Risk Prediction of Anterior Cruciate Ligament Injuries: A New Model

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1.0 Abstract

It is estimated that a quarter of a million anterior cruciate ligament (ACL) injuries occur each year in Canada and in the United States. Injuries lead to time away from sports and physical activity, which has obvious health disadvantages and also causes a great deal of personal suffering (Dallinga, Benjaminse, & Lemmink, 2012). The real solution to this problem does not lie in improvement of surgical techniques but in prevention of ACL injuries altogether. The challenge is identifying individuals that are at an increased risk. The current methods to assess ACL injury risk include motion analysis. Motion analysis systems have shown that jumping dynamics can reliably predict the risk of knee injury, but such systems are expensive and are only available in well-equipped research centers (Hewett, Roewer, Ford, & Myer, 2015a). Our goal is to develop a tool that will predict at-risk athletes based solely on a jumping movement they can perform anywhere. Through the integration of modern tools and technologies, we created an injury prevention application that is powerful, easy to use, and can be downloaded on any computer with a 3-D capture camera. This low-cost tracking application will record, identify and analyze an individual's movements and determine their likelihood of injury based on known prognostic jumping angles.

Our data has shown comparable results with the motion analysis system. Therefore, providing a cheaper alternative to assessing athletes risk of an ACL injury. The practicality and ease of use of our system will support an injury prevention program in order to have more people assessed for ACL injury.

2.0 Résumé

Il est estimé qu'un million de déchirures de ligaments croisés antérieurs (LCA) surviennent chaque année au Canada et aux États-Unis. Ces blessures résultent en une diminution de participation des athlètes à leur sport ainsi qu'une diminution des niveaux d'activité physique de manière globale, ce qui présente non-seulement des désavantages sur la santé physique, mais qui cause aussi de la souffrance personnelle (Hewett, Roewer, Ford, Myer, 2015). À l'encontre de plusieurs cadres de pensé actuels, la solution à ce problème se trouve dans la prévention primaire des blessures et non dans l'innovation de nouvelles techniques chirurgicales pour assurer une bonne guérison des blessures. Un des grands enjeux dans la prévention primaire est l'identification des individus à risque élevé. Une des méthodes utilisées pour l'évaluation des blessures du LCA est l'analyse du mouvement, qui est réalisée dans des laboratoires précis à ces fins. L'analyse du mouvement a déjà démontré que la biomécanique observée lors des sauts standardisés peut prédire, de manière fiable, le risque de blessure au genou. Ces systèmes sont malheureusement très dispendieux et sont seulement disponibles dans des centres de recherche de haut calibre (Hewett, Roewer, Ford, & Myer, 2015). Notre but est de développer un outil qui peut prédire le risque de blessure du LCA, ce qui permettrait d'identifier les athlètes qui présentent un risque élevé de blessure du LCA. En intégrant les atouts de la technologie moderne avec celles de la médecine actuelle, nous avons développé une application électronique facile d'accès et d'utilisation, qui peut être téléchargée sur n'importe quel ordinateur à condition qu'il soit équipé d'une caméra avec capture 3-D. Cette application à bas coût peut enregistrer, et analyser les mouvements biomécaniques d'un individu et, à l'aide d'angles pronostiques de sauts, déterminer le risque de blessure. Nos données ont démontré de résultats comparables au système d'analyse du mouvement, fournissant une méthode d'évaluation alternative pour la détermination du risque de blessure

du LCA. Notre système pourra éventuellement informer des programmes de prévention, dans le but de réduire le nombre de blessures du LCA subit chaque année.

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I would like to thank my mom for the immense help with this thesis, from proofreading to discussions about the best approach for various stages of this project. Your guidance shaped the direction I took with this project. I would like to thank my dad for his critical analysis of this project which only helped improve this work. I would also like to thank my siblings and my significant other for their emotional support and continued encouragement during these two years of work.

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I would also like to acknowledge the financial support I received from the department of Experimental Medicine at McGill University along with the Max E. Binz fellowship which enabled me to pursue graduate studies in the department.

4.0 Dedication

I would like to dedicate this thesis to my mom, dad, brother, sister and grandmother for their continuous support and unconditional love. Their emotional support and guidance helped shape this work. You keep pushing me every day to be a better version of myself and I am forever grateful for this.

5.0 Introduction

Six million Canadian adults and five million Canadian youth participate in sports activities (Mullholland, 2008). Given their competitive nature, team sports often involve body contact and aggressive behaviour leading to injuries (Coakley, Donnelly, & Coakley, 2009). Consequently, 18% of Canadians stop participating in sports due to injuries. With an increase in the prevalence of obesity among the youth, encouraging participation in sports without increasing the risk of injury, is of prime importance. Injuries lead to time away from sports and physical activity, which has obvious health disadvantages and also causes a great deal of personal suffering (Dallinga et al., 2012). Furthermore, the economic costs of these sport injuries (i.e. medical consultations, medications, medical devices and productivity loss) have been estimated at 10.1 billion USD/year and are increasing (Rush, 2013), reinforcing the multifaceted burden of these injuries. Forty-four percent of sports injuries are injuries to the knee; other types of sports injuries can be seen in Figure 1 (Noyes, Mooar, Matthews, & Butler, 1983). Taking a closer look at sport-specific injuries, high injury rates are observed amongst individuals participating in basketball, soccer, and football as seen in Figure 2 (AmericanSportsData, 2006).

