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Validation of Microsoft Kinect for Use in Detecting Balance Impairment in ACL Repaired Patients

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VALIDATION OF MICROSOFT KINECT FOR USE IN DETECTING BALANCE
IMPAIRMENT IN ACL REPAIRED PATIENTS

By

Andre Marcos Alvarez

A THESIS

Submitted to the Faculty
of the University of Miami
in partial fulfillment of the requirements for
the degree of Master of Science

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UNIVERSITY OF MIAMI

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VALIDATION OF MICROSOFT KINECT FOR USE IN DETECTING BALANCE
IMPAIRMENT IN ACL REPAIRED PATIENTS

Andre Marcos Alvarez

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                                                                    (May 2017)

Validation of Microsoft Kinect for Use in
Detecting Balance Impairment in ACL
Repaired Patients

Abstract of a thesis at the University of Miami.

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The anterior cruciate ligament (ACL) is a critical part of normal knee function. With as many as 250,000 injuries every year, most of which occur through little or no contact, ACL reconstruction and rehabilitation are extremely important and relevant topics. One way to test a patient's rehabilitation from ACL reconstruction is through the Star Excursion Balance Test (SEBT). A subject's reach distance in the SEBT can be determined using motion capture systems. However, state of the art motion capture systems present some difficulties, such as cost and complexity of use. The Microsoft Kinect©, an inexpensive, markerless motion capture system, was predicted to solve the issues facing modern motion capture systems, while portraying acceptable levels of accuracy. It was also predicted that subjects who had undergone ACL reconstruction within the previous three months would not perform as well as controls in the SEBT. It was concluded that in most directions of the SEBT, the Kinect© performed within an acceptable range for use by clinicians in determining a patient's advancement through rehabilitation. It was also concluded that the pathological subjects did not perform as well as controls. Future directions for this study include testing more pathological subjects and controls, as well as determining ways to capture more difficult directions of the SEBT.

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Chapter 1

Anterior Cruciate Ligament

Anatomy and Physiology

The anterior cruciate ligament (ACL) is named so because it crosses and attaches to the tibia anterior to the posterior cruciate ligament, specifically anterior and lateral to the medial intercondylar tubercle. Climbing to the femur, it attaches at the posteromedial surface of the lateral femoral condyle. As it does this, the ACL twists on itself approximately 90°, creating a slight lateral spiral facilitated by its bone attachments (Figure 1) (Arnoczky, 1983; Goldblatt & Richmond, 2003). An adult ACL has an average length of 28mm and an average width of 11mm (Drake, Vogl, Mitchell, Tibbitts, & Richardson, 2014).
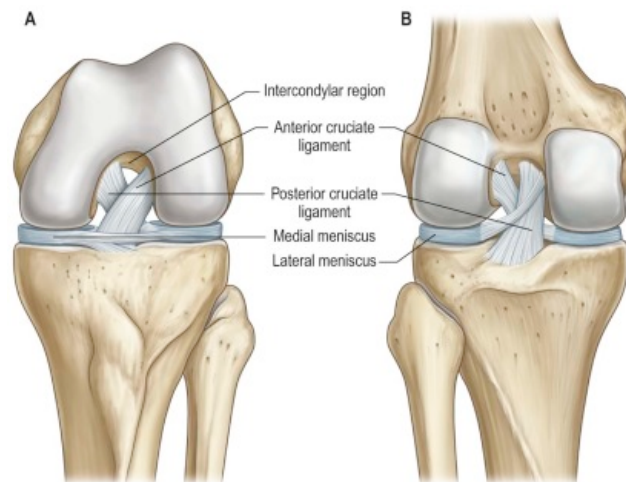
Figure 1.1: Anatomy of the knee, A) Anterior view in full flexion. B) Posterior view in extension. (Drake et al., 2014)

Because it is a collection of fascicles and not a singular cord, it is often suggested that two functional bundles form the ACL: the anteromedial (AM) and posterolateral

(PL) bundles, named according to their tibial attachments (Figure 2). While these bundles are not easily visible to the eye, they can be seen through microdissection (Arnoczky, 1983; Drake et al., 2014).
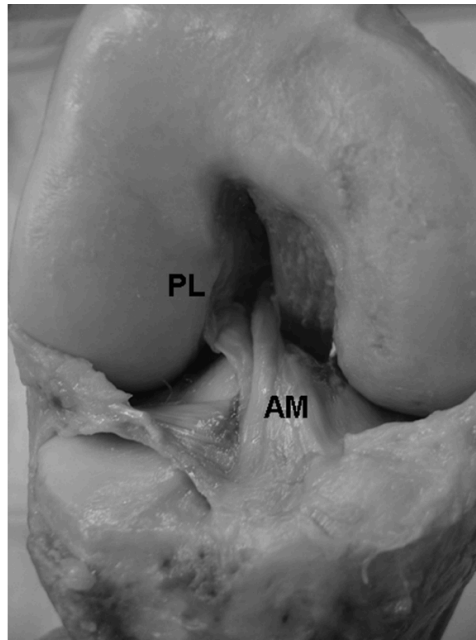
Figure 1.2: The two distinct bundles of an ACL (Petersen & Zantop, 2007)

The distinction of the AM and the PL is made during extension and flexion of the knee. When the knee is flexed to 90°, the AM becomes tight while the PL loosens, due to the horizontal orientation of the femoral attachment during knee flexion. Conversely, as the knee extends, the PL tightens and the AM becomes moderately lax. This shows that in all positions of the knee, the ACL is under tension and functional (Arnoczky, 1983; Goldblatt & Richmond, 2003).

The ACL is made up of a collagen matrix, 90% of which is type I while the remaining 10% is type II, in 20-400μm diameter groups made up of multiple fibers (Markatos, Kaseta, Lallos, Korres, & Efstathopoulos, 2013). At the attachments to the

tibia and the femur, the fibrils of the collagen link to the bone fibrils. This distinct

structure allows for a gradual change in stiffness by preventing the concentration of stress

at the attachment site. The middle genicular artery supplies blood to the ligament and the

bony attachments do little to help with the vascularity (Arnoczky, 1983). Innervated by

branches of the posterior tibial nerve, the ACL has few free nerve endings that respond to

pain. This is the reason for little initial pain during an isolated ACL injury (Goldblatt &

Richmond, 2003). These free nerve endings, as well as many mechanoreceptors, help the

ACL serve an important proprioceptive and vasomotor function, which recruit dynamic

stabilizers to help stabilize the knee joint (Markatos et al., 2013).

 The ACL is critical to the normal function of the knee through flexion and

rotation. It has been found that the ACL provides about 86% of the total restraining force

to anterior translation at knee flexion between 30° and 90° (Goldblatt & Richmond, 2003;

Markatos et al., 2013). Studies have found that sectioning the ACL results in increased

overall knee instability, leading to much greater anterior displacement at full extension, a

25% increase in hyperextension, and a complete lack of internal rotation during anterior

translation (Goldblatt & Richmond, 2003). Studies also show that the ACL helps oppose

medial displacement of the tibia at full extension and 30° of flexion, resists tibial rotation

both internally and externally, and works as a secondary stabilizer for varus-valgus

angulation at full extension (Takeda, Xerogeanes, Livesay, Fu, & Woo, 1994).

Mechanism of Injury

 Injuries to the anterior cruciate ligament are extremely prevalent, especially in

athletes age 15 to 25, with an estimated 80,000 to 250,000 injuries every year (Griffin et

al., 2006). ACL injuries are often classified in one of two ways: either contact or noncontact injuries. However, the definition of each can vary depending on the study. Injuries that occur as a result of direct contact to the knee are often categorized as contact injuries, while injuries where the injured athlete makes no contact with another player are classified as noncontact. The trouble lies in those situations where there is contact between the injured athlete and another player, but without direct contact to the injured leg. Because it is difficult to classify, some researchers consider these mechanisms of injury noncontact with pertubation (Hewett, Myer, & Ford, 2006). Studies have shown that between 65 to 72% of ACL injuries are noncontact, with the remaining being contact injuries or those occurring during accidents, such as in motorsports (Hewett et al., 2006; Kobayashi et al., 2010). With a large amount of ACL injuries occurring with no contact to the injured leg, it is important to understand the different factors that contribute to such an injury.

Anatomical factors are thought to play a major role in ACL injuries. One example is the quadriceps (Q) angle, calculated as the angle between the line from the anterior superior illiac spine and the patella center and the line from the patella center and the tibial tuberosity center (France & Nester, 2001). It has been found to be larger in athletes with knee injuries, and along with ankle strength, can predict 32.4 to 46% of the variance in valgus-varus knee position, which has shown to be dangerous to the ACL (Griffin et al., 2006). However, studies have found mixed results, with some showing that ACL injury risk cannot be predicted during dynamic movement using static Q angles (Hewett et al., 2006).

Another example of a structural factor is the femoral notch width, located on the distal end of the femur. There is evidence that smaller notches could mean smaller ACLs, which have been shown to be at an increased risk of injury (Griffin et al., 2006; Hewett et al., 2006). Conversely, other reports refute this, showing that notch widths and the incidence of noncontact ACL injuries show no correlation (Griffin et al., 2006). Joint laxity has been shown to be a contributing cause, as knee hyperextension and valgus can lead to a 2.7 times greater risk of ACL injury (Hewett et al., 2006). It has been found that ACL injured athletes have more flexible hamstrings compared to controls, and this has been thought to lead to a delay in hamstring muscle activation, resulting in an uneven contraction between the quadriceps and hamstrings and imbalance in the knee joint (Boden, Dean, Feagin, & Garrett, 2000; Hewett et al., 2006). Navicular drop, as well as both muscle activation and joint laxity, contributes to anterior tibial translation, leading to increased stress on the ACL (Hewett et al., 2006). It has also been found that increased Body Mass Index could be a contributing factor in the increased risk of ACL injuries (Hewett et al., 2006). However, there are no clear conclusions that can be drawn for the data (Griffin et al., 2006).

Neuromuscular factors have also shown to contribute to the risk of ACL injuries. It has been well documented that isolated quadriceps contraction leads to increased strain in the ACL from full knee extension to 45° of flexion due to anterior tibial translation, and that these forces are more than enough to produce ACL tensile failure (Griffin et al., 2006; Hewett et al., 2006). In patients with ACL deficient knees, the hamstrings are important joint stabilizers, and underdeveloped hamstrings have been shown to limit the potential for muscular co-contraction. This can lead to high knee abduction torques,

anterior tibial translation, and increased ground reaction forces when leading and cutting, further increasing the risk of ACL injury (Griffin et al., 2006; Hewett et al., 2006). Unanticipated movements can also cause different lower extremity muscle activation and increased varus-valgus and internal-external knee moments when compared to preplanned condition. This is caused by unplanned cutting and jumping movements in high-risk sports not allowing for postural adjustments (Hewett et al., 2006). Muscular fatigue could also be a factor in ACL injury risk, as a decrease in knee flexion angle and increasing in proximal tibial anterior shear force and knee varus moment when performing was shown with lower extremity fatigue (Griffin et al., 2006). Finally, some studies show that those who suffer ACL tears are twice as likely to have a relative with a previous ACL injury (Griffin et al., 2006).

Environmental factors, such as meteorological conditions, playing surface, footwear and knee bracing are all potential contributors to ACL injury risk, but the evidence is mixed and not clear (Griffin et al., 2006). This is also true of hormonal factors, specifically estrogen and the menstrual cycle. While evidence is mounting, it is not conclusive (Griffin et al., 2006; Hewett et al., 2006).

Biomechanically, ACL injuries occur through unsuccessful postural adjustments, often when the base of support is in front of and away from the body's center of mass, leading to abnormal dynamic loading of the knee (Griffin et al., 2006; Hewett et al., 2006). Quadriceps activation, hamstring weakness and laxity, excessive ankle eversion, large posterior ground reaction forces, and muscle fatigue are all associated with anterior tibial translation (Griffin et al., 2006; Hewett et al., 2006; Yu & Garrett, 2007). Most descriptions of noncontact ACL injuries include knee extension between 0 and 30° of

flexion, hip extension, pronation of the grounded foot, external tibial rotation and knee valgus (Boden et al., 2000; Hewett et al., 2006; Kobayashi et al., 2010). While sagittal plane biomechanics, specifically anterior tibial translation, is the main cause of ACL loading, other factors such as knee valgus have been shown to lead to ACL injuries when accompanied with high sagittal plane forces (Yu & Garrett, 2007).

Reconstruction

With ACL injuries, 80% of tears occur in the middle portion of the ligament. Even in the 18% of tears considered proximal, there is a small amount of ligament that remains on the distal end of the femur (Warrren, 1983). Because of this, primary repair of the ACL, where the two ends are sutured together, was common for some time. However, this was found to be unsuccessful in most cases, with as many as 100% of repairs failing and finding no difference between primary repair and conservative treatment (Kiapour & Murray, 2014). Today, reconstruction has replaced suture repair as the main treatment of ACL injuries.

In choice of grafts, surgeons often select autografts and, less commonly, allografts. Though allografts allow for decreased surgical morbidity and easier rehabilitation, they have higher costs and a slower period of incorporation (West & Harner, 2005). While synthetic grafts have been developed, they have yet to lead to satisfactory results, with research showing an increased risk of complications, instability and infection (West & Harner, 2005; Woo, Wu, Dede, Vercillo, & Noorani, 2006). The two most used grafts are bone-patellar tendon-bone (BPTB) and hamstring tendon (HT) grafts (Figures 3,4). The more common are BPTB grafts, as they have similar stiffness

and ultimate load values as young human femur-ACL-tibia complexes. They also offer better knee stability and faster healing through the bone blocks available for graft fixation in the osseous tunnels and have shown to be beneficial for patients who participate in sports that require cutting or jumping (West & Harner, 2005; Woo et al., 2006). While the isolateral patellar is commonly used, the contralateral tendon can be used for faster rehabilitation due to less pain in the operative leg, benefiting athletes returning to play as soon as possible (Meisterling, Schoderbek, & Andrews, 2009). However, studies have shown that HT grafts are similar in terms of anterior knee pain, range of motion, isokinetic strength, or instance of graft failure, and have been found to benefit older patients and reduce kneeling pain in the host knee (Meisterling et al., 2009; Spindler et al., 2004).
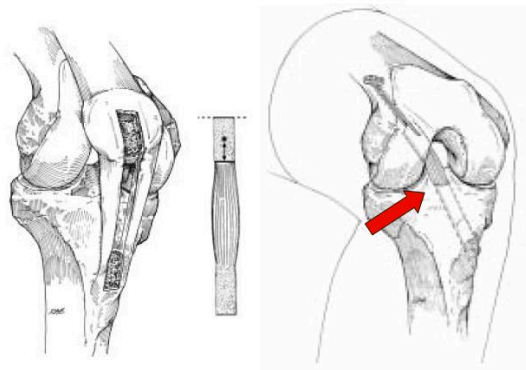
Figure 1.3: BPTB graft harvest and use in ACL reconstruction (Gee, 2013)

Femoral tunnel placement is often chosen to be at the footprint of the AM bundle, but studies have shown that placement closer to the footprint of the PL bundle may yield

better results (Markatos et al., 2013; Woo et al., 2006). However, no single position has

been found that could reproduce the rotatory knee stability of a healthy knee (Woo et al.,

2006). In terms of graft tension, research has led to mixed results and has shown no

conclusive answers. Graft fixation promotes range of motion of the knee when fixed at

full extension, while knee stability is helped most when fixed at 30° (Woo et al., 2006).

