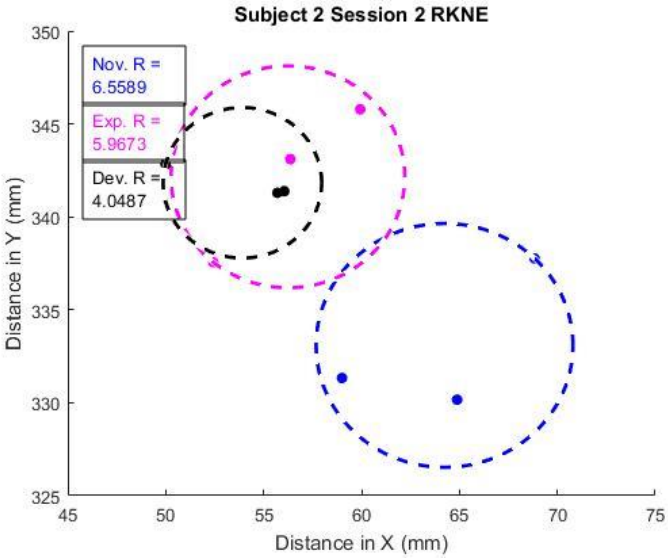

Fig. B.4: Subject 2 Session 2 Right Knee Marker Repeatability Graph

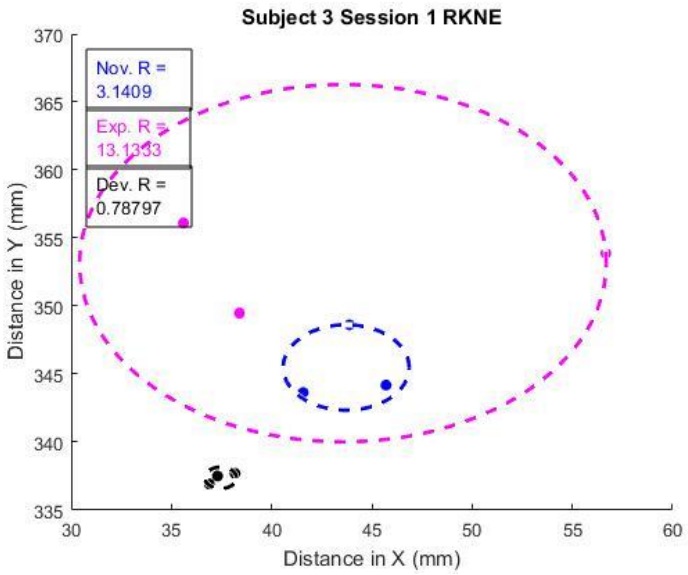

Fig. B.5: Subject 3 Session 1 Right Knee Marker Repeatability Graph

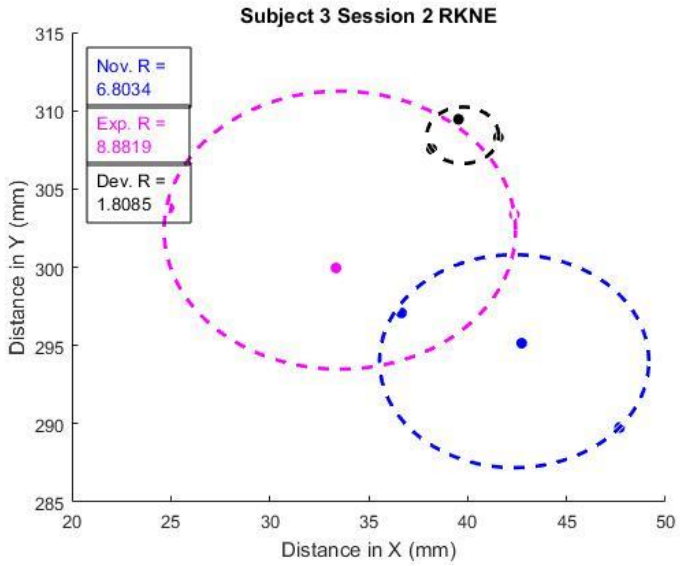

Fig. B.6: Subject 3 Session 2 Right Knee Marker Repeatability Graph

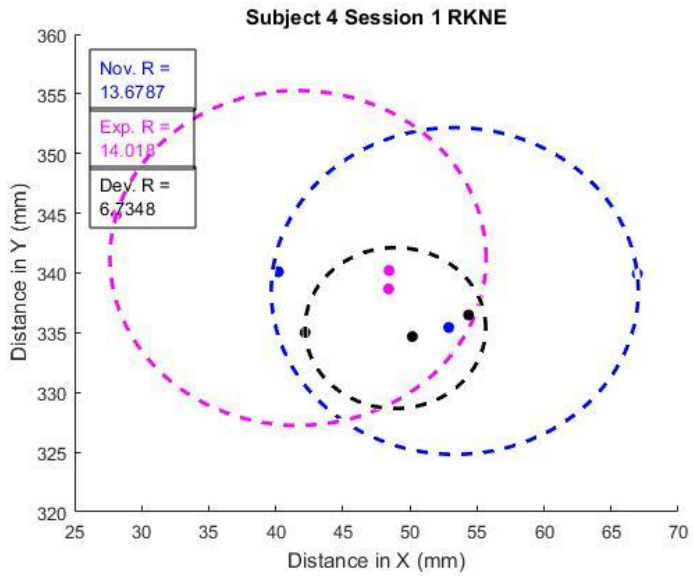

Fig. B.7: Subject 4 Session 1 Right Knee Marker Repeatability Graph

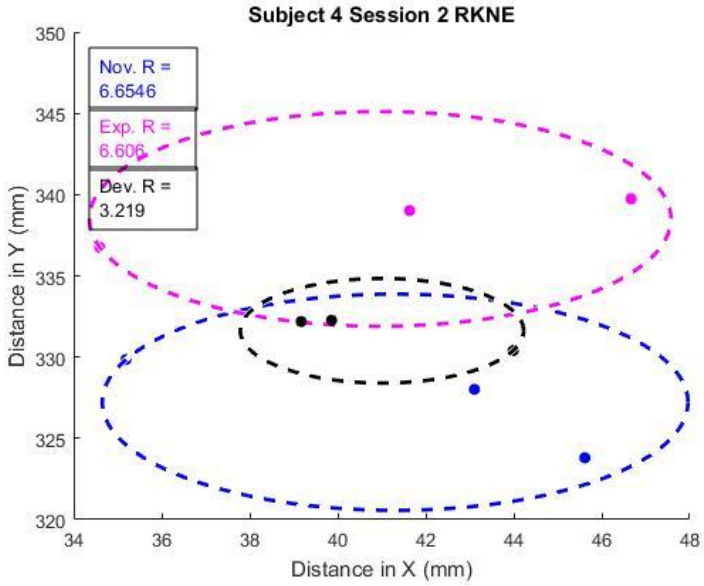

Fig. B.8: Subject 4 Session 2 Right Knee Marker Repeatability Graph

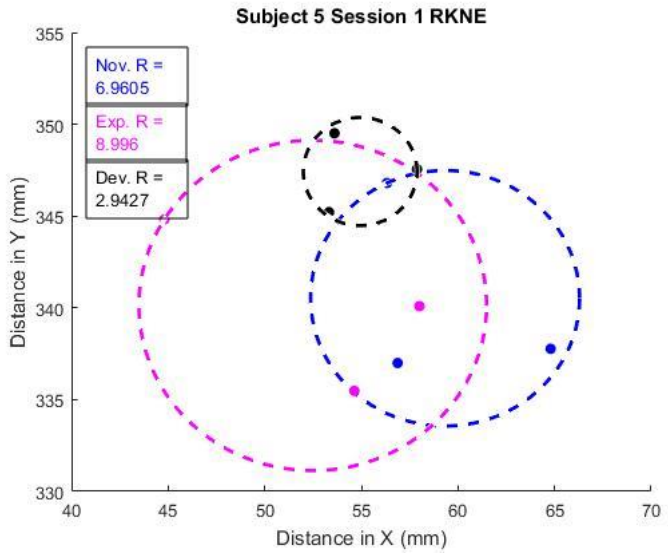

Fig. B.9: Subject 5 Session 1 Right Knee Marker Repeatability Graph

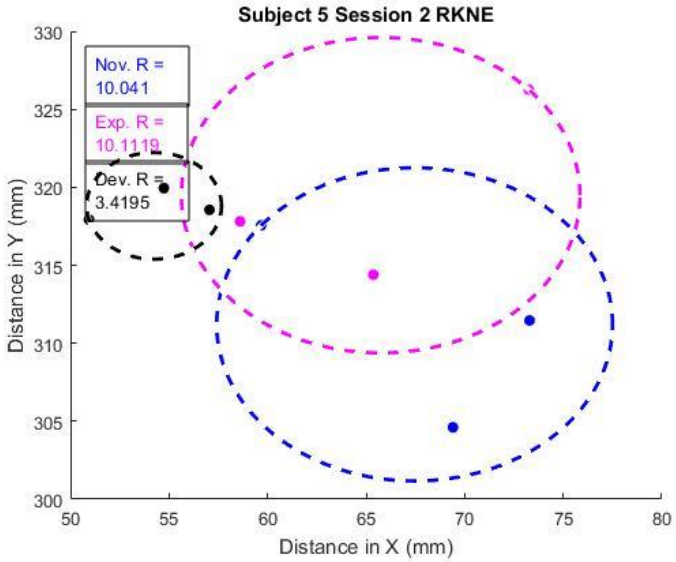

Fig. B.10: Subject 5 Session 12 Right Knee Marker Repeatability Graph

BIBLIOGRAPHY

[1] "Cinema Motion Capture Isometric Composition Actor Search and Download for Vector Illustrations, Stock Images | Macrovector," Macrovector.com [Online]. Available: https://macrovector.com/vector-images/cinema+motion+capture+isometric+composition+actor. [Accessed: 23-Oct-2020].

[2] "Equipment | Vision, Cognition, and Action VR Lab" [Online]. Available: https://www.cs.utexas.edu/~dana/vrlab/equipment.html. [Accessed: 23-Oct-2020].

[3] "Mocap Suit" [Online]. Available: https://sdm.scad.edu/intranet/students/cage/eqpages/mocapsuit.html. [Accessed: 23-Oct-2020].