Figure 1: Types of Sport Injuries

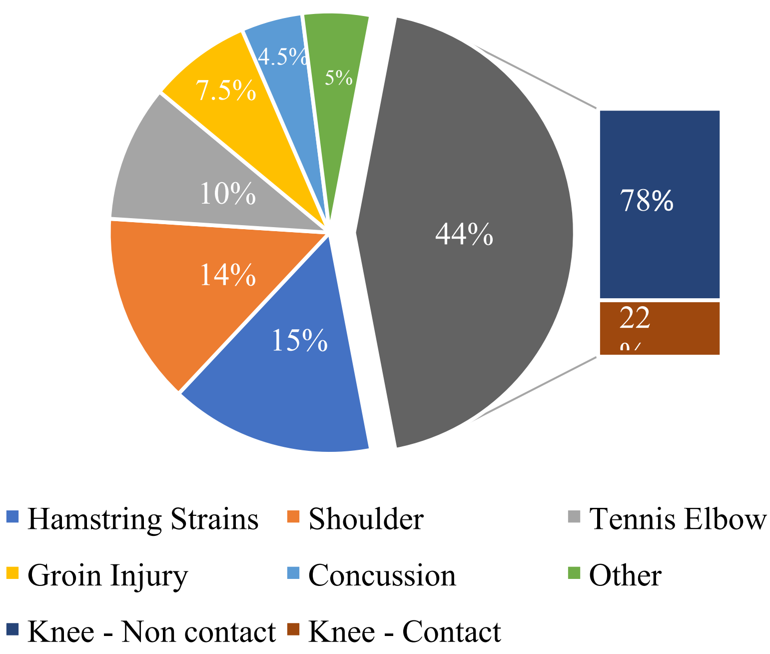
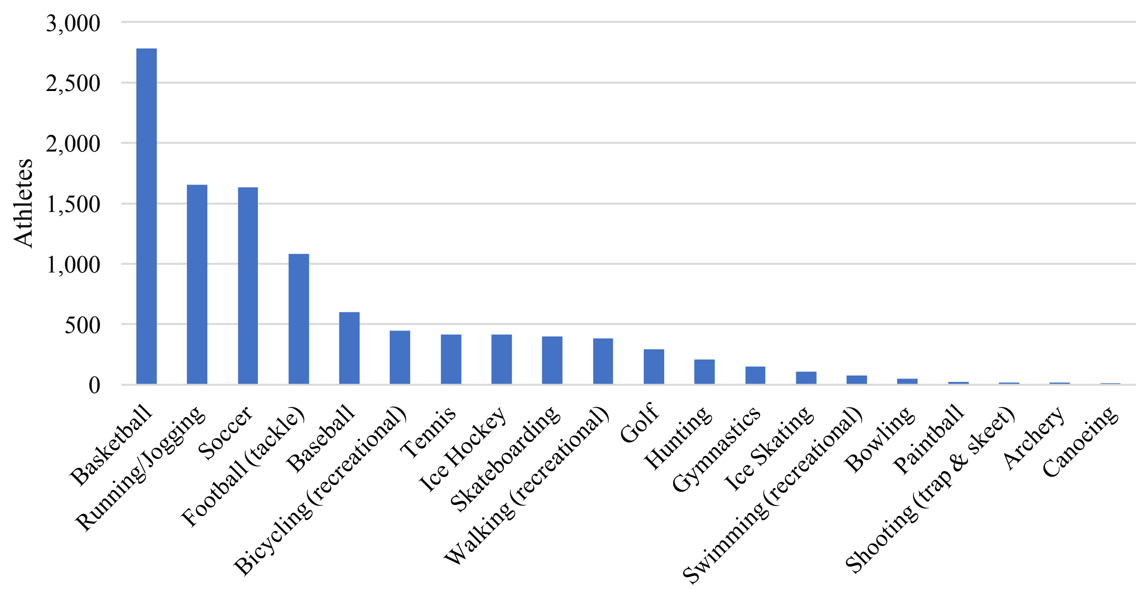


Figure 2: Injuries by sport



In recognition of this alarming incidence, numerous training programs have been developed have implemented preventive measures and guidelines seeking to reduce the occurrence of these injuries (Campbell et al., 2014). In the face of this unfortunate sport-related epidemic, the Canadian Academy of Sport and Exercise Medicine (CASEM) has proposed the adoption of injury prevention programs, ranging from sport-specific injury prevention programs to those who target injury prevention more globally. Sport-related injuries and their physical, psychological, economical and societal consequences can dissuade people from participating in sports as a whole, which as a plethora of evidence demonstrates, is deleterious to maintaining a healthy lifestyle. Moving forward, it will be of prime importance to enable early identification and correction of possible injuries with the help of injury prevention programs to prevent consequences in sports participation, health and social activities.

Injuries that is on the rise across all sports are anterior cruciate ligament (ACL) injuries. It is estimated that a quarter of a million ACL injuries occur each year in Canada and in the United States (Noyes et al., 1983). Given the nature of the sports, individuals playing either competitive or non-competitive sports in football, basketball, soccer or alpine skiing are at a higher risk of anterior cruciate ligament (ACL) injuries (Gornitzky et al., 2016).