There are many forms of graft fixations, ranging from anatomic fixation methods, such as

interference screws, to extraarticular methods, such as the EndoButton CL (Acufex

Microsurgical, Inc., Mansfield Massachusetts). Studies have shown methods such as the

EndoButton CL offer more fixation strength, but this cannot be generalized to all

extraarticular methods against anatomical ones, as differences in individual implants can

vary the strength of fixation (Kousa, Jarvinen, Vihavainen, Kannus, & Jarvinen, 2003).

Regardless of method, the rigidity of the chosen device highly affects the stiffness of the

implant, with more rigid devices such as the Bone Mulch Screw (Arthrotek Inc., Warsaw,

Indiana) and the Smart Screw ACL (Bionx Implants Inc., Blue Bell, Pennsylvania)

exceling when tested for fixation strength of HT grafts (Kousa et al., 2003).

Traditionally, ACL reconstruction has used single bundles, lacking the ability to

replicate the rotatory knee stability of a healthy knee. Interest has grown in anatomic

double bundle ACL reconstruction, seeking to replicate the AM and PL bundles of the

ACL using two separate grafts. Double bundle reconstruction has led to a decrease in

anterior tibial translation as well as an increase in in-situ force (Woo et al., 2006).

However, a consensus has not been reached, as there are concerns of force distribution in

double bundle grafts and the possibility that either graft could become strained. Also,

studies show that it is not superior to single bundle reconstruction in preventing post-traumatic osteoarthritis (Kiapour & Murray, 2014; Woo et al., 2006).

Rehabilitation

When rehabilitating an injured ACL, there are two accepted methods used by medical professionals: traditional, or delayed, rehabilitation and accelerated rehabilitation. Delayed rehabilitation programs are often similar to the protocols described by Paulos et al. In this method, patients are to wear a cast immobilizing the knee at 30° for 2 to 4 weeks, followed by a hinged brace for weeks 4 to 10, and finally a custom molded polycentric brace until about 4 months post-surgery. During this time period, patients slowly work up to full weight bearing and continually test the range of motion of the reconstructed knee. Exercises include non-weighted or lightly weighted exercises in the first 10 to 12 weeks, eventually incorporating agility drills as well as walking and jogging in months 4 through 8. A traditional program such as this one suggests patients return to normal activity levels no earlier than 9 to 12 months post-surgery.

Accelerated rehabilitation programs, such as the one described by Adams et al, often start the rehabilitation process pre-surgery, attempting to obtain full knee extension range of motion as well as aggressive quadriceps strengthening. The aim immediately post-surgery is to once again achieve full knee extension range of motion along with quadriceps strength, using voluntary exercise or neuromuscular electrical stimulation. The second week of rehabilitation sets out to have the patient begin testing knee flexion, while also using step exercises, cycling and stair climber without difficulty. Starting in

week 4, the patient should be close to normal knee flexion and increasing quadriceps strength, using balance and neuromuscular re-education exercises. Normal gait pattern and a full range of motion in the injured knee are achieved within weeks 6 to 8, as well as quadriceps strength in the injured leg approaching that of the uninjured one. During this period, patients increase the intensity and duration of the exercises, and can begin running progression. At 12 weeks the patients should gain relatively even quadriceps strength and begin to incorporate agility and sport-specific exercises. Finally, athletes may begin low-level participation in practice with the goal of full participation. While this and many accelerated programs can be completed in about 12 weeks, the authors stress that patients are required to meet the criteria before moving on to the next stage of the program, and that each patient should be assessed individually, regardless of the time frame.

Research has shown that a more aggressive, accelerated rehabilitation can lead to athletes returning to their field of play much quicker. Programs that emphasized the reduction on pain and swelling, regaining full knee range of motion, and the strength and neuromuscular control of the quadriceps led to faster recovery and did not lead to any stability problems (van Grinsven, van Cingel, Holla, & van Loon, 2010). Pre-surgical rehabilitation and controlled criteria help lead to a straightforward rehabilitation. Some researchers also suggest that using at-home rehabilitation can be successful for motivated patients (Kruse, Gray, & Wright, 2012). Using accelerated methods may help athletes return to full competition in as little as 4 to 6 months, after they have displayed full range of motion, quadriceps and hamstring strength within 85% of the uninjured leg, a hamstring/quadriceps strength ratio of at least 85% compared to the uninjured leg, and

successful hop and isokinectic tests with no increase in pain and swelling (De Carlo,

Shelbourne, McCarroll, & Rettig, 1992; van Grinsven et al., 2010).

Chapter 2

Motion Capture for Functional Recovery

Motion Capture Technology

The analysis of biomechanical movements is often used in rehabilitation and treatment as it provides an opportunity to obtain information that is difficult or impossible to acquire otherwise (Pfister, West, Bronner, & Noah, 2014). While kinematics can provide information on dynamic joint motion, kinetics is of primary concern when dealing with motor impairments and their responses (Asfour & Eltoukhy, 2011). To this end, motion capture systems such as Vicon Nexus Motion Capture System (Oxford Metrics, UK), a commercially available and validated gait analysis package, provide invaluable kinetic data to assist researchers in studying gait, balance and other biomechanical tasks (Pfister et al., 2014). While there are more affordable alternatives to three-dimensional (3D) systems, such as the two-dimensional (2D) video cameras, accelerometers and electrogoniometers, 3D motion capture systems are often preferred due to their high reliability and accuracy (Pfister et al., 2014).

The Vicon Nexus system works by using a number of reflective markers placed on the subject at key locations to be able to construct body segments for both the upper and lower body (Figure 1). High-speed cameras capture reflected light from the markers, recording X, Y and Z coordinates of the body segments and joints (Asfour & Eltoukhy, 2011). The data is then reconstructed into a stick figure of the subject using the body segments as determined by the reflective markers, as well as the segments' center lines and reference frames (Figure 2). With this, the distance, velocity and acceleration of any point, body segment or joint can be found.

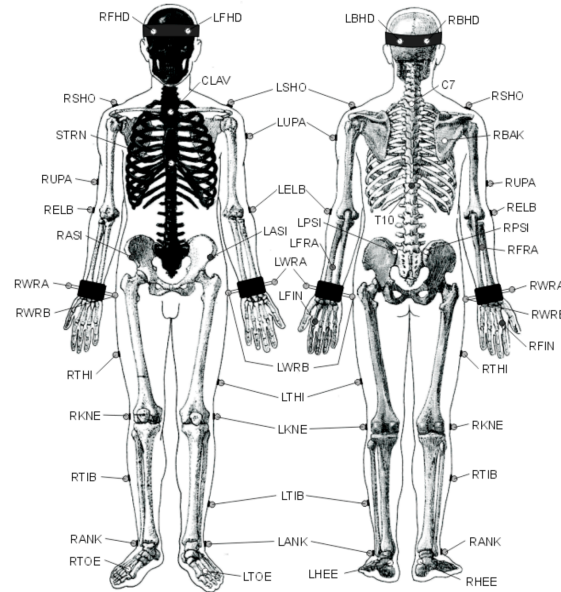**Figure 2.1: Marker placement for full body motion capture (Marker Placement Protocols)**
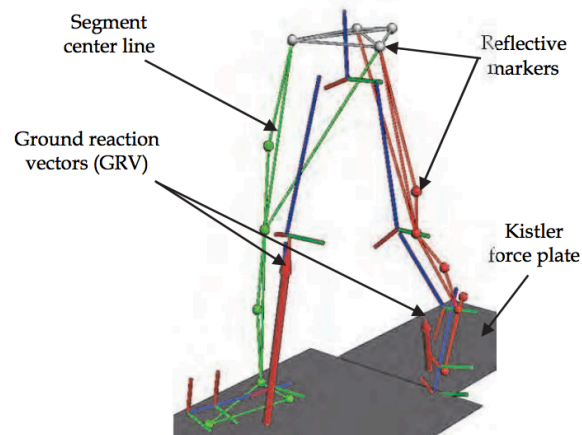
Figure 2.2: Lower body figure reconstructed through motion capture data (Asfour & Eltoukhy, 2011)

Shortcomings of Modern Motion Capture Systems

While modern motion capture systems such as Vicon can be powerful tools for research and study, they present some complications. First, a system such as Vicon is

extremely expensive and requires training to set up and run properly and efficiently. The preparation for a motion capture study can be long, as the system and cameras need to be calibrated and the markers need to be placed on the subject. Small setbacks in the setup of an experiment can lead to unnecessarily long run times. Second, a specified space is needed to set up the system, such as a laboratory, which may not be in a location that is convenient for subjects. These inconveniences can lead to a lower number of participants in studies as well as subjects dropping out, and the high cost of acquiring and maintaining a motion capture system may not be considered worthy of the outcome. A system that is relatively inexpensive, portable, and easy to operate could solve many of the shortcomings that a modern motion capture systems presents.

Microsoft Kinect©

The Mircosoft Kinect© (Microsoft Corporation, Redmond, WA) was originally launched in 2010 as a motion based game controller for Microsoft's Xbox 360. In 2011, Microsoft released a Software Development Kit (SDK) to enable users to create human motion tracking programs, allowing for real time tracking of dynamic human motion. In 2014, Microsoft released the Kinect© v2, an updated version of the Kinect© that could allow for improved depth sensing and color image resolution. There are many medical and healthcare applications for the Kinect©, including operating room assistance, fall detection and prevention, physical therapy and rehabilitation (Lun & Zhao, 2015).

Before the Kinect©, many of the available affordable systems were only able to track a few points at a time through conventional digital imaging, leading to low quality real time results (Mousavi Hondori & Khademi, 2014). One of the advantages of the

Kinect© is its depth sensing technology. The Kinect© v2's calculates depth based on

time of flight (Lun & Zhao, 2015). The depth sensor collects the reflected light given off

by the infrared (IR) laser diode, synchronized by the timing generator (Figure 3). The

phase shift between the emitted light and the reflected light can be used to calculate the

depth of each pixel (Lun & Zhao, 2015). In order to more accurately calculate depth, the

IR emitter is periodically turned off. When this occurs, the depth sensor records only the

ambient light. This output can then be subtracted from the output of both the ambient

light and the IR light, leaving only the reflected modulated light from the IR emitter (Lun

& Zhao, 2015). Using this, the Kinect© v2 can track 26 full body positions

simultaneously without the use of markers (Figure 4).
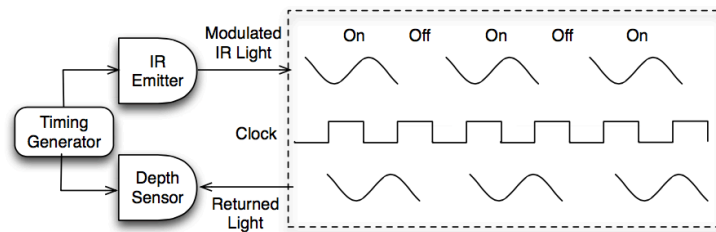
Figure 2.3: Time of flight method used by Kinect© v2 for depth sensing (Lun & Zhao, 2015)
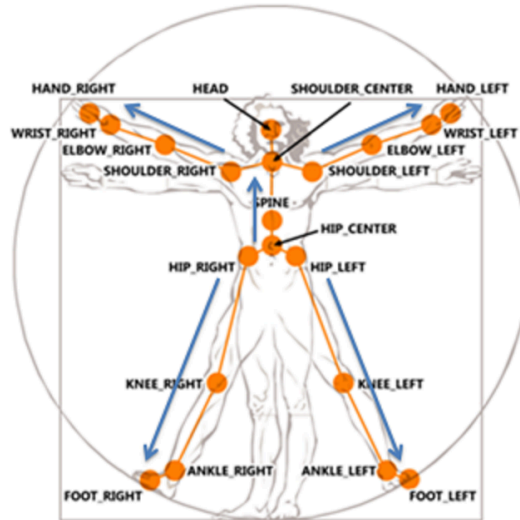
Figure 2.4: Joints tracked by the Kinect© v2 (Tracking Users with Kinect Skeletal Tracking)

When using the Kinect©, human motion recognition is done using one of two different methods: template or algorithm based tracking (Lun & Zhao, 2015). Template based tracking compares the motions of a subject with a pre-recorded template via pattern recognition, while an algorithmic approach attempts to identify gestures or movements based on a set of defined rules (Lun & Zhao, 2015). For medical and healthcare applications, an algorithmic based approach is considered ideal due to most movements or exercises having a pre-defined start and end that can be used to identify what activity the subject performs and how well they perform it. This requires a movement or exercise to be carefully defined by experts, simple enough to be outlined with a simple set of rules and for the boundary conditions to be tuned exactly (Lun & Zhao, 2015).

Due to its affordability and usefulness, many have sought to compare and validate the Kinect© to state of the art marker based motion capture systems, but results have been mixed. Some studies concluded that the Kinect© is comparable when assessing anatomical landmark position, angular displacement and planar motions while showing

reasonable repeatability in range of motion testing (Bonnechere, Jansen, Salvia, Bouzahouene, Omelina, et al., 2014; Clark et al., 2012). It has also been shown that the Kinect© falls short in tracking hip abduction and knee flexion through movement, following lower body markers when in a sitting position, and finding joint center locations (Bonnechère et al., 2013; Xu & McGorry, 2015). However, it should be noted that marker based systems also have questionable joint center estimation, and that the Kinect© is superior to other markerless based systems in terms of lower body and whole body tracking (Bonnechere, Jansen, Salvia, Bouzahouene, Omelina, et al., 2014; Mousavi Hondori & Khademi, 2014). Finally, while the Kinect© succeeds at tracking joint angles such as the hip and knee during motions such as squatting, it does struggle to acquire precise segment lengths during motion, but this can be addressed using a regression equation that can be found when calibrating the Kinect© with a marker system such as Vicon (Bonnechère et al., 2013).

Star Excursion Balance Test

When evaluating a patient's rehabilitation program, clinicians often use postural-control to determine improvement. While static balance tests can be useful, dynamic postural-control tests are thought to be more closely related to movement tasks during physical activity as they require a movement to be performed while maintaining balance on a base of support (Gribble, Hertel, & Plisky, 2012). The Star Excursion Balance Test (SEBT) is one form of dynamic postural-control testing.

The SEBT is performed on a grid of 8 lines extending out 45° from a center point. The subject stands on the center point and performs single-leg squats, using their free leg

to perform maximal reach excursion along the line in each direction while keeping a stable base of support with their stance leg. Each direction is named relative to the stance leg as anterior, anterolateral, lateral, posterolateral, posterior, posteromedial, medial, and anteromedial, whose combination tests the subject in all planes of movement (Figure 2.5). Once the subject has reached maximal excursion, they are to lightly touch the line without shifting their weight from their stance leg, then return to the starting position. Should the subject make excessive contact with the ground with their reaching leg to maintain balance or shifts the foot of their stance leg at any point of the trial, the trial should be discarded (Gribble et al., 2012). The goal of the SEBT is to measure the maximal excursion distance of the subject in each direction.
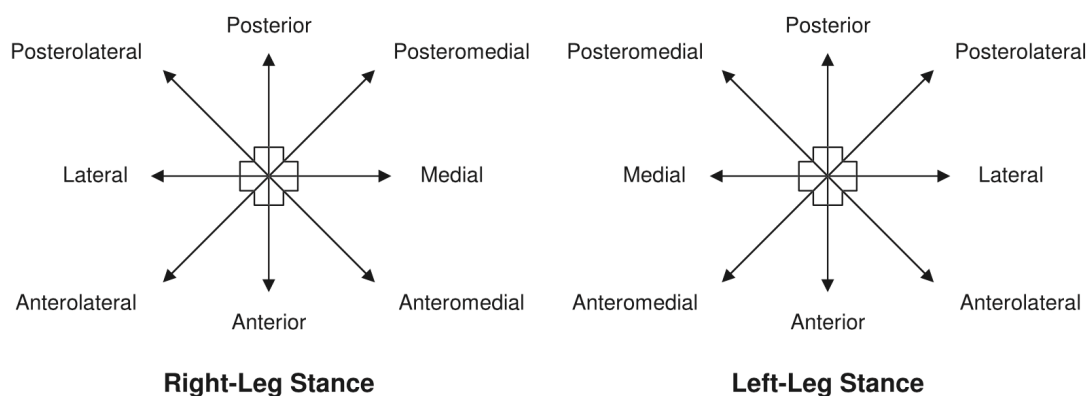
Figure 2.5: Reaching Directions for the Star Excursion Balance Test (Gribble et al., 2012)

When using the SEBT as a dynamic balance assessment tool, a few things should be noted. First, researchers have shown that there is a "practice effect", with subjects reaching farther as they performed more trials. It is suggested that subjects perform 6 practice trials to minimize this effect (Gribble & Hertel, 2003). Second, to be able to make comparisons across multiple subjects and groups, reaching distances should be

normalized to the subject's leg length, with the performance reported as percentage of leg length (Gribble & Hertel, 2003).