[4] "FIGURE 1. Visual Hull Reconstruction Concept. The Silhouettes of The...," ResearchGate [Online]. Available: https://www.researchgate.net/figure/Visual-hull-reconstruction-concept-The-silhouettes-of-the-subject-from-different-camera_fig1_6999610. [Accessed: 23-Oct-2020].

[5] "J2289_DV Gait Lab Brochure UPDATE V1.Pdf."

[6] "Patellofemoral Pain Syndrome," Anterior Knee Pain [Online]. Available: http://ddxanteriorkneepain.weebly.com/patellofemoral-pain-syndrome.html. [Accessed: 23-Oct-2020].

[7] Andriacchi, T. P., Alexander, E. J., Toney, M. K., Dyrby, C., and Sum, J., 1998, "A Point Cluster Method for In Vivo Motion Analysis: Applied to a Study of Knee Kinematics," J. Biomech. Eng., **120**(6), p. 743.

[8] "Gait Analysis Models" [Online]. Available: http://www.clinicalgaitanalysis.com/faq/sets/. [Accessed: 23-Oct-2020].

[9] "LifeMOD Appendix | Marker Placements" [Online]. Available: http://www.lifemodeler.com/LM_Manual_2010/A_motion.shtml#Gait_marker. [Accessed: 02-Sep-2020].

[10] "Tutorial: Plug-In Gait Full-Body - Visual3D Wiki Documentation" [Online]. Available: https://www.c-motion.com/v3dwiki/index.php/Tutorial:_Plug-In_Gait_Full-Body. [Accessed: 23-Oct-2020].

[11] Noehren, B., Manal, K., and Davis, I., 2010, "Improving Between-Day Kinematic Reliability Using a Marker Placement Device," J. Orthop. Res., **28**(11), pp. 1405–1410