To better understand ACL injuries the following will be described: 1. the anatomy of the ACL; 2. the susceptibility of the ACL to damage; 3. ACL injury aetiology; 4. diagnosis of ACL injury; 5. current treatment and prevention methods, and 6. current challenges and gaps in the diagnosis and prevention

5.1 Anatomy of the ACL

The knee is made up of three primary bones including the femur, the tibia and the patella. The femur, more commonly known as the thighbone, lies superior to the knee while the tibia, referred to as the shinbone, lies inferior to the knee. In front of these two structures lies the patella, which provides protection to the structures beneath it (Purnell, Larson, & Clancy, 2008). The anterior cruciate ligament (ACL) is one of the four main ligaments in the knee that is responsible for maintaining stability in this joint. There are two ligaments on each side of the knee, known as collateral ligaments, which support against sideways motion of the knee. The other two ligaments, one being the ACL and the other being the posterior cruciate ligament (PCL), support against forward and backward movement of the knee, respectively. Anatomically, the PCL and ACL form a cross, which further provides stability when the knee performs rotational movements. The ACL is responsible for preventing the tibia from sliding forward in front of the femur, while the PCL is responsible for preventing the tibia from sliding backward, relative to the femur. In addition, the ACL is also responsible for preventing internal rotation of the tibia. The ACL originates from the lateral condyle of the femur and inserts itself into the anterior side of the tibia. The PCL originates from the medial condyle of the femur and inserts into the posterior part of the tibia. The ACL has been further subdivided into the anteromedial (AM) and posterolateral (PL) bundles. These bundles are different in that they insert into different locations of the anterior tibia. The PL bundle resists tibial rotation while the AM bundle resists against translation of the tibia (Amis & Dawkins, 1991).

The ligaments within the knee are made up of dense type I collagen fibres which form a rope-like structure (Petersen & Tillmann, 1999). The vascularization of these cruciate ligaments gives insight into their ability to heal. A study by Petersen et al. demonstrated that the ACL and PCL both have areas that are not vascularized. Coincidentally, these avascular areas are composed of fibrocartilage. It is believed that these fibrocartilaginous regions have developed due to shearing and compressive stress when the knee is full extended. Consequently, this avascular region of the ligament indicates the poor ability of these ligaments to heal (Giori, Beaupre, & Carter, 1993).

5.2 Why is the ACL particularly susceptible to injury?

The PCL is a much broader and therefore stronger ligament than the ACL (Peterson, 2017). The cross-sectional area of the PCL is 140% greater than that of the ACL (Trilha Junior, Fancello, Mello Roesler, & Ocampo More, 2009). For this reason, PCL injuries make up a smaller percentage of total knee injuries (Naraghi & White, 2014). The location of the ACL causes for it to be fully tensed when the knee is extended and fully relaxed when the knee is flexed. Conversely, the PCL is tightened when the knee is flexed and loosened when the knee is extended. Given the biomechanical nature of these ligaments and the fact that most non-contact knee related injuries occur while the knee is extended (such as when an athlete is kicking a soccer ball), there is an increased incidence of ACL injuries compared to PCL injuries.

Of equal importance are the muscles surrounding and supporting the knee, which include the quadriceps and the hamstring muscle groups. Acting together, these muscles play an important role in decreasing an individual's likelihood of injury. Athletes often make quick changes in direction during sports play, which significantly increases the amount of force placed on the knee, increasing the likelihood of injury. If the surrounding muscles are not strong enough to compensate for the tension within the ligaments, this generates additional strain on the knee joint.

5.3 ACL injury etiology

Contact vs non-contact

Before diving into the etiology of an ACL injury it is important to differentiate between an injury that is a direct cause of some external force and one that is caused by one's own movement. In the literature, this has been distinguished by classifying the injuries as either contact or non-contact ACL injuries. A direct contact ACL injury, as the name suggests, is an injury that occurs when the knee joint, or region surrounding the knee is "forcefully struck, leading to an injury" (Marshall, 2010). A non-contact/indirect contact (NCIC) ACL injury is defined as "an injury as a result of an athletes own movement which is typically disturbed by a physical or cognitive perturbation during or immediately before the injury event" (Marshall, 2010). Understanding this difference in the mechanism of injury is very important especially since it has been reported that non-contact knee injuries occur in 78% of all sport related knee injuries (Noyes et al., 1983). Thus, implying that the athletes themselves can possibly help prevent this injury.

5.3.1 Grades 1,2,3

Ligament related injuries are considered sprains and they are typically classified as grade 1, 2, or 3. A grade 1 sprain implies that the ligament has been stretched beyond the natural ability but it still provides enough stability to the joint. A grade 2 sprain refers to an ACL that has been stretched and is partially torn. Finally, a grade 3 sprain of the ACL is denoted to one that has been completely torn and no longer provides any stabilisation of the knee (JohnsHopkins, 2018). Interesting to note is another, less commonly addressed type of ACL injury, called a tibial spine avulsion ACL injury. This type of injury occurs when the insertion point of the ACL, on the anterior side of the tibia, is torn off. This is an uncommon injury that is seen among children, usually due to the weakness of their incompletely ossified tibia relative to the strength of their ligaments (POSNA, 2018).