Many researchers have shown that subjects with injured or reconstructed ACLs perform worse on tests of neuromuscular control, postural-control and functional performance compared to healthy subjects. Using the SEBT specifically, when compared to a control group, subjects using their injured legs as the stance leg performed 5 to 28% worse than controls in the anterior, lateral, posteromedial and medial directions (Herrington, Hatcher, Hatcher, & McNicholas, 2009). Even the healthy leg of ACL injured patients performed 15 to 23% worse in the medial and lateral directions when compared to control groups (Herrington et al., 2009). It has also been shown that the SEBT can predict lower extremity injuries in athletes (Plisky, Rauh, Kaminski, & Underwood, 2006). These results show the need and usefulness of dynamic postural-control testing with regards to the prevention and rehabilitation of lower extremity injuries, specifically ACL injuries.

Chapter 3

Development of Software

Stated Goals

  With the prevalence of ACL injuries and rehabilitation, it is important to be able to measure the progress of a patient through the rehabilitation process to confirm that the assigned protocol is achieving the desired goals. Using the SEBT recorded by a motion capture system would allow clinicians the ability to confirm that a patient's rehabilitation protocol is working as expected. As traveling to a lab can present inconveniences to the patient, a portable motion capture system that can be used in a clinician's office would allow the patient to perform the SEBT at the time of their meeting with a clinician, and would give the clinician the information to determine if the patient is responding well to the rehabilitation protocols.

  As such, this thesis has two stated goals: first, to validate the Kinect© with a modern motion capture system, such as Vicon Nexus, to confirm that the Kinect© can obtain data that would be comparable to that of Vicon. To this end, it is expected that the Kinect© will show some error when compared to Vicon, but that this error would be within reasonable measures. The second goal is to see if there is a difference between ACL repaired patients and a control group in SEBT performance, and whether the Kinect© will be able to show that difference. It is predicted that the pathological subjects will perform worse using both their injured and uninjured legs on the SEBT when compared to controls, and that the Kinect© will be able to record the difference.

Acquiring Kinect© Data

To be able to use the Kinect© and obtain data, the Software Development Kit 2.0 from Microsoft was used in conjunction with MATLAB R2016a (The Mathworks, Inc., Natick, MA). A variety of programs were written in MATLAB to be able to perform the tasks needed to acquire data from the Kinect© and compare its output to the Vicon data.

When the Kinect© is in position and connected, the first program run is "Kinect_Setup." This program sets necessary functions to the MATLAB path, creates objects that allow for data acquisition, and enables skeletal tracking. This is only run at the beginning of the acquisition process. Next, the function "Kinect_Acquire" is used, with the trial name as the input of the function. This begins the data acquisition process by triggering the color and depth cameras to record data, then extracting the joint world coordinates and writing them to a Microsoft Excel file. Once all data is recorded, the function "Kinect_Aesthetic" is run to read a single Excel file and organize the data in a way similar to the output of Vicon, also in an Excel file. This can be done in mass using the function "Mass_Aesthetic" and inputting whether the trials are from a pathological patient or a control.

To combine the Kinect© and Vicon data in a single Excel file, "Export_Stats" is used. The first input for this function identifies whether the data being run is from a pathological subject or a control, and the second uses the name or number of the specific subject. "Export_Stats" call upon another function, "Export_Data," to combine the data created by "Kinect_Aesthetic" and taken from Vicon into a single Excel file, complete with a graph of the data. Within "Export_Data," "Export_Kinect" is used to process the Kinect© data, to determine the start and end of the trial and to export the relevant graph

data, while "Export_Vicon" does the same for the Vicon data. The data is then examined by hand to determine if it qualifies to move on to data analysis.

Output of Validation Data

The following is the series of programs written with the intention of outputting the data relevant to the validation of the Kinect© against Vicon.

To compare the Kinect© to Vicon, the mean of all Kinect© data in each direction was compared graphically to the mean of all Vicon in the same direction by using the function "Control_Average_Graph." As seen in Figure 5.1, the function "Error_Calc" receives both sets of data and determines the error and standard deviations of the errors. "MeanSD_Graph" is then used to graph the error of the Kinect© as points along with the standard deviation, taking this information from "Combine_Stats," which in turn also uses "Error_Calc." This result of "MeanSD_Graph" can be seen in Figure 5.2. Finally, "Control_Dist" uses "Dist_Calc" to calculate the reach distance of control subjects and graphs the combine average plus the standard deviation, as shown in Figure 5.3.

Output of ACL versus Controls Data

The following is the series of programs written with the intention of outputting the data relevant to comparing SEBT performance of the ACL injured patients and controls.

To compare pathological subjects with controls, "Patient_vs_Control" is used to read in reach data from controls, using "Control_Dist," and pathological subjects, using "Patient_Dist," and produces a graph. This program is to be amended to fit the specific

patient being examined, their injured and uninjured leg, and the trials that were recorded

for that patient (Figure 5.4, 5.5, 5.7 – 5.9). "Patients_Uninjured" is then run to receive all

of the data from uninjured legs of pathological subjects to graph a comparison (Figure

5.10), while "Patients_Injured" does the same for the injured legs (Figure 5.6). Both use

"Patient_Dist" to achieve this. Finally, "Intra_Patient" is used to compare the injured and

uninjured legs of a single pathological subject. As with "Patient_vs_Control," this

program is to be amended to fit the specific patient being examined and the trials that

were recorded for that patient (Figures 5.11, 5.12).

Chapter 4

Methodology

Validation of Kinect© versus Vicon

For the validation, the Star Excursion Balance Test data capture by the Kinect© and Vicon was compared at 10-90% of the total movement, in increments of 10%. Afterwards, the error and standard deviation of all the points were taken. This would allow for an accurate comparison of the ability of the Kinect© system to track the Star Excursion Balance Test against a modern marker-based system such as Vicon.

Subjects

Ten male subjects were recruited to come to the Biomechanics Research Laboratory at the University of Miami and perform the Star Exertion Balance Test while being recorded by both the Kinect© and Vicon systems. The subjects reported no prior lower body injuries that would affect their performance.

Preparations

The Kinect© was placed on a flat surface about one meter in height and about two meters away from where the subjects would stand, outside the view of the Vicon system. Four to ten Vicon cameras were used, including one camera placed about two meters from the subject, facing down towards their feet.

When the subject arrived, the experiment was explained and they were given a consent form to sign. After giving the subjects a few moments to familiarize themselves with and practice the Star Excursion Balance Test, a single reflective marker was placed

on the first metatarsal of each foot, and the subject was asked to step in front of the Kinect©. Once it could be confirmed that the both the Kinect© and Vicon systems could see and capture the subject's full range of motion, the testing began.

Protocol Design

The subjects performed the Star Excursion Balance Test, reaching out with their right foot and using their left as the stance leg. Each reach direction was performed twice. The Kinect© captured world coordinates of the full body, while Vicon captured only the marker on each of the subject's feet.

Measurements and Calculations

The distance between the two feet was calculated for both the Kinect© and Vicon data. The true distance was then calculated by subtracting the initial distance between the feet at the start of the movement, defined as a change of at least 1% between two points, and dividing by the maximum distance reached, as shown in Equation 4.1.

$$true\ distance = \frac{(distance - initial\ distance)}{maximum\ distance}$$

Equation 4.1: True Distance

Data Analysis

When tracking full body motion, the Kinect© chooses markers based on joint locations. Because of this, the chosen marker for the foot may not be the same as the location of the reflective marker placed that was tracked by Vicon. This may lead to

different measurements of the reach distance. For this reason, the percentage of movement was compared between Kinect© and Vicon. A graph of the true distance versus the percent of total movement was made for each trial, with 0% being the start of movement and 100% being the maximum true distance between the two feet. If the trial did not contain at least ten data points, the trial was excluded from future calculations.

To accurately compare the Kinect© and Vicon data, points at 10-90% of the movement were taken in increments of 10%. The mean was then taken across all trials in similar directions for both the Kinect© and Vicon data. Each data set was then graphed against the other for each direction. The error was taken for all data points, assuming Vicon to be the true value, as well as the standard deviation of the error. This was also graphed.

ACL Patients versus Controls

To determine if the uninjured leg of patients with ACL reconstructed knees have an altered performance, the normalized reach distance was compared to controls in the Star Excursion Balance Test. A comparison of injured and uninjured leg of each patient was done to determine if ACL reconstruction has an effect on SEBT performance. Then, the injured leg of each patient was compared to determine if rehabilitation time was a factor in SEBT performance.

Subjects

Three males, two 3 weeks and the third 3 months post operation, were asked to perform the Star Excursion Balance Test while being recorded by the Kinect© system. Subjects were referred from and recorded at the Hommen Orthopedic Institute at Baptist Hospital (Miami, FL). The reconstructed knee had an injured ACL repaired, and may have had other injures as well. The opposite knee was healthy, with no recent injuries that would affect their performance. The subjects that performed the validation were used as a control group.

Preparations

The Kinect© was placed on a flat surface about 1.5 meters in height, about 2 meters from where the subject would stand. The camera was angled down to be able to capture full body data during the trials.

Subjects arriving at the Institute for their appointment were asked if they would participate in the study. Following an explanation of the study and their requirements, the subject would be asked to sign the consent form. After giving the subjects a few moments to familiarize themselves with and practice the Star Excursion Balance Test, the subject was asked to step in front of the Kinect©. Once it was confirmed that the subject's full body and full range of motion was in view of the Kinect©, testing began.

Protocol Design

The subjects performed the Star Exertion Balance Test using both their injured and uninjured legs as the stance leg. Each direction was performed once per leg. The Kinect© recorded full body movements for all trials.

Measurement and Calculations

The distance between the two feet was calculated from the Kinect© data. The normalized distance was then calculated by taking the distance between the two feet and dividing by subject's leg length, as shown in Equation 4.2. The subject's leg length was taken from the Kinect© data.

$$normalized\ distance = \frac{distance}{leg\ length}$$

Equation 4.2: Normalized Distance

Data Analysis

A graph of the normalized distance versus the percent of total movement was made for each trail, with 0% being the start of movement and 100% being the maximum normalized distance between the two feet. If the trial did not contain at least ten data points, the trial was excluded from future calculations. Also, if a subject did not feel comfortable performing the test on their reconstructed knee, distances for those trials were considered zero.

To more closely equate the pathological and control data, the points at 10-90% of the movement, taken in increments of 10%, were compared. This was compared to the

mean taken across all trials of the control group in similar directions. Bar graphs were

made comparing each pathological subject's uninjured leg against the control group,

comparing the injured and uninjured legs for each pathological subject, and comparing

both the injured and uninjured legs of each pathological subjects.

Chapter 5

Results

Validation of Kinect© versus Vicon

Ten control subjects were recorded performing the Star Excursion Balance Test

by both the Kinect© and Vicon. The average of all data in each direction is shown below.
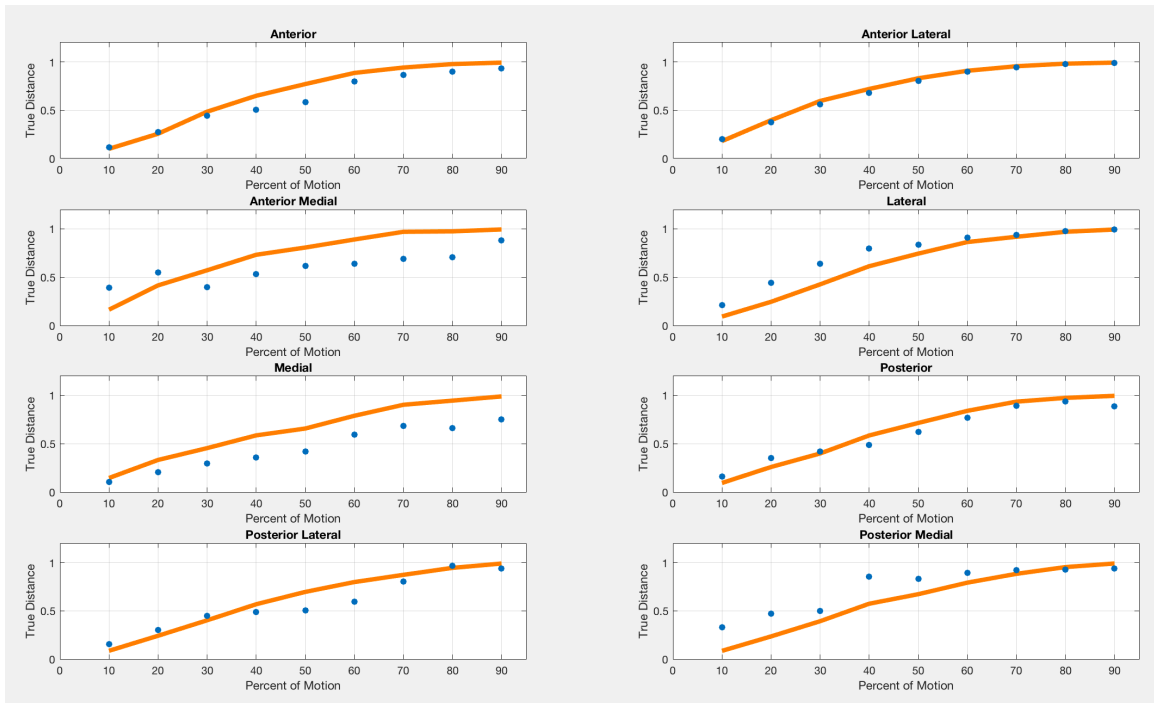
Figure 5.1: Kinect© versus Vicon Data

Anterior	Anterior Lateral	Anterior Medial	Lateral	Medial	Posterior	Posterior Lateral	Posterior Medial
12	15	12	19	6	16	17	13