[12] Hutchinson, L., Schwartz, J. B., Morton, A. M., Davis, I. S., Deluzio, K. J., and Rainbow, M. J., 2018, "Operator Bias Errors Are Reduced Using Standing Marker Alignment Device for Repeated Visit Studies," J. Biomech. Eng., **140**(4), p. 041001.

[13] Mündermann, L., Corazza, S., and Andriacchi, T. P., 2006, "The Evolution of Methods for the Capture of Human Movement Leading to Markerless Motion Capture for Biomechanical Applications," J. NeuroEngineering Rehabil., **3**(1), p. 6.

[14] Kirk, A. G., O'Brien, J. F., and Forsyth, D. A., 2005, "Skeletal Parameter Estimation from Optical Motion Capture Data," IEEE, pp. 782–788.

[15] Ceseracciu, E., Sawacha, Z., and Cobelli, C., 2014, "Comparison of Markerless and Marker-Based Motion Capture Technologies through Simultaneous Data Collection during Gait: Proof of Concept," PLOS ONE, **9**(3), p. e87640.

[16] "What Is Motion Capture? | What Can I Use Motion Capture For?," Vicon [Online]. Available: https://www.vicon.com/about-us/what-is-motion-capture/. [Accessed: 14-Jul-2020].

[17] "Toward Pervasive Gait Analysis With Wearable Sensors: A Systematic Review - IEEE Journals & Magazine" [Online]. Available: https://ieeexplore.ieee.org/abstract/document/7574303. [Accessed: 25-Oct-2020].