5.4 Diagnosis

The diagnosis of an ACL injury is done following a thorough history of the mechanism of injury as well as a number of tests. The health care practitioner begins by examining the injured knee, while comparing it to the uninjured side. They will look for deformities, swelling and any other evidence that can give insight into the mechanism of the injury. Additionally, the injured individual will be asked to specify if they heard the infamous “pop”, a sound commonly associated with a torn ACL. Before ordering further tests, the physician might perform one of the following four physical assessments:

A. Anterior drawer test

During the early phase of the injury, the inflammation causes swelling and pain which leads to the patient guarding their knee (Malanga, Andrus, Nadler, & McLean, 2003). This makes the anterior drawer test (ADT) a difficult assessment to perform during the acute phase of an ACL injury. The ADT is a physical exam performed with the patient lying on their back with the hip flexed to 45 degrees and the knee flexed at 90 degrees. The examiner sits on the subjects’ foot in order to stabilize the subject’s leg, while placing their thumbs on the subject’s tibial plateau and hands behind the tibia. A force is then applied anteriorly to assess the translation of the tibia over the femur, in order to test if the ACL offers any resistance (Malanga et al., 2003). If one side demonstrates more anterior displacement than the other, this is indicative of an ACL that is torn. The ADT has demonstrated a sensitivity between 22% and 40% (Tanaka et al., 2017).

B. Lachman test

The Lachman test is the most reliable test for diagnosis of ACL injury in the acute phases of the injury (Tanaka et al., 2017). The subject lies on their back with their knee flexed between 10 and 20 degrees. The femur is then held with one hand while the other is placed on the posterior side of the tibia. Force is applied to the posterior aspect of the tibia, attempting to translate the tibia anteriorly, the exact movement the ACL resists (Malanga et al., 2003). When there is anterior translation of the tibia with a "soft" endpoint, this indicates a ruptured ACL. This subjective judgment of a "soft endpoint" leads to inevitable discrepancies between trained physicians and less experienced residents. Nevertheless, the Lachman test has demonstrated a sensitivity of 80% to 99% (Tanaka et al., 2017).

C. Pivot shift test

For the pivot shift test, the leg is picked up at the level of the ankle and the knee is flexed. As the knee is being extended, the tibia is exposed to a valgus strain. At 30 degrees of flexion, the tibia will suddenly reduce if the ACL is in fact torn. Although the pivot shift test has shown sensitivity of only 32%, the specificity of the test is 98%, the highest of all physical assessments (Prins, 2006).

D. Lever sign test

The lever sign test, also known as the Lelli's test, is a recently developped assessment for ACL injury. For this assessment, the subject lies flat on their back. The examiner places a closed fist beneath the proximal third of the tibia and the other hand applies a force on the distal third of the subjects' quadriceps muscle. An intact ACL will lead to extension of the knee and the subject's heal will rise up off the examination table. A partially torn or fully torn ACL will cause the heal to not rise as the femur will simply slide below the tibia. Although the lever sign test is a more recent test, studies have shown that it has a specificity of 90% with a sensitivity of only 63% (Jarbo, Hartigan, Scott, Patel, & Chhabra, 2017).

Other tools such as instrumented arthrometers can also be used for to diagnose an ACL injury. The KT-1000, KT-2000, and the Rolimeter are example of such devices. These tools measure the laxity of the ACL which provides an objective assessment of the anterior translation of the tibia while maintaining the femur in a neutral position (Genourob, 2018). These devices however, have been shown to not agree with radiographic measurements and more significantly, clinical outcomes (Tanaka et al., 2017). Furthermore, newer devices such as the Telos and Genourob (GNRB) have been developed which have automated these older devices. Studies have shown that some of these newer automated devices provide better diagnostic values than the preferred Lachman test (Ryu, Na, & Shon, 2018).

Following these physical exams and objective assessments, the physician has the option of ordering a magnetic resonance imaging (MRI). This scan images the soft tissue as well as the bone, which will give further indication on the integrity of the ACL. The MRI is currently a physician’s best tool given the high tissue contrast and high spatial resolution (Li et al., 2017). However, there is evidence that the overuse of the MRI as a diagnostic technique for ACL injury has led to misdiagnosis in 47% of cases (Orlando Junior, de Souza Leao, & de Oliveira, 2015). Furthermore, MRI costs in Canada are between 300-650$ with an average wait time of 10.8 weeks (Fraser, 2017). Despite this, the MRI is the number one choice for physicians to make a diagnosis of an ACL injury, in combination with the rest of the clinical history and a careful physical examination. Another alternative test is a knee arthroscopy, which is the gold standard for ACL tear diagnosis. Knee arthroscopy is an invasive procedure that requires an orthopaedic surgeon to place a camera (arthroscope) into the knee in order to view and explore the area. This method remains the most accurate and precise for knee injury diagnosis (Orlando Júnior, de Souza Leão, & de Oliveira, 2015). However, it costs 1,300$ per procedure, which makes it less available to the public.

5.5 Risk Groups for ACL injury

There are different demographic groups at higher risk of ACL injury, including, but not limited to women, younger individuals, and athletes playing football, basketball, soccer, or alpine skiing. There is a notable difference between sexes, with regards to ACL injuries. Female athletes are more prone to ACL injuries, tearing their ACL two to eight times more frequently than male athletes (Ireland, 2002). Factors associated with a higher risk of ACL injury in women athletes include hormonal status and increased knee laxity. Other risk factors that have been associated with ACL injury include the size of the femoral notch, the diameter of the ACL, the mechanical axis of the lower extremities and other specific anatomical features (Ireland, 2002). Although these factors are not amendable to change, other factors, such as core stability, quadriceps dominance and jumping/landing mechanics are.