Table 5.1: Total Trials for Each Direction

Table 5.1 shows the total number of trials used in each direction. Figure 5.1

shows the true distance versus the percent of motion of the average of each direction,

with the Vicon data in orange and the Kinect© data in blue. Most directions have the Kinect© data line up well against the Vicon data, with the two directions with the largest gap being Anterior Medial and Medial. Medial also has the least amount of trials, which may contribute to the displacement.
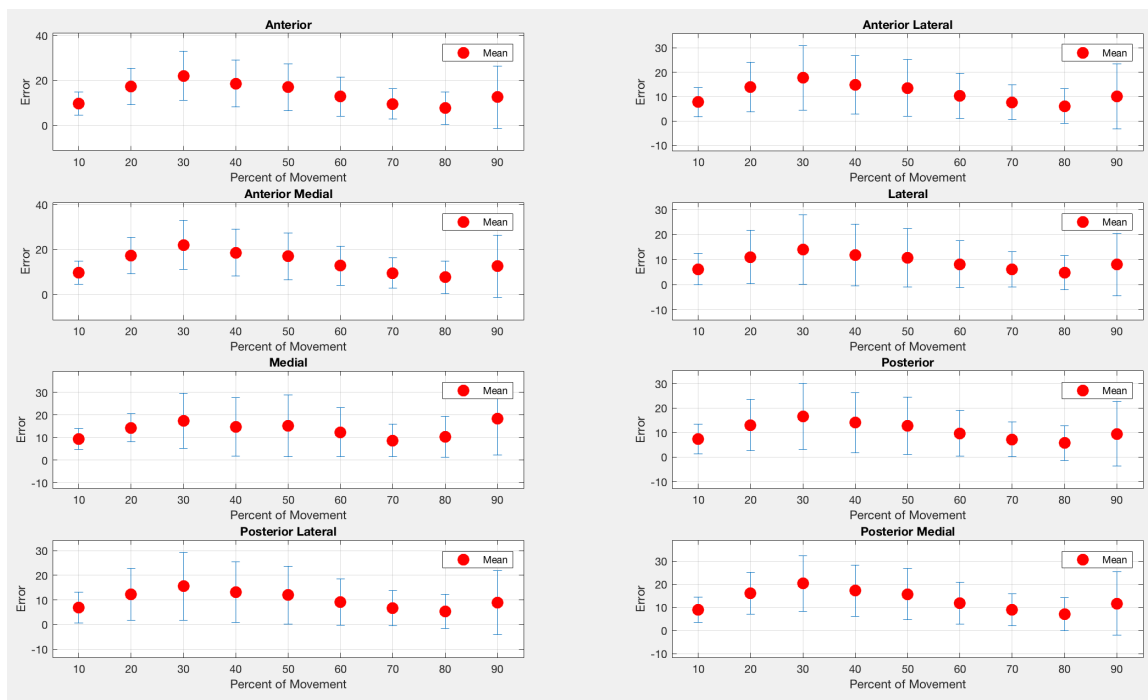
Figure 5.2: Error of Kinect© versus Vicon Data

The error, +/- 1 standard deviation for each direction versus the percent of movement is shown in Figure 5.2. For all directions, the mean is rarely higher than 20%, with error increasing at 20-40% of the movement, and then decreasing until 90% of the movement where a small increase in error occurs. Across all directions, the maximum error is often found at 30% of the movement.
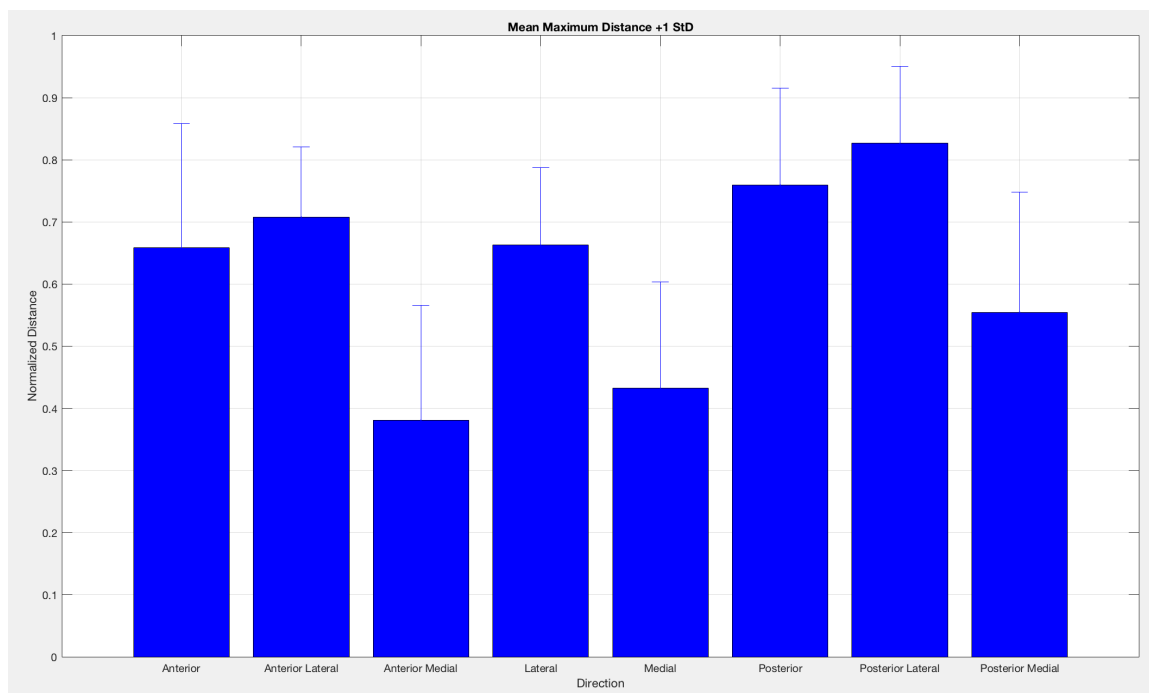
Figure 5.3: Mean Reach Distance

The mean reach distance +1 standard deviation for each direction is shown in Figure 5.3. The directions with the shortest distance were Anterior Medial, Medial and Posterior Medial. The longest distances were in the directions of Anterior Lateral, Posterior, and Posterior Lateral.

ACL Patients versus Controls

Three pathological subjects were included in the study. The first subject was recorded three weeks post surgery, which included ACL and meniscal repair. They did not feel comfortable performing the Star Excursion Balance Test on their injured leg, but was able to perform the test on their uninjured leg. The second subject was also three

weeks post surgery and performed the SEBT on both their injured and uninjured leg.

Finally, the third subject was three months post surgery and performed the SEBT on both

legs. The legs and directions recorded are shown in Table 5.2.

Patient 1	Uninjured	Anterior, Anterior Lateral, Lateral, Posterior, Posterior Lateral, Posterior Medial
Patient 2	Injured	Anterior, Anterior Lateral, Medial, Posterior, Posterior Lateral
	Uninjured	Anterior, Anterior Lateral, Lateral, Medial, Posterior, Posterior Lateral, Posterior Medial
Patient 3	Injured	Anterior, Anterior Lateral, Lateral, Medial, Posterior, Posterior Lateral, Posterior Medial
	Uninjured	Anterior, Anterior Lateral, Anterior Medial, Lateral, Medial, Posterior, Posterior Lateral, Posterior Medial

Table 5.2: Legs and Directions for Pathological Subjects
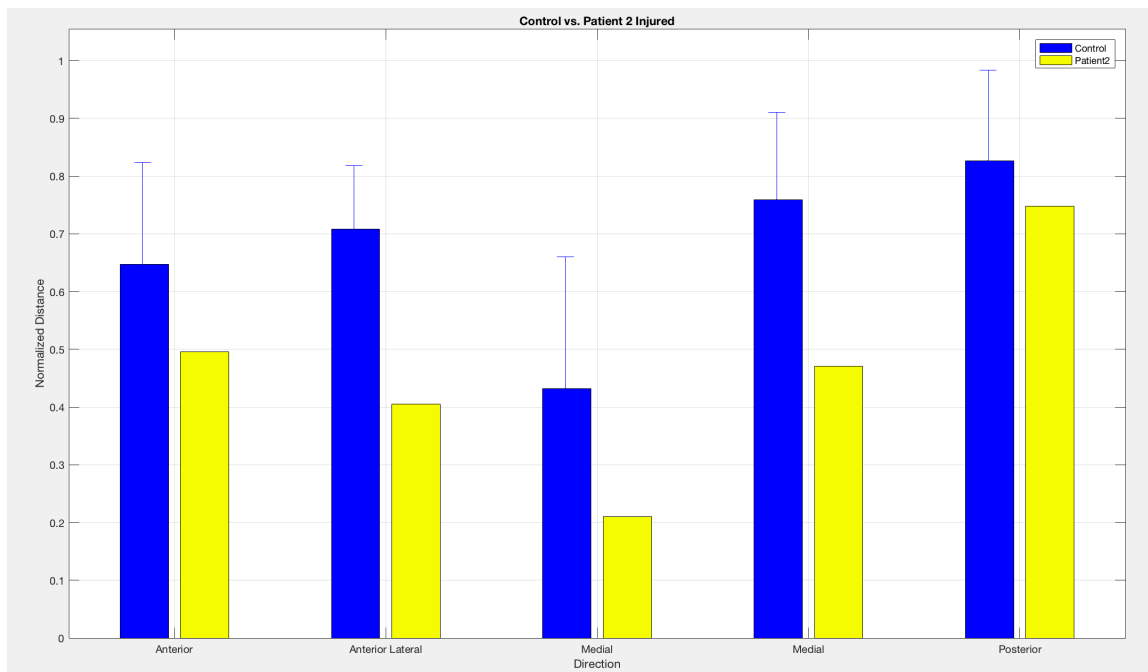
Figure 5.4: Control versus Patient 2's Injured Leg
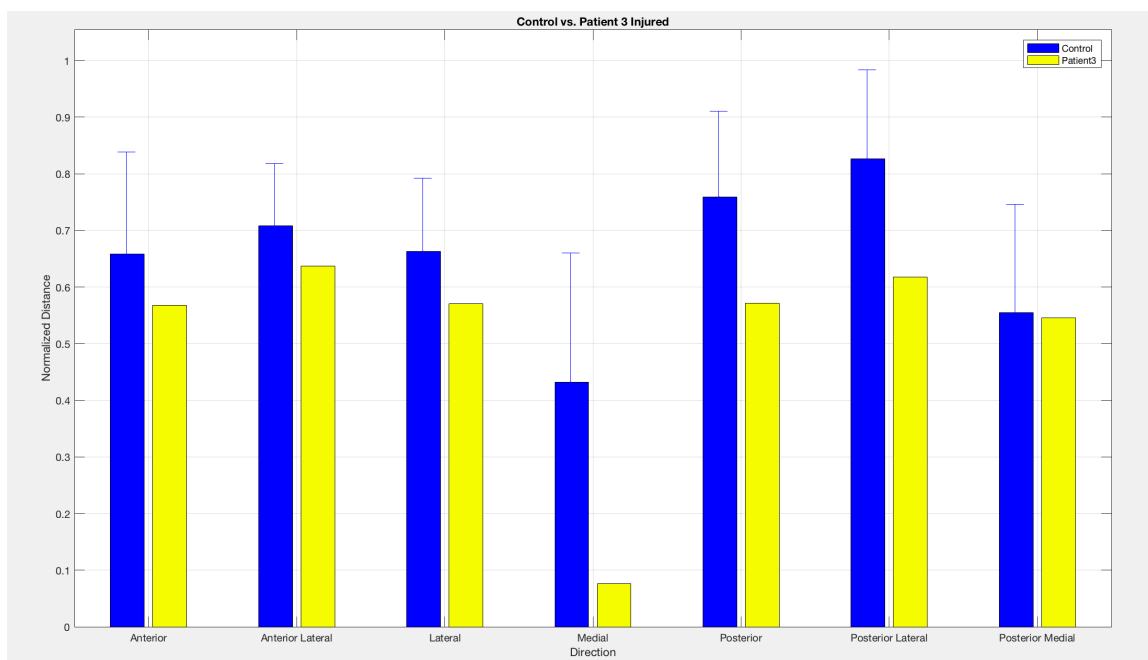
Figure 5.5: Control versus Patient 3's Injured Leg

In Figure 5.4 and Figure 5.5, the normalized reach distance of the control group is compared to that of Patient 2 and Patient 3's injured leg, respectively. In all directions, the control group achieved farther distances than either of the pathological subjects.
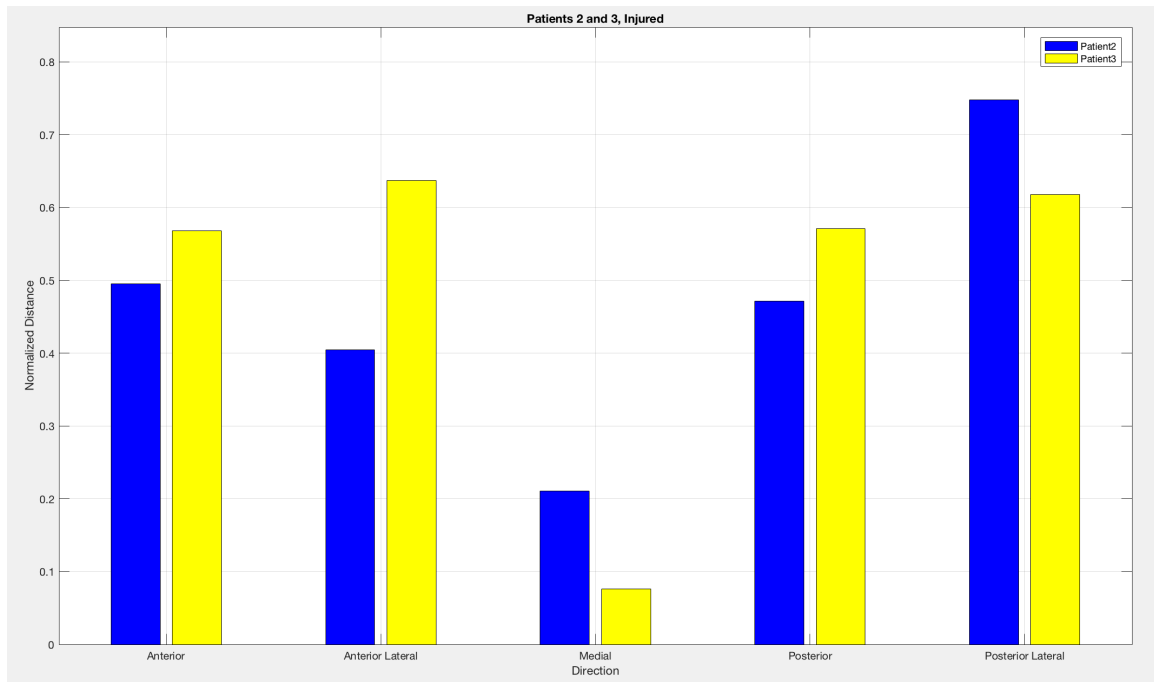
Figure 5.6: Patient 2 versus Patient 3 Injured Legs