[18] Lerner, Z. F., Damiano, D. L., and Bulea, T. C., 2017, "A Lower-Extremity Exoskeleton Improves Knee Extension in Children with Crouch Gait from Cerebral Palsy," Sci. Transl. Med., **9**(404).

[19] Narayanan, U. G., 2012, "Management of Children With Ambulatory Cerebral Palsy: An Evidence-Based Review," J. Pediatr. Orthop., **32**, p. S172.

[20] 2014, "Motion Analysis of the Upper Extremity in Children with Unilateral Cerebral Palsy—An Assessment of Six Daily Tasks," Res. Dev. Disabil., **35**(11), pp. 2950–2957.

[21] Shurtleff, T. L., and Engsberg, J. R., 2010, "Changes in Trunk and Head Stability in Children with Cerebral Palsy after Hippotherapy: A Pilot Study," Phys. Occup. Ther. Pediatr., **30**(2), pp. 150–163.

[22] 2020, "How Motion Capture Is Revolutionising Spinal Care," Spinal Surg. News.

[23] Arazpour, M., Bahramian, F., Abutorabi, A., Nourbakhsh, S. T., Alidousti, A., and Aslani, H., 2016, "The Effect of Patellofemoral Pain Syndrome on Gait Parameters: A Literature Review," Arch. Bone Jt. Surg., **4**(4), pp. 298–306.

[24] Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., and Cochran, G. V. B., 1989, "Repeatability of Kinematic, Kinetic, and Electromyographic Data in Normal Adult Gait," J. Orthop. Res., **7**(6), pp. 849–860.

[25] Kouchi, M., and Mochimaru, M., 2011, "Errors in Landmarking and the Evaluation of the Accuracy of Traditional and 3D Anthropometry," Appl. Ergon., **42**(3), pp. 518–527.

[26] Croce, U. D., Cappozzo, A., Kerrigan, C., and Lucchetti, L., 1997, "Bone Position and Orientation Errors: Pelvis and Lower Limb Anatomical Landmark Identification Reliability," Gait Posture, **2**(5), pp. 156–157.

[27] Osis, S. T., Hettinga, B. A., Macdonald, S., and Ferber, R., 2016, "Effects of Simulated Marker Placement Deviations on Running Kinematics and Evaluation of a Morphometric-Based Placement Feedback Method," PLOS ONE, **11**(1), p. e0147111.

[28] Gorton, G. E., Hebert, D. A., and Gannotti, M. E., 2009, "Assessment of the Kinematic Variability among 12 Motion Analysis Laboratories," Gait Posture, **29**(3), pp. 398–402.

[29] Ferber, R., Davis, I. M., Williams, D. S., and Laughton, C., 2002, "A Comparison of Within- and between-Day Reliability of Discrete 3D Lower Extremity Variables in Runners," J. Orthop. Res., **20**(6), pp. 1139–1145.

[30] Merriaux, P., Dupuis, Y., Boutteau, R., Vasseur, P., and Savatier, X., 2017, "A Study of Vicon System Positioning Performance," Sensors, **17**(7), p. 1591.

[31] Dunk, N. M., Chung, Y. Y., Sullivan Compton, D., and Callaghan, J. P., 2004, "The Reliability of Quantifying Upright Standing Postures as a Baseline Diagnostic Clinical Tool," J. Manipulative Physiol. Ther., **27**(2), pp. 91–96.

[32] "About Us | The Vicon Difference | Motion Capture Systems," Vicon [Online]. Available: https://www.vicon.com/about-us/. [Accessed: 26-Oct-2020].

[33] Croce, U. D., Cappozzo, A., and Kerrigan, D. C., 1999, "Pelvis and Lower Limb Anatomical Landmark Calibration Precision and Its Propagation to Bone Geometry and Joint Angles," Med. Biol. Eng. Comput., **37**(2), pp. 155–161.

[34] Chiarello, C. M., Gundersen, L., and O'Halloran, T., 1997, "The Effect of Continuous Passive Motion Duration and Increment on Range of Motion in Total Knee Arthroplasty Patients," J. Orthop. Sports Phys. Ther., **25**(2), pp. 119–127.

[35] Liao, C.-D., Huang, Y.-C., Lin, L.-F., Chiu, Y.-S., Tsai, J.-C., Chen, C.-L., and Liou, T.-H., 2016, "Continuous Passive Motion and Its Effects on Knee Flexion after Total Knee Arthroplasty in Patients with Knee Osteoarthritis," Knee Surg. Sports Traumatol. Arthrosc., **24**(8), pp. 2578–2586.

[36] Hancock, G. E., Hepworth, T., and Wembridge, K., 2018, “Accuracy and Reliability of Knee Goniometry Methods,” J. Exp. Orthop., **5**.