A recent study conducted by Tompkins et al. concluded that peak incidence of ACL injuries occurs when individuals are in high school between the ages of 14-18 years old (Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017). More specifically it was found that girls are at an increased risk at the age of 16 while for boys it is at 17.

Individuals playing either competitive or non-competitive sports in football, basketball, soccer or alpine skiing are at a higher risk of anterior cruciate ligament (ACL) injuries (Gornitzky et al., 2016), with soccer remaining the sport with the highest risk for an ACL injury (Agel, Rockwood, & Klossner, 2016). The one commonality between these sports in terms of the movements performed is that they require a lot of quick cutting and rapid changes of direction. This unnatural and repetitive stress on the ACL is what leads to noncontact ACL injury. By planting one foot on the ground during a rapid change of direction, the femur typically wants to continue its forward motion due to its momentum, but the planted tibia wants to go in an opposite direction. If the surrounding muscles are not strong enough to buffer the force of these displacements as well as the shear stress being placed on the ACL, injury may result.

5.6 Treatment for ACL tears

Depending on the severity of the ACL injury there are a number of possible options. Minor ACL injuries or Grade 1 sprains can be treated by icing the knee and resting it for a given period of time. A physician might also prescribe anti-inflammatory medication to help reduce any swelling or pain that might be felt. If the injury is more severe, physical therapy might be necessary in order to strengthen the muscles surrounding the knee. If the ACL has been torn completely (grade 3), surgery might be the only option to regain proper function. The surgery most commonly performed is ACL reconstruction, where the ACL ligament is rebuilt using a graft. It is important to note that it is not uncommon to sustain damage to other ligaments in the knee when the ACL is torn (Naraghi & White, 2014).

5.7 Prevention: Predictive methods

The assessments described in the *diagnosis* section only work when the athlete is injured. They do not inform the physician or physiotherapist whether or not the individual is at a high risk of obtaining an ACL injury in the future; they are not predictive tools. In order to accurately predict injury risk, a full in-depth analysis of an individual's jump must be performed. This is currently only performed at dedicated motion analysis laboratories.

5.7.1 Motion analysis

The only current method to assess risk of ACL injury is motion analysis. Motion analysis systems have shown that jumping dynamics can reliably predict the risk of knee injury, but such systems are expensive and are only available in well-equipped research centers (Hewett et al., 2015a). As photography and filming started to see advancements in the 1970s, this technology started to be used to visualize human locomotion as it has never been seen before. With the subsequent introduction of infrared cameras and the computational power of computers in the 1980s, motion analysis exploded. The motion system used for this study made use of 10 infrared cameras. These cameras identify a set of markers that are placed on different anatomical locations of the subject being tested (Arneja & Leith, 2009). This specific system has the ability to identify these markers in space at a rate of 120Hz (Vicon, 2018). The system captures all the markers in space and then with the help of the Vicon® Bodybuilder™ software, angles of each joint are extracted based on where they were at a given point in time. This allows for the user to obtain angles at each frame of the movement. In addition to being extremely accurate with a precision of less than 2mm, this motion analysis system is very costly with a price tag of 400$ per individual tested (Merriaux, Dupuis, Boutteau, Vasseur, & Savatier, 2017). Testing takes 2 hours to perform and analysis of the data takes a trained individual approximately 2 hours to obtain meaningful results (Tombrowski, 2014).

Research has been conducted using such systems to assess an individual's knee angles when they perform a jump. There is currently one set of parameters present in the literature that seems to be validated (Hewett et al., 2015a). The study by Hewett et. al demonstrated that individuals with greater initial knee coronal angle and smaller peak knee sagittal angles, when performing a standardized drop vertical jump, have a decreased risk of injury (Hewett et al., 2015a). In order to evaluate these angles, the motion analysis system was used. Coronal angles are the angles also referred to as varus and valgus, or simply how much the knee moves medially and laterally. Conversely, sagittal angles refer to the angles of flexion and extension. Initial and peak angles are referring to the angle of the knee during initial contact with the floor and the peak angle during the jump, respectively (Hewett et al., 2015a). The angles considered to indicate an individual's risk of ACL are initial coronal, peak coronal and peak sagittal angles. The study done by Hewett et al., used the Drop Vertical Jump (DVJ), which is the gold standard for physical ACL injury risk assessment. This jump is an assessment that is often times used in the literature as it is has been validated for prediction of ACL injury. A drop vertical jump (DVJ) test is a standardised test where individuals leap down from a 31cm block and then proceed to jump as high as they can while reaching up with their arms. The theory being that this jump displays those individuals who demonstrate poor lower extremity biomechanics, therefore placing them at higher risk of ACL injury (Redler, Watling, Dennis, Swart, & Ahmad, 2016). This is a great tool that can be used by many individuals seeing as it has proven good inter- and intra-rater reliability, and can be performed without significant training (Redler et al., 2016).

5.7.2 Biomechanical assessment

The biomechanical assessment done by a trained coach is the easiest and most cost-effective analysis of jumping mechanics. Experts in biomechanics such as trained strength and conditioning coaches or kinesiologists will likely be able to identify which athletes are at an increased risk of injury based on a number of parameters that they have learned through years of experience. This technique has not been extensively studied but there is evidence that trained professionals in sports medicine are in fact able to assess with a high degree of certainty whether or not an athlete is prone to ACL injuries. The anecdotal evidence suggest that said professionals do so by observing stability of the knee during movements where the knee is near end range of motion.