When comparing the normalized reach distance of Patient 2 and 3's injured legs in Figure 5.6, Patient 3 has a longer reach distance in the Anterior, Anterior Lateral and Posterior directions, while Patient 2 reaches further in the Medial and Posterior Lateral directions.
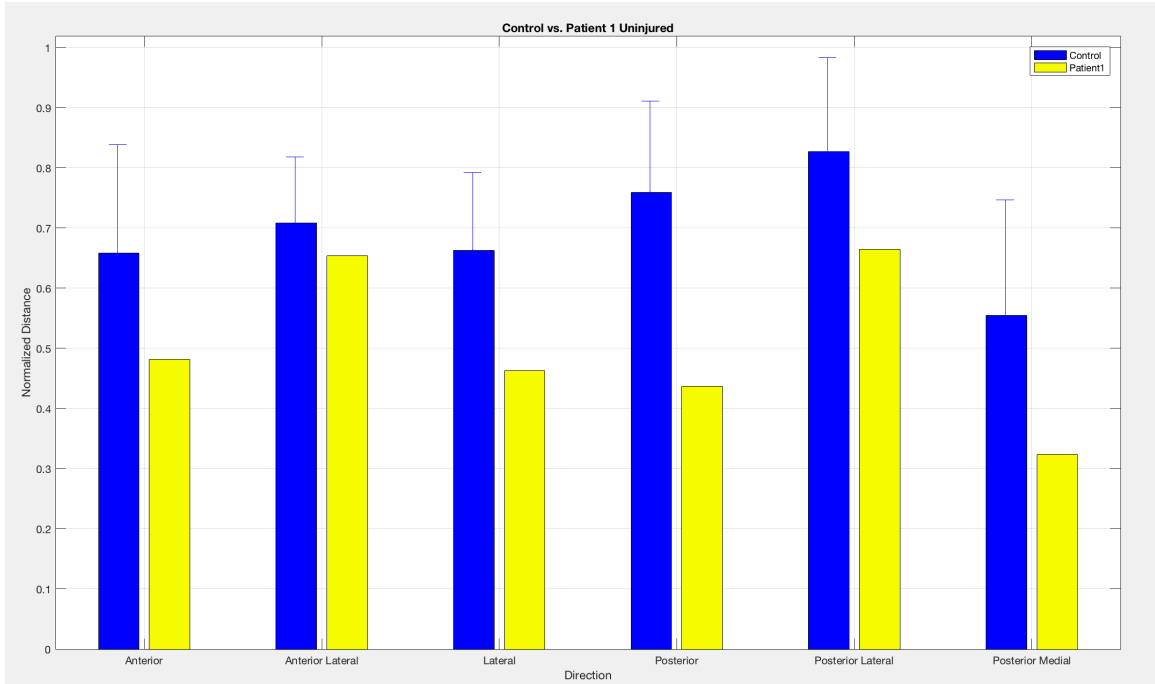
Figure 5.7: Control versus Patient 1's Uninjured Leg
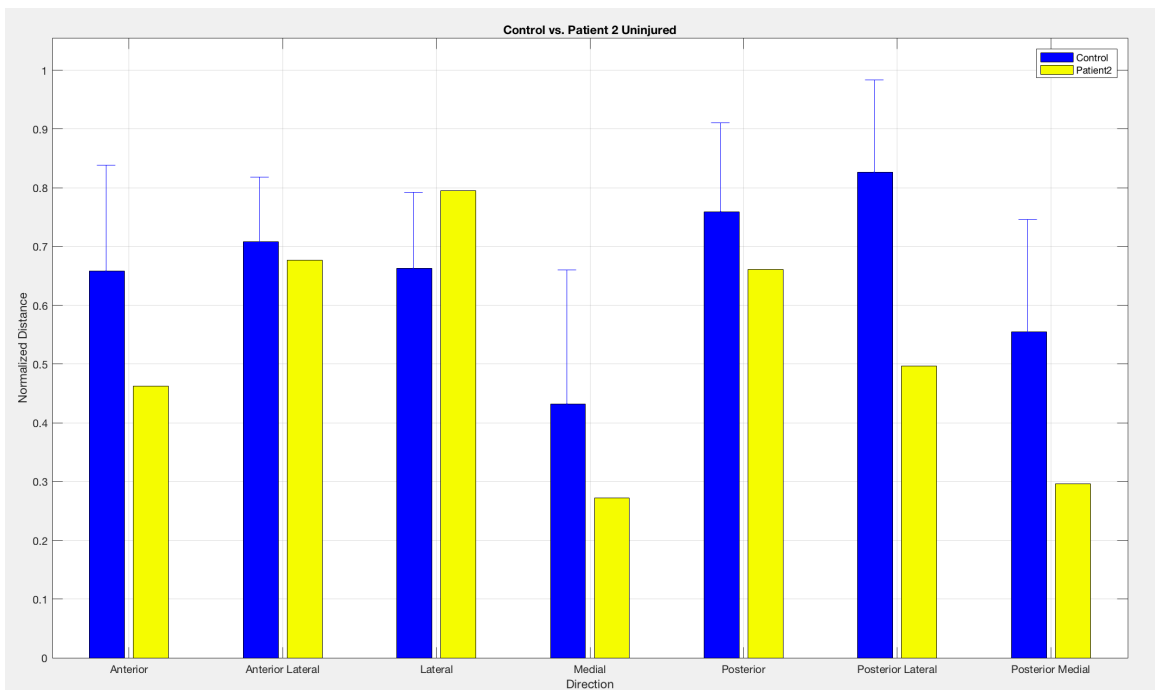
Figure 5.8: Control versus Patient 2's Uninjured Leg
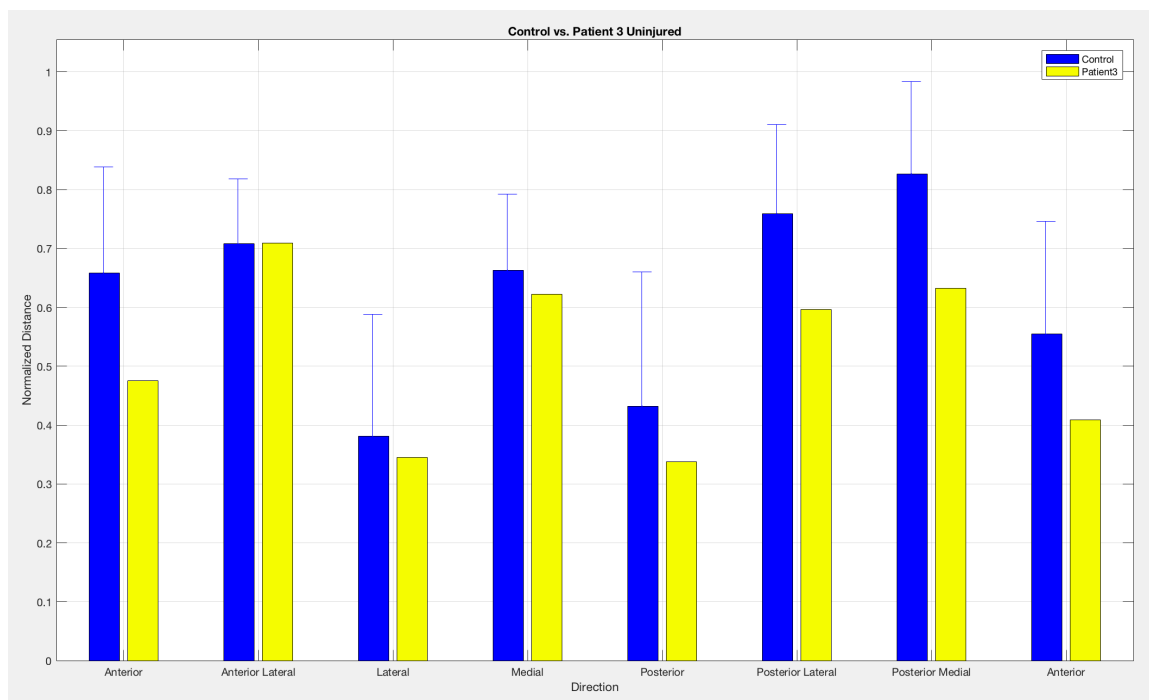
Figure 5.9: Control versus Patient 3's Uninjured Leg

The normalized reach distance of the control group versus that of each of the three ACL patients using their uninjured leg as the stance leg are shown in Figures 5.7, 5.8 and 5.9. With the exception of the Patient 2 in the Lateral direction and Patient 3 in the Anterior Lateral direction, all trials for the pathological subjects reached a distance less than the control group.
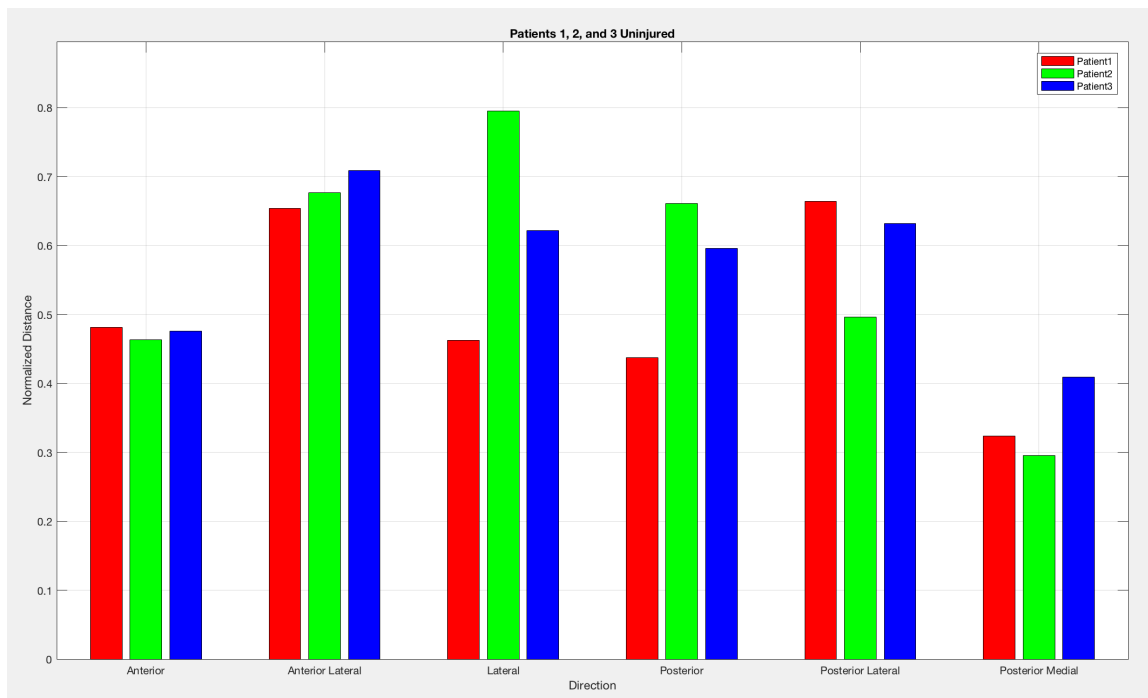
Figure 5.10: All Patients, Uninjured Leg

The normalized reach distance reached for the uninjured leg of all pathological subjects is compared in Figure 5.10. Patient 3 performed at or near the top for all but one direction, while Patient 1 had shorter distances on average.
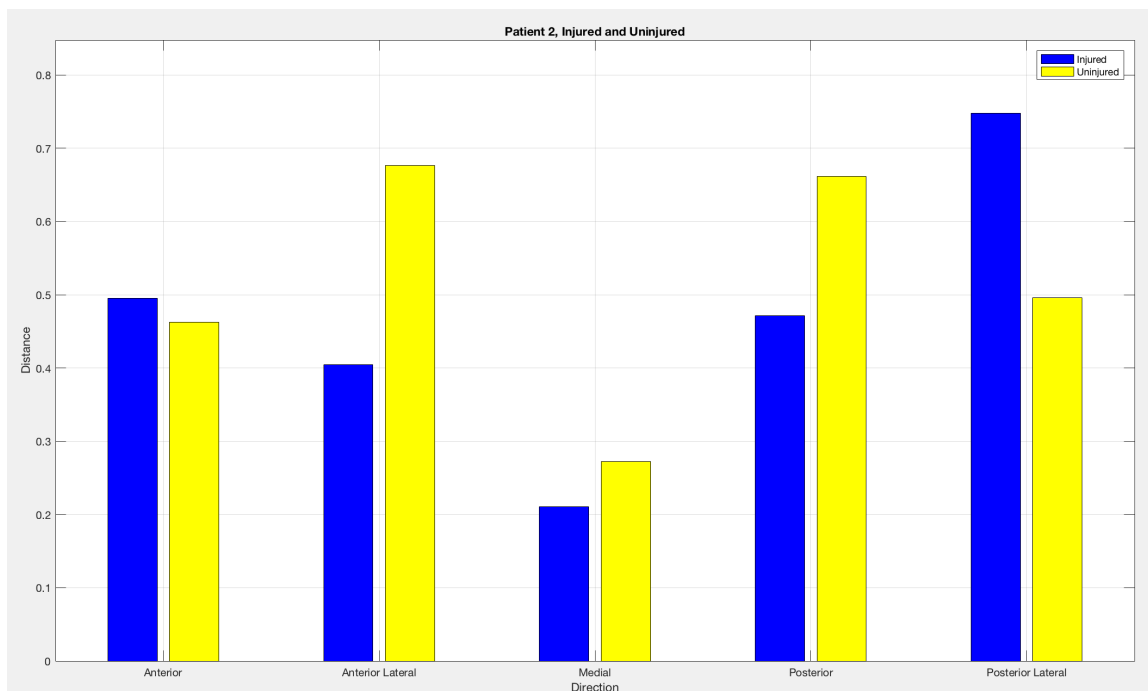
Figure 5.11: Patient 2, Injured versus Uninjured Leg

Figure 5.11 shows the normalized reach distance for Patient 2, using their injured and uninjured leg as the stance leg. In most directions, the injured leg performed worse or equal to the uninjured leg. The Posterior Lateral direction is the only direction where the injured leg outperformed the uninjured leg.
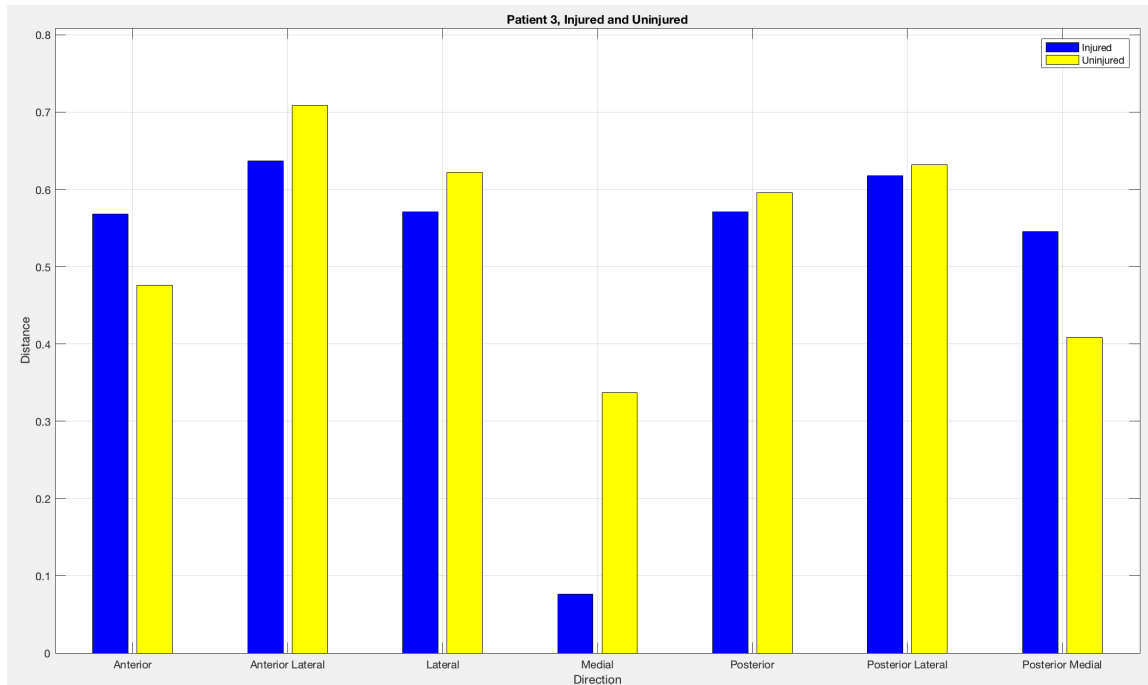
Figure 5.12: Patient 3, Injured versus Uninjured Leg

Figure 5.12 shows the normalized reach distance for Patient 3, using their injured and uninjured leg as the stance leg. In most directions, the uninjured leg outperformed the injured leg, with the exceptions being the Anterior and Posterior Medial directions.