Furthermore, physical performance tests (PPTs) have been created. These tests are easy to administer assessment tools that can be performed with little amounts of training. They are practical assessment tools with an instruction guide explaining the steps necessary to complete the test. There is however, conflicting evidence in the literature regarding the reliability and validity of such tools (Hegedus, 2015). Following analysis and risk of ACL injury the athletes are provided with feedback on exercise and muscle strengthening regimens based on their risk. This is the only currently available prophylactic method and it is solely based on the trained biomechanics expert's opinion and judgment.

Typically, if an athlete has been identified as being at a high risk of ACL injury, they will be put on a specific exercise training program. This exercise program is designed by a trained strength & conditioning coach or kinesiologist. These exercise programs focus on strengthening muscles of the quadriceps and hamstrings, which as previously described, contribute to the stability of the knee. Strengthening those muscles serves to alleviate the amount of stress being put on the ligaments of the knee, thus reducing the chance of tearing the ACL due to an indirect force. Numerous studies have reported the effects of neuromuscular training to reduce ACL injuries (Benjaminse, Otten, Gokeler, Diercks, & Lemmink, 2017; Ericksen et al., 2016; Hewett, Ford, Xu, Khoury, & Myer, 2016; Liebert, 2016; Lopes et al., 2017; Pappas et al., 2015; Rodriguez, Echegoyen, & Aoyama, 2017; Shultz, Silder, Malone, Braun, & Dragoo, 2015; Sugimoto et al., 2017; Whyte, Richter, O'Connor, & Moran, 2017; Zebis et al., 2016; Zhiyu et al., 2015). Furthermore, recent studies have found that instability in the trunk predicts ACL injury (Whyte, Richter, O'Connor, & Moran, 2018). There has been substantial evidence indicating that injury prevention programs focusing on core stability reduces injury rates (Whyte et al., 2018). Following the increase in non-contact ACL injury, in 2009, the Fédération Internationale de Football Association (FIFA), created an injury prevention program (FIFA, 2007). This program was designed as a warmup prior to sport participation in order to decrease the incidence of injury. This was done by incorporating core stabilisation, eccentric training of thigh muscles, proprioceptive training, dynamic stabilisation and plyometrics with straight leg alignment (FIFA, 2007).

5.7.3 Imaging methods

As mobile health begins to emerge as a field, sports teams are looking to incorporate more medical technology with regards to testing and assessing their athletes. This provides a quick and easy method of obtaining results on the sideline without requiring intensive resources. One such device is Microsoft's Xbox Kinect camera. This device, equipped with infrared depth sensors and a skeletal tracker has proved to be convenient and inexpensive for kinematic imaging (Livingston, Sebastian, Ai, & Decker, 2012). Although originally designed for gaming, Microsoft's open source software development kit known as Kinect V2, has allowed programmers to use the built in skeleton tracking for a number of healthcare applications including, stroke rehabilitation, Parkinson's disease rehabilitation, at-home cardiovascular rehabilitation, and now athlete kinematics (Gray et al., 2017; Park, Lee, Lee, & Lee, 2017; Shih, Wang, Cheng, & Yang, 2016; Vieira, Gabriel, Melo, & Machado, 2017).

Given these advancements with the motion analysis capabilities of the Microsoft Kinect camera and the advancements in injury prediction, it only makes sense that the next step would be to integrate the two together. Currently there is one such company that has used this avenue to attempt to address this issue. A company known as *Virtusense Technologies*, has created a software that was aimed at assessing jumping angles for athletes. Following preliminary testing of their platform, it was determined that their algorithm and approach caused for a lack in precision between the system and clinical examination. This project was discontinued and focus was rerouted into fall prevention as an alternative. The biggest challenge with the gold standard of motion analysis, is that it is a system that is extremely expensive, requires a trained professional to run the test, takes thirty minutes to set up markers on the individual being tested, and the data processing and analysis takes several hours. The injury prevention community needs a tool/system that can screen athletes at high risk in order to get them into a prevention program as fast as possible to avoid injury and other associated repercussions. The poor natural history of the ACL injured knee and failure of current surgical techniques to overcome long-term deterioration suggest research should be directed at injury prevention and prediction of susceptibility for improved long-term patient outcome.

6.0 Methodology

Throughout this report, the motion analysis system will be referred to as the Vicon system or motion lab. Both terms are used interchangeably. It must be noted that a motion analysis system by itself does not have the ability to assess the risk of an ACL injury. The system, coupled with other criteria allows the estimation of angles in order to provide a risk score. In this report when referring to the results of a motion analysis system it is implied that this has been coupled with an analysis method. Angles of interest refer to initial coronal angle, peak coronal angle, and peak sagittal angle.

6.1 Ethics Approval

This is a prospective unblinded randomized clinical trial that was performed at McGill University and the Shriners hospital for kids. Ethics approval was obtained by McGill University's Research Ethics Board (see Appendix 1: Protocol). The first version of the protocol only included registered McGill athletes, however to increase our enrollment we amended the protocol to include non-McGill athletes. After consultation with the coaches and training staff, all participants were approached during predetermined times. Informed consent was obtained from all participants in this study (Appendix 2: Informed Consent Form).