Chapter 6

Discussion

Validation of Kinect© versus Vicon

Ten control subjects were recorded performing the Star Excursion Balance Test by both the Kinect© and Vicon systems in order to validate the Kinect© with a state of the art motion capture system. Each of the eight directions was performed twice, resulting in 16 trials per subject, and 20 total trials per direction. However, if the Kinect© recorded less than ten relevant data points, the trial was discarded. With this, it is clear that some directions are more easily identified and recorded by the Kinect© than others (Table 5.1). For example, the Lateral direction had 19 trials, meaning only one trial in that direction was unusable. On the other hand, the Medial direction had only 6 trials, meaning a large number of trials in that direction were not usable. This would lead to the hypothesis that SEBT trials where the moving leg moves away from the stance leg are more easily and accurately captured. This is reflected in Figure 5.1, where trials that had medial movement (Anterior Medial, Medial, Posterior Medial) have the largest disparity from the Vicon data, while those trials with lateral movement (Anterior Lateral, Lateral, Posterior Lateral) more closely align with the Vicon data.

When examining the error of the Kinect© data against the Vicon data in Figure 5.2, the maximum error is about 20%, with the highest error for each direction occurring at about 30% of the movement. This is consistent with the findings in the literature (Clark et al., 2012). Although there are no concrete guidelines as to what constitutes acceptable clinical error for kinematic measurements, it is important to note that the 20% error found may lead to a loss of subtle changes in position and posture, resulting in a loss of

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important kinematic data that may make it inappropriate for detailed research. However, this may be within an acceptable range for use as a tool for clinicians in determining the advancement of a patient through the process of rehabilitation (Pfister et al., 2014). For the purpose of this analysis and the scope of this research, this level of accuracy may be acceptable.

ACL Patients versus Controls

Three pathological subjects, two who were 3 weeks post-surgery and a third who was 3 months post-surgery, were recorded performing the Star Excursion Balance Test using the Kinect©. Each direction was recorded once, with the subject performing the test with both their injured and uninjured leg. Patient 1 was not able to perform the SEBT using their injured leg as the stance leg, so only the uninjured leg was recorded. Also, if the Kinect© recorded less than ten relevant data points, then the trial was discarded. This reaffirmed the difficulty of recording trials in the medial directions, as those were the trials that most often were unusable, with the Anterior Medial direction being usable in only one of the five attempts (Table 5.2).

When comparing the reach distance of Patients 2 and 3 with the mean reach distance of the control group, the pathological subjects reached shorter distances in all directions (Figures 5.4, 5.5). This confirms the hypothesis that a subject with an ACL injury and reconstruction will not perform the SEBT as well as a healthy subject. In Figure 5.6, the reach distances for Patients 2 and 3 with their injured legs are compared against each other. In the Anterior, Anterior Lateral and Posterior directions, Patient 3 had a longer reach distance, while Patient 2 outperformed Patient 3 in the Medial and

Posterior Lateral directions. While the hypothesis was that a pathological subject further along in rehabilitation (Patient 3) would outperform a subject with less recovery time (Patient 2), this data shows that is not the case. However, with the small sample size and each patient's relative injury and rehabilitation protocol, this cannot be considered conclusive. In addition, differences in reach distance can be attributed to the flexibility and fitness level of the patients, which are more evident when comparing a small number of patients. The effects of fitness and flexibility of each patient would decrease with the increase in sample size following further experiments.

When compared with the control group, the pathological subject using their uninjured leg did not reach as far in all but two of twenty-one trials (Figures 5.7 - 5.9). This lends to the hypothesis that a pathological patient, even when using their healthy leg, would not reach as far a control group, perhaps due to neurophysiological factors. Figure 5.10 shows the reach distance of all three subjects, where no single subject outperforms the others. Again, this can be contributed to the small sample size, as well as each patient's relative injury and rehabilitation protocol. The comparison of Patient 2 and 3's injured leg to uninjured leg shows that neither subject had one leg that significantly outperformed the other. This may also be due to a difference in the patients' flexibility and fitness.

There are some limitations to this study that should be considered. First, the sample size for the pathological subjects is small, which does not allow for the reporting of statistics, as they would be irrelevant. Also, as Patient 1 could not perform the SEBT on their injured leg, there is no comparison between their injured and uninjured legs. The importance of inter-subject reliability must be stressed, as each subject may have had

suffered more or less severe injuries, affecting not only their performance of the SEBT, but also their overall rehabilitation and recovery timeline.

A factor that may have affected the results is the Kinect©'s potential trouble at obtaining accurate segment lengths, which could affect the calculation of leg length and in turn the normalized distance results (Bonnechere, Jansen, Salvia, Bouzahouene, Sholukha, et al., 2014).

Future Directions

Future directions of this study include recruiting more control subjects to better and more accurately validate the Kinect© with the Vicon system. More data would allow for more fine-tuning of the Kinect©, as well as allow for the formulation of a regression equation. More trials may also be beneficial to potentially capture some directions that have proven difficult to capture, such as the Medial direction.

In regards to comparing ACL injured subjects to controls, more pathological subjects should be included in the study to be able to expand upon the current data so that more relevant statistics can be run. Also, just as the Y test has been developed for the study of ankle instability, a similar test could be formulated that reduces the number of directions needed to determine the progress of rehabilitation of the subject (Gribble et al., 2012). If it could be determined that performance in a smaller number of directions correlates with a subject's performance for all direction in the SEBT, it is possible that some directions that are difficult to capture may be eliminated.

Appendix A

Kinect_Setup

```matlab
clear all
clc

% Add necessary functions to the MATLAB path.
utilpath = fullfile(matlabroot, 'toolbox', 'imaq', 'imaqdemos', ...
    'html', 'KinectForWindows');
addpath(utilpath);

% Check that the Kinect is being read and that both cameras are
% operational.
hwInfo = imaqhwinfo('kinect');
hwInfo.DeviceInfo(1);
hwInfo.DeviceInfo(2);

% Create objects for the two streams.
colorVid = videoinput('kinect',1);
depthVid = videoinput('kinect',2);

% Set trigger mode to 'manual' and set the amount of frames per
trigger.
% Infinite frames per trigger allows the Kinect to log data
continuously
% until the 'stop' funtion is given.
triggerconfig([colorVid depthVid], 'manual');
colorVid.FramesPerTrigger = inf;
colorVid.Triggerrepeat = 0;
depthVid.FramesPerTrigger = inf;
depthVid.Triggerrepeat = 0;

% Change the FrameGrabInterval to allow the system to keep up with data
% from the incoming video stream.
colorVid.FrameGrabInterval = 1;
depthVid.FrameGrabInterval = 1;

% Enable skeletal tracking.
depthSrc = getselectedsource(depthVid);
depthSrc.EnableBodyTracking = 'on';
```

Appendix B

Kinect_Acquire

```matlab
function Kinect_Acquire(filename)
%% Log Data

sheet = 1;

for i = 1:1

    % Begin camera input.
    start([colorVid depthVid]);
    disp('Press any key to begin caputring data.');
    pause();

    % Trigger camera to log data on user prompt.
    trigger([colorVid depthVid]);
    disp('Press any key to end data capture.');
    pause();

    % Stop camera input and logging on user prompt.
    stop([colorVid depthVid]);

    %% Acquire Data

    % Acquire data from camera.
    [~,colorTimeData,colorMetaData] = getdata(colorVid);

    [~,depthTimeData,depthMetaData] = getdata(depthVid);

    % Convert data from structure to cell.
    a = struct2cell(depthMetaData);

    % Convert joint data from cell to scalar.
    b = a(12,:)';
    c = cell2mat(b);

    % Search depthMetaData.IsBodyTracking to determine the skeleton
being
    % tracked.
    x = 1;
    n = 0;
    while n == 0
        n = c(:,:,x);
        if n == 0
            x = x+1;
        end
    end

    % Select the skeleton from the joint data.
    d = c(:,:,x);

    % Convert frame numbers from cell to scalar.
    g = a(6,:)';
```

```matlab
    h = cell2mat(g);

% Write logged data into an Excel file with specified sheet.
    xlswrite(filename, d, sheet, 'B1');
    xlswrite(filename, h, sheet, 'A1');


end
```

Appendix C

Kinect_Aesthetic

```matlab
%%% This program takes the "JointWorldCoordinate" data from the Kinect
and
%%% outputs to an Excel file, in a form similar to the output of Vicon.
%%% This is purely for aesthetic reasons, and is not necessary.

function Kinect_Aesthetic(trial)
%%
tic
% Read in Kinect data.
% trial = 'L_Ant';
kinect_data = xlsread(strcat(trial, '.csv'));

% Create output file name.
filename = strcat(trial, '_C.csv');

% Create headers for the Excel file.
header1 = {'Frame', 'Spine Base', '', '', 'Spine Mid', '', '', ...
    'Neck', '', '', 'Head', '', '', 'Left Shoulder', '', '', ...
    'Left Elbow', '', '', 'Left Wrist', '', '', 'Left Hand', '', '',
...
    'Right Shoulder', '', '', 'Right Elbow', '', '', 'Right Wrist', '',
'', ...
    'Right Hand', '', '', 'Left Hip', '', '', 'Left Knee', '', '', ...
    'Left Ankle', '', '', 'Left Foot', '', '', 'Right Hip', '', '', ...
    'Right Knee', '', '', 'Right Ankle', '', '', 'Right Foot', '',
''...
    'Spine Shoulder', '', '', 'Left Hand Tip', '', '', 'Left Thumb',
'', '',...
    'Right Hand Tip', '', '', 'Right Thumb', '', ''};
header2 = {'', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y',
'Z', ...
    'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', ...
    'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', ...
    'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', ...
    'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z',...
    'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z', 'X', 'Y', 'Z',...
    'X', 'Y', 'Z'};

% Find the number of frames in the trial
frames = kinect_data(:,1);
frames = frames(~isnan(frames));


% Preallocate variables.
[Spine_Base, Spine_Mid, Neck, Head, Left_Shoulder, Left_Elbow,...
    Left_Wrist, Left_Hand, Right_Shoulder, Right_Elbow, Right_Wrist,...
    Right_Hand, Left_Hip, Left_Knee, Left_Ankle, Left_Foot,
Right_Hip,...
    Right_Knee, Right_Ankle, Right_Foot, Spine_Shoulder,
Left_Hand_Tip,...
    Left_Thumb, Right_Hand_Tip, Right_Thumb] =
deal(zeros(length(frames),3));
```

```matlab
% Assign joint data to variables.
for i = 1:length(frames)

    Spine_Base(i,1:3) = kinect_data(((i*25)-24),2:4);
    Spine_Mid(i,1:3) = kinect_data(((i*25)-23),2:4);
    Neck(i,1:3) = kinect_data(((i*25)-22),2:4);
    Head(i,1:3) = kinect_data(((i*25)-21),2:4);
    Left_Shoulder(i,1:3) = kinect_data(((i*25)-20),2:4);
    Left_Elbow(i,1:3) = kinect_data(((i*25)-19),2:4);
    Left_Wrist(i,1:3) = kinect_data(((i*25)-18),2:4);
    Left_Hand(i,1:3) = kinect_data(((i*25)-17),2:4);
    Right_Shoulder(i,1:3) = kinect_data(((i*25)-16),2:4);
    Right_Elbow(i,1:3) = kinect_data(((i*25)-15),2:4);
    Right_Wrist(i,1:3) = kinect_data(((i*25)-14),2:4);
    Right_Hand(i,1:3) = kinect_data(((i*25)-13),2:4);
    Left_Hip(i,1:3) = kinect_data(((i*25)-12),2:4);
    Left_Knee(i,1:3) = kinect_data(((i*25)-11),2:4);
    Left_Ankle(i,1:3) = kinect_data(((i*25)-10),2:4);
    Left_Foot(i,1:3) = kinect_data(((i*25)-9),2:4);
    Right_Hip(i,1:3) = kinect_data(((i*25)-8),2:4);
    Right_Knee(i,1:3) = kinect_data(((i*25)-7),2:4);
    Right_Ankle(i,1:3) = kinect_data(((i*25)-6),2:4);
    Right_Foot(i,1:3) = kinect_data(((i*25)-5),2:4);
    Spine_Shoulder(i,1:3) = kinect_data(((i*25)-4),2:4);
    Left_Hand_Tip(i,1:3) = kinect_data(((i*25)-3),2:4);
    Left_Thumb(i,1:3) = kinect_data(((i*25)-2),2:4);
    Right_Hand_Tip(i,1:3) = kinect_data(((i*25)-1),2:4);
    Right_Thumb(i,1:3) = kinect_data(((i*25)),2:4);

end

% Create output data.
output = [Spine_Base, Spine_Mid, Neck, Head, Left_Shoulder,
Left_Elbow,...
    Left_Wrist, Left_Hand, Right_Shoulder, Right_Elbow, Right_Wrist,...
    Right_Hand, Left_Hip, Left_Knee, Left_Ankle, Left_Foot,
Right_Hip,...
    Right_Knee, Right_Ankle, Right_Foot, Spine_Shoulder,
Left_Hand_Tip,...
    Left_Thumb, Right_Hand_Tip, Right_Thumb];


% Export everything to Excel.
xlswrite(filename, frames, 1, 'A3');
xlswrite(filename, output, 1, 'B3');
xlswrite(filename, header1, 1, 'A1');
xlswrite(filename, header2, 1, 'A2');

toc
```

Appendix D

Mass_Aesthetic

```matlab
function Mass_Aesthetic(trial_type)

if strcmp(trial_type, 'control') == 1

    trials = {'R_Ant','R_AntLat', 'R_AntMed','R_Lat', 'R_Med',...
        'R_Pos', 'R_PosLat', 'R_PosMed','R_Ant2','R_AntLat2',
'R_AntMed2',...
        'R_Lat2', 'R_Med2','R_Pos2', 'R_PosLat2', 'R_PosMed2',};

    for n = 1:length(trials)
        trial = trials{n};

        Kinect_Aesthetic(trial)
    end
end

if strcmp(trial_type, 'patient') == 1

    trials = {'R_Ant','R_AntLat', 'R_AntMed','R_Lat', 'R_Med',...
        'R_Pos', 'R_PosLat', 'R_PosMed', 'L_Ant','L_AntLat',
'L_AntMed',...
        'L_Lat','L_Med', 'L_Pos', 'L_PosLat', 'L_PosMed'};

    for n = 1:length(trials)
        trial = trials{n};

        Kinect_Aesthetic(trial)
    end
end
```

Appendix E

Export_Stats

```matlab
function Export_Stats(trial_type, subject_name)

if strcmp(trial_type, 'control') == 1

    trials = {'R_Ant', 'R_Ant2', 'R_AntLat', 'R_AntLat2',...
        'R_AntMed', 'R_AntMed2', 'R_Lat','R_Lat2',  'R_Med',
'R_Med2',...
        'R_Pos','R_Pos2', 'R_PosLat', 'R_PosLat2', 'R_PosMed',
'R_PosMed2'};


    for n = 1:length(trials)
        trial = trials{n};

        kinect_trial = strcat(trial, '_C.csv');
        vicon_trial = strcat(trial, '_V.csv');
        export_sheet = strcat(subject_name, '_', trial, '.xls');

        Export_Data(export_sheet, kinect_trial, vicon_trial);
    end

end

if strcmp(trial_type, 'patient') == 1

    trials = {'R_Ant','R_AntLat', 'R_AntMed','R_Lat', 'R_Med',...
        'R_Pos', 'R_PosLat', 'R_PosMed', 'L_Ant','L_AntLat',
'L_AntMed',...
        'L_Lat','L_Med', 'L_Pos', 'L_PosLat', 'L_PosMed'};

    for n = 1:length(trials)
        trial = trials{n};

        kinect_trial = strcat(trial, '_C.csv');
        export_sheet = strcat(subject_name, '_', trial, '.xls');

        Export_Data(export_sheet, kinect_trial);
    end

end
```

Appendix F

Export_Data

```matlab
function Export_Data(filename, trial1, trial2)
tic

% Run Export_Kinect to receive Kinect data
Export_Kinect(trial1, filename)

% If there is a Vicon trial, it will be added. If not, it will be
skipped.
if nargin == 3
    Export_Vicon(trial2, filename)
end

% Unsupress figures so that future figures are not effected.
set(0, 'DefaultFigureVisible', 'on');

% Save the figure as an image and find its directory.
img = 'plot.png';
print('-dpng', img);
file = strcat('C:\Users\Andy\Documents\MATLAB\', filename);

% Open Excel and add the image of the figure to the sheet.
Excel = actxserver('Excel.Application');
Excel.Visible = 1;
Workbook = Excel.Workbooks.Open(file);
eSheets = Excel.ActiveWorkbook.Sheets;
eSheet1 = eSheets.get('Item',1);
eSheet1.Activate

eSheet1.Shapes.AddPicture([pwd '\' img], 0,1,400,75,350,235);

% Save the worksheet and close Excel.
SaveAs(Workbook, file)
Workbook.Saved = 1;
Close(Workbook)
Quit(Excel)
delete(Excel)

toc
```

Appendix G

Export_Kinect

```matlab
%Export_Kinect(trial,filename)
% This function reads in Kinect joint data and exports the relevant
data to
% and Excel sheet for further processing. This function is to be used
in
% conjunction with the 'Export_Vicon' function.
%
%    'trial': string, the name of the Kinect trial being read in.
%    'filename': string, the name of the exported Excel file.

function Export_Kinect(trial, filename)

% Write the titles to the Excel sheet.
xlswrite(filename, {'Kinect'}, 1, 'T1');


line1 = {'Left Foot', '', '', '', 'Right Foot', '', '', 'Distance',...
    'Max Distance', 'True Distance', 'Normalized Distance', 'Percent of
Motion',...
    'Leg Length', 'Normalized by Leg Length'};
line2 = {'X', 'Y', 'Z', '', 'X', 'Y', 'Z'};

xlswrite(filename, line1, 1, 'Q2');
xlswrite(filename, line2, 1, 'Q3');

% Read in the data.
sheet = xlsread(trial);

% Extract the relevant data.
L_foot = sheet(:,47:49);
R_foot = sheet(:,59:61);
L_hip = sheet(:,38:40);
L_ank = sheet(:,44:46);
R_hip = sheet(:,50:52);
R_ank = sheet(:,56:58);


% Create variables for X, Y, and Z.
Lx = L_foot(:,1);
Ly = L_foot(:,2);
Lz = L_foot(:,3);
Rx = R_foot(:,1);
Ry = R_foot(:,2);
Rz = R_foot(:,3);
L_hip_x = L_hip(:,1);
L_hip_y = L_hip(:,2);
L_hip_z = L_hip(:,3);
R_hip_x = R_hip(:,1);
R_hip_y = R_hip(:,2);
R_hip_z = R_hip(:,3);
L_ank_x = L_ank(:,1);
L_ank_y = L_ank(:,2);
L_ank_z = L_ank(:,3);
```

```matlab
R_ank_x = R_ank(:,1);
R_ank_y = R_ank(:,2);
R_ank_z = R_ank(:,3);

% Find the distance and write it to the Excel sheet.
dist = sqrt((Lx-Rx).^2 + (Ly-Ry).^2 + (Lz-Rz).^2);
leg_dist_l = sqrt((L_hip_x-L_ank_x).^2 + (L_hip_y-L_ank_y).^2 +...
    (L_hip_z-L_ank_z).^2);
leg_dist_r = sqrt((R_hip_x-R_ank_x).^2 + (R_hip_y-R_ank_y).^2 +...
    (R_hip_z-R_ank_z).^2);

% Find the maximum distance and write it to the Excel sheet.
max_dist = max(dist);

max_dist_l = max(leg_dist_l);
max_dist_r = max(leg_dist_r);

leg_length = max_dist_l;

leg_dist = dist/leg_length;

% Find where in the distance array the maximum distances is.
stop_here = find(dist==max_dist);

% This loop is used to find when the motion starts.
check = false;
for i = 1:stop_here-1
    if check == false
        k = 0;
        % Find if the distance changes at least 10% between data
points.
        if (dist(i+1)-dist(i))/dist(i+1) >= 0.10
            start_here = dist(i);
            % See if the distance gets smaller over the next 10 points
compared
            % to 'start_here'.
            % This is used for the event of small movements before the
actual
            % start of the trial.
            for n = i:i+20
                % If all the distances are smaller than 'start_here',
break and
                % continue main for loop. If not, break out of all
loops.
                if dist(n) > dist(n+1)
                    k = k+1;
                    if k == 5
%                         check = true;
                        break
                    end
                elseif n == i+20
                    check = true;
                    break
                end
            end
        end
    end
end
```

```matlab
    end

% Reassign 'dist' to equal when the trial starts and ends at the
maximum
% distance.
dist2 = dist(find(dist==start_here):stop_here);
leg_dist2 = leg_dist(find(dist==start_here):stop_here);

% This loop accounts for random noise at the end of a trial that may
% effect the location of the maximum distance.
check = false;
for i = 1:length(dist2)
    if check == false
        k = 0;
        % If the data set contains a distance smaller than the one that
starts
        % the trial, that point is the new end. A new max is found, and
a new
        % array is formed from the start of the trials to the new max.
        if dist2(1) > dist2(i)
            for n = i:i+10
                if dist2(1) > dist2(n)
                    k = k+1;
                    if k == 10
                        check = true;
                        new_stop = find(dist2==dist2(i));
                        new_max = max(dist2(1:new_stop));
                        stop_here = find(dist2==new_max);
                        dist3 = dist2(1:stop_here);
                        leg_dist3 = leg_dist2(1:stop_here);
                        break

                    end
                end
            end
        end
    end
end

% Find the true distance, i.e. the start of the trial = 0.
% This is dependant on whether the loop immediately above this was
used.
if 1 == exist('dist3', 'var')
    true_dist = dist3 - start_here;
    leg_true = leg_dist3 - leg_dist2(1);
else
    true_dist = dist2 - start_here;
    leg_true = leg_dist2 - leg_dist2(1);
end

% Find the maximum of the true distance and the normalized distance.
max_dist = max(true_dist);
norm_dist = true_dist/max_dist;

% Attribute each data point to a certain percentage of the movement.
percent_motion = zeros(length(norm_dist),1);
for i = 2:length(norm_dist)
```

```matlab
        percent_motion(i) = percent_motion(i-1)+(1/(length(norm_dist)-1));

end
percent_motion = percent_motion*100;

% Find the location of start of the trial in relation to the 'dist'
array.
% This is where the data will be written in the Excel sheet.
location = find(dist==dist2(1))+3;
loc = num2str(location);
true_loc = strcat('Z',loc);
norm_loc = strcat('AA',loc);
pm_loc = strcat('AB',loc);
leg_loc = strcat('AD',loc);

% Write the data into the new Excel sheet.
xlswrite(filename, L_foot, 1, 'Q4');
xlswrite(filename, R_foot, 1, 'U4');
xlswrite(filename, dist, 1, 'X4');
xlswrite(filename, max_dist, 1, 'Y4')
xlswrite(filename, true_dist, 1, true_loc);
xlswrite(filename, norm_dist, 1, norm_loc);
xlswrite(filename, percent_motion, 1, pm_loc);
xlswrite(filename, leg_length, 1, 'AC4')
xlswrite(filename, leg_true, 1, leg_loc)


% Plot a scatter plot of the 'norm_dist' data against the percent of
% motion.
scatter(percent_motion, norm_dist, 'filled')
grid on
hold on
```

Appendix H
Export_Vicon

```matlab
%Export_Vicon(trial,filename)
% This function reads in Kinect joint data and exports the relevant data to
% and Excel sheet for further processing. This function is to be used in
% conjunction with the 'Export_Kinect' function.
%
%    'trial': string, the name of the Kinect trial being read in.
%    'filename': string, the name of the exported Excel file.


function Export_Vicon(trial, filename)
%%
% Write the titles to the Excel sheet.
xlswrite(filename, {'Vicon'}, 1, 'D1');

line1 = {'Left Foot', '', '', '', 'Right Foot', '', '', 'Distance',...
    'Max Distance', 'True Distance', 'Normalized Distance', 'Percent of
Motion'};
line2 = {'X', 'Y', 'Z', '', 'X', 'Y', 'Z'};

xlswrite(filename, line1, 1, 'A2');
xlswrite(filename, line2, 1, 'A3');


%%
% Read in the data and find the total length.
sheet = xlsread(trial);
l = length(sheet);

% Extract the relevant data.
L_foot = sheet(5:l,30:32);
R_foot = sheet(5:l,48:50);

% Create variables for X, Y, and Z.
Lx = L_foot(:,1);
Ly = L_foot(:,2);
Lz = L_foot(:,3);
Rx = R_foot(:,1);
Ry = R_foot(:,2);
Rz = R_foot(:,3);

% Find the distance and write it to the Excel sheet.
dist = sqrt((Lx-Rx).^2 + (Ly-Ry).^2 + (Lz-Rz).^2);

% Find the maximum distance and write it to the Excel sheet.
max_dist = max(dist);

% Find where in the distance array the maximum distances is.
stop_here = find(dist==max_dist);

% This loop is used to find when the motion starts.
check = false;
for i = 1:stop_here-1
```

```matlab
    if check == false
        % Find if the distance changes at least 1% between data points.
        if (dist(i+1)-dist(i))/dist(i+1) >= 0.01
            start_here = dist(i);
            % See if the distance gets smaller over the next 10 points compared
            % to 'start_here'.
            % This is used for the event of small movements before the actual
            % start of the trial.
            for n = i:i+10
                % If there is a distance smaller than 'start_here', break and
                % continue main for loop. If not, break out of all loops.
                if dist(n) > dist(n+1)
                    break
                elseif n == i+10
                    check = true;
                    break
                end
            end
        end
    end
end

% Reassign 'dist' to equal when the trial starts and ends at the maximum
% distance.
dist2 = dist(find(dist==start_here):stop_here);

% This loop accounts for random noise at the end of a trial that may
% effect the location of the maximum distance.
for i = 1:length(dist2)
    % If the data set contains a distance smaller than the one that starts
    % the trial, that point is the new end. A new max is found, and a new
    % array is formed from the start of the trials to the new max.
    if dist2(1) > dist2(i)
        new_stop = find(dist2==dist2(i));
        new_max = max(dist2(1:new_stop));
        stop_here = find(dist2==new_max);
        dist3 = dist2(1:stop_here);
        break
    end
end

% Find the true distance, i.e. the start of the trial = 0.
% This is dependant on whether the loop immediately above this was used.
if 1 == exist('dist3', 'var')
    true_dist = dist3 - start_here;
else
    true_dist = dist2 - start_here;
end
```

```matlab
% Find the maximum of the true distance and the normalized distance.
max_dist = max(true_dist);
norm_dist = true_dist/max_dist;

% Attribute each data point to a certain percentage of the movement.
percent_motion = zeros(length(norm_dist),1);
for i = 2:length(norm_dist)

    percent_motion(i) = percent_motion(i-1)+(1/(length(norm_dist)-1));

end
percent_motion = percent_motion*100;

% Find the location of start of the trial in relation to the 'dist'
array.
% This is where the data will be written in the Excel sheet.
location = find(dist==dist2(1))+3;
loc = num2str(location);
true_loc = strcat('J',loc);
norm_loc = strcat('K',loc);
pm_loc = strcat('L',loc);

% Write the data into the new Excel sheet.
xlswrite(filename, L_foot, 1, 'A4');
xlswrite(filename, R_foot, 1, 'E4');
xlswrite(filename, dist, 1, 'H4');
xlswrite(filename, max_dist, 1, 'I4')
xlswrite(filename, true_dist, 1, true_loc);
xlswrite(filename, norm_dist, 1, norm_loc);
xlswrite(filename, percent_motion, 1, pm_loc);

% Supress figure from appearing on the screen.
set(0, 'DefaultFigureVisible', 'off');

% Plot the line of 'norm_dist' against the percent of motion.
plot(percent_motion, norm_dist, 'r', 'LineWidth', 4, 'Color', [1 0.5
0])
axis([0 120 0 1.2])
hold off
```

Appendix I

Control_Average_Graph

```matlab
%Control_Average_Graph
% This function averages the data of Kinect and Vicon for all trials in
% each direction and graphs the comparison.

function Control_Average_Graph

% The trials that will be read in.
trials = {'R_Ant','R_Ant2', 'R_AntLat', 'R_AntLat2' 'R_AntMed',
'R_AntMed2',...
    'R_Lat', 'R_Lat2', 'R_Med', 'R_Med2','R_Pos', 'R_Pos2',...
    'R_PosLat', 'R_PosLat2', 'R_PosMed', 'R_PosMed2'};

% FOR loop for the amount of trials so that every trial type is done
% seperately.
for i = 1:length(trials)

    % Create the search term and find the appropriate files.
    trial = trials{i};
    search =
strcat('/Users/AndyAlvarez/Documents/MATLAB/*',trial,'.xls');
    list = dir(search);

    % Convert from structure to cell.
    a = struct2cell(list);
    names = a(1,:);

    % Find the amount of trials there are in this trial type.
    total_trials(i) = length(names);

    % FOR loop that will create matrices to hold the outputs from
    % Error_Calc.
    for n = 1:length(names)

        [Err(:,n), devi(n), total_kin(i,:), total_vic(i,:)] =
Error_Calc(names(n));

    end
end

% Transpose 'total_kin' and 'total_vic' for ease in following
procedures.
total_kin = total_kin';
total_vic = total_vic';

% Find the mean of both the Kinect and Vicon data for each direction.
for n = 1:2:length(trials)

    com_kin(:,(n+1)/2) = mean(total_kin(:,n:n+1),2);
    com_vic(:,(n+1)/2) = mean(total_vic(:,n:n+1),2);

end
```

```matlab
% Graph the mean Kinect and Vicon data together for each direction.
nike = (10:10:90)';
for n = 1:min(size(com_kin))

    figure(1)
    subplot(4,2,n)
    plot(nike, com_vic(:,n), 'r', 'LineWidth', 4, 'Color', [1 0.5 0])
    hold on
    grid on
    scatter(nike, com_kin(:,n), 'filled')
    ylabel('True Distance')
    xlabel('Percent of Motion')
    axis([0 95 0 1.2])

end

% Put titles on each of the subplots.
subplot(4,2,1)
title('Anterior')
subplot(4,2,2)
title('Anterior Lateral')
subplot(4,2,3)
title('Anterior Medial')
subplot(4,2,4)
title('Lateral')
subplot(4,2,5)
title('Medial')
subplot(4,2,6)
title('Posterior')
subplot(4,2,7)
title('Posterior Lateral')
subplot(4,2,8)
title('Posterior Medial')
```