6.2 Athlete Cohort

One hundred and fourteen athletes were consented for all studies described. Both men and women from McGill's Varsity Sports Program were recruited. Exclusion criteria included those aged less than 18 years of age and greater than 30 years of age, lower limb injury at time of consent, and non-athletic defined as less than 150 minutes of exercise per week. The participants included McGill athletes and athletes from the general population. Each McGill athlete was followed till the end of the season. Data collection included injury reports and clinical data, shown in table 1.

Table 1: Clinical Data Collection
Gender
Age
BMI
Sport Played
Previous knee Injury
Previous knee Surgery
Abnormal Knee Exam
Knee laxity (KT-1000)
Oral Contraceptive Pill use

6.3 Shriners Validation: Motion Analysis

The motion analysis facility at the Shriners Hospital for Children (Montreal, Quebec) was used, under the supervision of Dr. Veilleux. The analysis was performed as described in the protocol from the "LABORATOIRE DU MOUVEMENT – Centre de réadaptation Marie-Enfant". The system includes 10 cameras shooting at a frame rate of 120 Hz. The 34 markers are placed according to the above-mentioned validated protocol. After the markers were attached to the participant they performed a static trial, for marker identification. They then performed three drop vertical jumps off of a 31cm box and the data was recorded. Their skeletal model was then labeled and reconstructed in order to extract usable angles using Mokka: Motion

Kinematic & Kinetic Analyzer (Mokka, 2013). Two angles (coronal and sagittal) from two different time points (initial and peak) were used for analysis. An example of data is shown in table 2 of the supplemental materials.

6.4 Experimental Validation system: Kinect Analysis

This system makes use of a 3-dimensional video recording input device along with a laptop computer. The specifications of the laptop computer can be found in table 3.

Table 3: Computer Specifications from Dr. Fevens and Dr. Rivaz

		Minimum	Ideal	Maximum
Central Processing Unit	Physical Cores	2	4	N/A
	Clock Speed	1.5GHz	3.1 GHz	N/A
	Instruction set	Intel x86_64 with support for Streaming SIMD Extensions (SSE2) instructions		
Graphics Processing Unit	Memory	1GB	4GB	N/A
	Clock Speed	1.1GHz	1.8GHz	N/A
	API Compatibility	DirectX11		
Output Screen Device Resolution		1024 x 768 pixels	1600 x 900 pixels	1920 x 1080 pixels
Power Input	Voltage	120 volts AC @ 60Hz		
	Amperage	3 amps		
Connectivity		USB 3.0 625 MBps		
RAM		4GB	8GB	N/A
Available Hard Drive Space		512MB	10GB	N/A

Microsoft's Xbox Kinect (Microsoft, 2013) system was used as the alternative capture device connected to a personal computer. In collaboration with Dr. Rivaz and Dr. Fevens from Concordia University a list of specifications was established in order to ensure that the software functioned adequately during the testing. Seeing as these details are out of the scope of the Experimental Medicine thesis submission, the specifications are outlined in appendix 3 but will not be further explored.

Testing was performed at two different sites. First, the Kinect system was tested simultaneously with the Motion Analysis system at the Shriners Hospital, allowing for a head to head comparison. The second site consisted of the McGill Currie Gymnasium (Montreal, QC) where the athletes were tested during their respective practice sessions.

The Kinect was mounted onto a tripod and from a distance of 2.5 meters, each participant performed a drop vertical jump, off of a 31cm high box, similar to during the motion analysis. The software then generated an excel file with two angles (coronal and sagittal) from two different time points (initial and peak) and one for the coronal (peak). An example of data is shown in the supplemental materials of table 4.

6.5 Data Analysis

6.5.1 Kinect device Validation

The statistical component of the program was run using SAS 9.3 statistics software. This was done with the help of Dr. Stephane Bergeron. For the DVJ a difference was calculated between the angles measured from the Kinect and Vicon for each participant. This led to 11 data sets being generated per jump per angle of interest. A Shapiro-Wilk test was performed to determine whether the data was normally distributed or not. This then informed whether or not a one-tailed student t-test on the data could be run. The significance value of the t-test was then used to determine the presence or absence of a significant difference between the tested method of screening and that of the motion lab. Skewness and kurtosis were also examined in order to inform on the distribution of the data and the presence of outliers.

6.5.2 Kinect Injury Prediction

To begin the Kinect testing, the user must input their login credentials to gain access to the list of participants and the testing interface. A new participant is then created, or an existing one is selected from the list. The user then begins a new recording and selects which test will be performed by the participant by using the drop-down menu. The system is now ready to record. Following the recording, the system displays a screen where the recording can be re-watched. Additionally, important parameters such jump angles from different frames are presented as well as the injury risk score prediction. Screen captures from the system used are shown in Appendix 4. Knee angles were calculated using vectors from the knee to the hip (femur) and from the knee to ankle (tibia) as seen in Equation 1. Sagittal angles were calculated using Equation 2 while the coronal angles were calculated using Equation 3.

Equation 1: Vector Definition of tibia and femur

$$\overrightarrow{tibia} = P_{knee} - P_{hip}$$
$$\overrightarrow{femur} = P_{knee} - P_{ankle}$$

Equation 2: Sagittal Angle Calculation

$$\theta_{sagittal} = 180^\circ - \mathrm{acos}\left(\frac{\overrightarrow{tibia} \cdot \overrightarrow{femur}}{\|\overrightarrow{tibia}\|\|\overrightarrow{femur}\|}\right)$$

Equation 3: Coronal Angle Calculation

$$\begin{aligned} x &= RotationAxis.x * sin(RotationAngle\ /\ 2) \\ y &= RotationAxis.y * sin(RotationAngle\ /\ 2) \\ z &= RotationAxis.z * sin(RotationAngle\ /\ 2) \\ w &= cos(RotationAngle\ /\ 2) \end{aligned}$$

The system then provides a risk score based on an algorithmic analysis. The risk score is calculated based on the parameters mentioned above and outlined in table 5.