Appendix J

Error_Calc

```matlab
%[Err, devi, total_kin, total_vic] = Error_Calc(name)
% This function takes Kinect and Vicon data and determines the percent
% error and standard deviation of the errors at 10:10:90% of the
% movement.
%
%INPUTS:
%   'name': string, the name of the trial being processed. Should match
the name of
%           the .xlsx file that will be read in.
%
%OUTPUTS:
%   'Err': 1x9 matrix, the error at 10:10:90% of the movement.
%   'devi': double, the standard deviation of the error values.
%   'total_kin': 9x1 matrix, the Kienct data at 10:10:90% of the
movement.
%   'total_vic': 9x1 matrix, the Vicon data at 10:10:90% of the
movement.

function [Err, devi, total_kin, total_vic] = Error_Calc(name)
trial = char(name);


%%
% Read in the trial and extract the relevant data.
sheet = xlsread(trial);
sheet(isnan(sheet)) = 0;

[v, x, y, z] = deal(1);
for i = 1:length(sheet)

    if sheet(i,28) ~= 0
        kinect_per(v) = sheet(i,28);
        v = v+1;
    end

    if sheet(i,27) ~= 0
        kinect_norm(x) = sheet(i,27);
        x = x+1;
    end

    if sheet(i,12) ~= 0
        vicon_per(y) = sheet(i,12);
        y = y+1;
    end

    if sheet(i,11) ~= 0
        vicon_norm(z) = sheet(i,11);
        z = z+1;
    end
end

n = 1;
for i = 9.5:10:89.5
```

```matlab
    kin_location(n) = find(i <= kinect_per, 1, 'first');
    n = n+1;

end

for i = 1:n-1

    new_per(i) = kinect_per(kin_location(i));

end

kinect_per = new_per;


for i = 1:length(kin_location)

   kin(i) = kinect_norm(kin_location(i));
   total_kin(i,:) = kinect_norm(kin_location(i));


end

for i = 1:length(kinect_per)

    vic_location(i) = find(kinect_per(i) <= vicon_per, 1, 'first');
    new_per(i) = vicon_per(vic_location(i));

end

vicon_per = new_per;

for i = 1:length(vic_location)

   vic(i) = vicon_norm(vic_location(i));
   total_vic(i,:) = vicon_norm(vic_location(i));


end


for i = 1:length(kin)

   Err(i) = (abs(kin(i) - vic(i)))*100;

end

devi = std(Err);
```

Appendix K

MeanSD_Graph

```matlab
function MeanSD_Graph

[Err, devi, com_trials] = Combine_Stats;
nike = 10:10:90;

for n = 1:length(com_trials)

    xmin = 5;
    xmax = 95;
    ymin = min(Err(:,n))-(max(devi(:,n)))-5;
    ymax = max(Err(:,n))+(max(devi(:,n)))+5;

    figure(n)
    errorbar(nike,Err(:,n),-devi(:,n),devi(:,n), 'o',...
        'MarkerSize',10, 'MarkerEdgeColor','red',...
        'MarkerFaceColor','red')
    grid on
    ylabel('Distance')
    xlabel('Percent of Movement')
    axis([xmin xmax ymin ymax])
    legend('Mean')

end

figure(1)
title('Anterior')
figure(2)
title('Anterior Lateral')
figure(3)
title('Anterior Medial')
figure(4)
title('Lateral')
figure(5)
title('Medial')
figure(6)
title('Posterior')
figure(7)
title('Posterior Lateral')
figure(8)
title('Posterior Medial')
```

Appendix L

Combine_Stats

```
%Combine_Stats
% This function finds the mean error and standard deviations across all
% trials at 10:10:90% of the movement for all directions.
%
%OUTPUTS:
%    'mean_Err': the mean error for each direction at 10:10:90% of the
%                movement.
%    'devi_Err': the standard deviation for each direction at 10:10:90%
of
%                the movement.
%    'com_trials': the number of trials for each direction.


function [mean_Err, devi_Err, com_trials] = Combine_Stats

% The trial names that will be searched for.
trials = {'R_Ant','R_Ant2', 'R_AntLat', 'R_AntLat2' 'R_AntMed',
'R_AntMed2',...
    'R_Lat', 'R_Lat2', 'R_Med', 'R_Med2','R_Pos', 'R_Pos2',...
    'R_PosLat', 'R_PosLat2', 'R_PosMed', 'R_PosMed2'};

% FOR loop for the amount of trials so that every trial type is done
% seperately.
for i = 1:length(trials)

    % Create the search term and find the appropriate files.
    trial = trials{i};
    search =
strcat('/Users/AndyAlvarez/Documents/MATLAB/*',trial,'.xls');
    list = dir(search);

    % Convert from structure to cell.
    a = struct2cell(list);
    names = a(1,:);

    % Find the amount of trials there are in this trial type.
    total_trials(i) = length(names);

    % FOR loop that will create matrices to hold the outputs from
Error_Calc.
    % Each trial type should be placed in their own column.
    for n = 1:length(names)

        if rem(i,2) == 1
            [Err(:,n,(i/2)+0.5), devi(n), total_kin(:,n,(i/2)+0.5),...
                total_vic(:,n,(i/2)+0.5)] = Error_Calc(names(n));

        else
            [Err(:,n+(total_trials(i-1)),(i/2)), devi(n),...
                total_kin(:,n+(total_trials(i-1)),(i/2)),...
                total_vic(:,n+(total_trials(i-1)),(i/2))]...
                = Error_Calc(names(n));
```

66

```matlab
        end

    end

end

% Combine the number of trials for similar trial types.
for n = 1:2:length(trials)

    com_trials(:,(n+1)/2) = total_trials(n) + total_trials(n+1);

end

% Find the mean and standard deviation of the error for
% similar trial types.
for n = 1:length(trials)/2

    for i = 1:size(Err,1)

        mean_Err(i,n) = mean(Err(i,1:com_trials(n)));
        devi_Err(i,n) = std(Err(i,1:com_trials(n)));

    end

end
```

Appendix M

Control_Dist

```
%Control_Dist
% This function finds the distances between the two legs, normalized by
% the leg length of the subject, for all Kinect trials.
%
%OUTPUTS:
%   'mean_dis': 9x8 matrix, the mean distances traveled at 10:10:90% of
the
%               movement in each direction.
%   'devi_dis': 9x8 matrix, the standard deviation at 10:10:90% of the
%               movement in each direction.
%   'mean_max': 1x8 matrix, the mean of the maximum distances in each
%               direction.
%   'devi_max': 1x8 matrix, the standard deviation of the maximum
distances
%               in each direction.
%   'com_trials': 1x8 matrix, the number of trials in each direction.
%
% At the bottom of the code (begining at line 90), it graphs the mean
of
% the maximum distances of each direction +1 standard deviation. For
other
% functions that use Control_Dist, this can be commented out so that it
does
% not create the figure when it is not necessary.

function [mean_dis, devi_dis, mean_max, devi_max, com_trials] =
Control_Dist
% clear all

% The trial names that will be searched for.
trials = {'R_Ant','R_Ant2', 'R_AntLat', 'R_AntLat2' 'R_AntMed',
'R_AntMed2',...
    'R_Lat', 'R_Lat2', 'R_Med', 'R_Med2','R_Pos', 'R_Pos2',...
    'R_PosLat', 'R_PosLat2', 'R_PosMed', 'R_PosMed2'};

% FOR loop for the amount of trials so that every trial type is done
% seperately.
for i = 1:length(trials)

    % Create the search term and find the appropriate files.
    trial = trials{i};
    search =
strcat('/Users/AndyAlvarez/Documents/MATLAB/*',trial,'.xls');
    list = dir(search);

    % Convert from structure to cell.
    a = struct2cell(list);
    names = a(1,:);

    % Find the amount of trials there are in this trial type.
    total_trials(i) = length(names);
```

```matlab
    % FOR loop that will create matrices to hold the outputs from
Dist_Calc.
    % Each trial type should be placed in their own column.
    for n = 1:length(names)

        if rem(i,2) == 1

            [dis(:,n,(i/2)+0.5), max_dist(:,n,(i/2)+0.5)] =
Dist_Calc(names(n));

        else
            [dis(:,n+(total_trials(i-1)),(i/2)),...
                max_dist(:,n+(total_trials(i-1)),(i/2))] =
Dist_Calc(names(n));

        end

    end

end

% Combine the number of trials for similar trial types.
for n = 1:2:length(trials)

    com_trials(:,(n+1)/2) = total_trials(n) + total_trials(n+1);

end

% Find the mean and standard deviation of the 'dis' and 'max_dist' data
for
% similar trial types.
for n = 1:length(com_trials)

    for i = 1:size(dis,1)

        mean_dis(:,n) = mean(dis(:,1:com_trials(n),n),2);
        devi_dis(:,n) = std(dis(:,1:com_trials(n),n),0,2);
        mean_max(:,n) = mean(max_dist(:,1:com_trials(n),n),2);
        devi_max(:,n) = std(max_dist(:,1:com_trials(n),n),0,2);

    end

end

% Graph the the mean of the maximum distances of each direction +1
% standard deviation as a bar graph.
bar(1:length(com_trials), mean_max, 'b')
hold on
grid on
e = errorbar(1:length(com_trials), mean_max,
devi_dis(length(mean_dis),:),...
    '.', 'color', 'b');
title('Mean Maximum Distance +1 StD')
ylabel('Normalized Distance')
xlabel('Direction')
```

```matlab
Labels = {'Anterior', 'Anterior Lateral', 'Anterior Medial',
'Lateral',...
    'Medial', 'Posterior', 'Posterior Lateral', 'Posterior Medial'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels);
```

Appendix N

Dist_Calc

```matlab
%Dist_Calc(name)
% This function finds the distance between the two legs in a Kinect
trial,
% normalized by the leg length, at 10:10:90% of the movement for a
% particular trial.
%
%INPUTS:
%    'name': string, the name of the trial being processed. Should match
the name of
%            the .xlsx file that will be read in.
%
%OUTPUTS:
%    'total_kin': 9x1 matrix, the normalized distances for the trial.
%    'max_dist': double, the maximum distance of the trial.

function [total_kin, max_dist] = Dist_Calc(name)

% Converts 'name' to a string array, if it is not already.
trial = char(name);

% Read in the trial.
sheet = xlsread(trial);
sheet(isnan(sheet)) = 0;

% Read in the percentage and distance data.
[v, x] = deal(1);
for i = 1:length(sheet)

    if sheet(i,28) ~= 0
        kinect_per(v) = sheet(i,28);
        v = v+1;
    end

    if sheet(i,27) ~= 0
        leg_norm(x) = sheet(i,30);
        x = x+1;
    end
end

% Find the maximum distance in the trial.
max_dist = max(leg_norm);

% Find the location 10:10:90% of the movement.
n = 1;
for i = 9.5:10:89.5

    kin_location(n) = find(i <= kinect_per, 1, 'first');
    n = n+1;

end
```

```
% Find the corresponding distances of 'kin_location'.
for i = 1:length(kin_location)

    total_kin(i,:) = leg_norm(kin_location(i));


end
```

Appendix O

Patient_vs_Control

```
patient = 'Patient3';

[con_dis, devi_dis, con_max, devi_max, con_trials] = Control_Dist;
[pat_dis, pat_max, pat_trials] = Patient_Dist(patient);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 3, 4, 5, 6, 7, 8];
i = 7;

for n = 1:length(m)

    con_data(n) = con_max(m(n));
    pat_data(n) = pat_max(n+i);
    devi_data(n) = devi_max(m(n));

end

graph_data(:,1) = con_data;
graph_data(:,2) = pat_data;


    figure(2)
    b = bar(graph_data);
    b(1).FaceColor = 'b';
    hold on
    grid on
    errorbar(0.85:1:length(m), graph_data(:,1), devi_data(1,:), '.',...
        'color', 'b')
    axis([0.5 (length(m)+0.5) 0
max(max(graph_data)+max(devi_data(1,:)))])
title('Control vs. Patient 3 Uninjured')
    ylabel('Normalized Distance')
    xlabel('Direction')
    legend('Control',patient)
        Labels = {'Anterior', 'Anterior Lateral', ...
            'Lateral', 'Medial', 'Posterior', 'Posterior Lateral',
'Posterior Medial'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels);
```

Appendix P

Patient_Dist

```matlab
function [dis, max_dist, names] = Patient_Dist(patient)

trials = {patient};

for i = 1:length(trials)

    trial = trials{i};
    search = strcat('/Users/AndyAlvarez/Documents/MATLAB/',trial,'*.xls');
    list = dir(search);

    a = struct2cell(list);
    names = a(1,:);

    total_trials(i) = length(names);

    for n = 1:length(names)

        [dis(:,n,i), max_dist(:,n,i)] = Dist_Calc(names(n));

    end

end
```

Appendix Q

Patients_Uninjured

```matlab
patient1 = 'Patient1';
patient2 = 'Patient2';
patient3 = 'Patient3';

%% Patient 1

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient1);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 4, 6, 7, 8];
i = 0;

for n = 1:length(m)

    pat_data1(n) = pat_max(n+i);

end

%% Patient 2

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient2);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 4, 5, 6, 7, 8];
i = 5;

for n = 1:length(m)

    pat_data2(n) = pat_max(n+i);

end

%% Patient 3

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient3);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 3, 4, 5, 6, 7, 8];
i = 7;

for n = 1:length(m)

    pat_data3(n) = pat_max(n+i);
```

```
end

pat_data2(4) = [];
pat_data3(3) = [];
pat_data3(4) = [];


graph_data(:,1) = pat_data1;
graph_data(:,2) = pat_data2;
graph_data(:,3) = pat_data3;

figure(2)
b = bar(graph_data);
b(1).FaceColor = 'r';
b(2).FaceColor = 'g';
b(3).FaceColor = 'b';
hold on
grid on
axis([0.5 length(graph_data)+0.5 0 max(max(graph_data))+0.1])
title('Patients 1, 2, and 3 Uninjured')
ylabel('Normalized Distance')
xlabel('Direction')
legend(patient1, patient2, patient3)
Labels = {'Anterior', 'Anterior Lateral', ...
    'Lateral', 'Posterior', 'Posterior Lateral', 'Posterior Medial'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels);
```

Appendix R

Patients_Injured

```matlab
patient2 = 'Patient2';
patient3 = 'Patient3';

%% Patient 2

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient2);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 5, 6, 7];

for n = 1:length(m)

    pat_data2(n) = pat_max(n);

end

%% Patient 3

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient3);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 4, 5, 6, 7, 8];

for n = 1:length(m)

    pat_data3(n) = pat_max(n);

end


pat_data3(3) = [];
pat_data3(6) = [];


graph_data(:,1) = pat_data2;
graph_data(:,2) = pat_data3;

figure(2)
b = bar(graph_data);
b(1).FaceColor = 'b';
b(2).FaceColor = 'y';
hold on
grid on
axis([0.5 length(graph_data)+0.5 0 max(max(graph_data))+0.1])
title('Patients 2 and 3, Injured')
```

```matlab
ylabel('Normalized Distance')
xlabel('Direction')
legend(patient2, patient3)
Labels = {'Anterior', 'Anterior Lateral', ...
    'Medial', 'Posterior', 'Posterior Lateral'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels);
```

Appendix S

Intra_Patient

```matlab
patient = 'Patient3';

[pat_dis, pat_max, pat_trials] = Patient_Dist(patient);
pat_trials = pat_trials';

% Ant AntLat AntMed Lat Med Pos PosLat PosMed

m = [1, 2, 4, 5, 6, 7, 8];

for n = 1:length(m)

    pat_i(n) = pat_max(n);

end

i = 1;
for n = length(m)+1:length(pat_trials)

    pat_u(i) = pat_max(n);
    i = i+1;

end


pat_u(3) =[];


graph_data(:,1) = pat_i;
graph_data(:,2) = pat_u;

figure(2)
b = bar(graph_data);
b(1).FaceColor = 'b';
b(2).FaceColor = 'y';
hold on
grid on
axis([0.5 length(m)+0.5 0 max(max(graph_data))+0.1])
title('Patient 3, Injured and Uninjured')
ylabel('Distance')
xlabel('Direction')
legend('Injured', 'Uninjured')
Labels = {'Anterior', 'Anterior Lateral', ...
    'Lateral', 'Medial', 'Posterior', 'Posterior Lateral', 'Posterior
Medial'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels);
```

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