Table 5: Risk Score Calculation based on Hewett et al.

	Initial Coronal Angle		Peak Coronal Angle		Peak Sagittal Angle	
Injured Athletes	*3.4°*		*1.4°*		*82.4°*	
Not Injured Athletes	*5°*		*9°*		*71.9°*	
	Angle	Risk	Angle	Risk	Angle	Risk
	3°	100%	1°	100%	85°	100%
Injured Athletes Angle	3.4°	100%	1.4°	100%	82.4°	100%
	3.9°	69%	3°	79%	79°	68%
	4.2°	50%	4.5°	59%	75.5°	34%
Worsening	4.6°	25%	7°	26%	73°	10%
Not Injured Athletes Angle	5°	0%	9°	0%	71.9°	0%
Worsening	5.5°	31%	10°	13%	70°	18%

These parameters were established based on a previous pilot project along with data from a study conducted by Hewett et al. In order to perform this analysis, the software must first identify the important jump frames (i.e. initial landing frame and peak landing frame). To identify the initial landing frame the system, the system identifies when the ankle joint stops travelling in a downward direction, indicating that the ankle has made contact with the floor. The peak landing frame is determined to be the moment when the ankle joint and the hip joint are closest to each other. The system calculates the distance between these two joints at each frame and the frame with the smallest distance is taken as the peak landing frame. Finally, the risk score is calculated by using the angles from the Hewett study, used in an algorithm described below, to find the likelihood of injury based on proximity to injured and non-injured angles. Hewett et al identified joint angles which placed the participants at increased risk of ACL injury. The equation used to calculate the predictive risk score determines the similarity between the jump angle (testing of the participant) and the values obtained in the Hewett et al study. The more the angles resemble each other (i.e. the closer the values), the greater the risk score of ACL injury. Equation 4 summarizes this calculation.

Equation 4: Risk Calculation

$$\text{risk score} = \min\left(\frac{|\theta - \alpha|}{|\beta - \alpha|}, 100\%\right) \qquad \begin{aligned} \alpha &= \text{no injury angle} \\ \beta &= \text{injury angle} \\ \theta &= \text{measured angle} \end{aligned}$$

Based on the literature, low risk was defined as a greater initial knee coronal angle and a smaller peak knee sagittal angle, whereas high risk was the opposite. The parameters for the risk prediction tool were the peak sagittal knee angles, the peak coronal knee angles, initial sagittal knee angles, and initial coronal knee angles. The motion analysis generated a series of angles which were then extrapolated to determine the risk score. Similarly, the Kinect device generated a series of angles which were also extrapolated to determine the risk score. The angles obtained the motion analysis system and those obtained from the Kinect system were then compared.

6.5.3 Data analysis of pre-season assessment

The final component involved comparing the device to the current assessment method used for athletes at McGill University's Sports Medicine Clinic. The method performed at the Sports Medicine Clinic involves a pre-season physical exam where the team physician and healthcare staff assess the athletes on their physical readiness to participate in the season. Any unusual physical exam result is noted in the athletes' charts. An unusual physical exam refers to a positive test result from the knee assessments described in the introduction. Author JC analyzed the files of the tested athletes to pull out any relevant information regarding their risk of an ACL injury. The criteria for injury is based on risk factors that are known to increase one's risk of an ACL injury. These factors include previous knee injury, previous knee surgery, abnormal knee exam, family history of ACL injury, gender, sport, and BMI. These risk factors are outlined in table 1 above. Positive risk factors gave one point while negative risk factors gave zero points. The score was then converted into a percentage in order to compare with the percentages outputted by the Kinect system. In addition, the results from the pre-season assessment were also compared to the results obtained by the device.

7.0 Results

7.1 Demographics of Shriners participants

A total of 11 participants were recruited for this component of the study; six females and five males. The average age was 21.64 years (±2.06), the average height was 1.74 meters (±0.115), the average weight 68.41 (±9.45), and the average BMI 22.64 (±3.16). Demographic distribution of the participants is summarized in table 7.

Table 7: Demographics of Participants (n=11)		
Gender	5 males	6 females
Age	21.64 (± 2.06)	
Height (m)	1.74 (± 0.12)	
Weight (kg)	68.42 (± 9.45)	
BMI (kg/m^2)	22.64 (± 3.16)	
*Data are shown as mean and standard deviation		

The analysis was performed on three drop vertical jumps, while looking at each leg independently and analyzing coronal and sagittal angles at three different time points (peak coronal angle, peak sagittal angle, and initial coronal angle) as seen in table 8.

Table 8: Angles of Interest			
	Initial Coronal Angle	Peak Coronal Angle	Peak Sagittal Angle
Injured Athletes	3.4°	1.4°	82.4°
Uninjured Athletes	5°	9°	71.9°

The Shapiro-Wilk test showed the data as being normally distributed for 17 of the 18 dependent variables (or data sets). In light of this, a student t-test was performed for 17 of the 18 data sets, while a Wilcoxon Sign Rank test was performed on the remaining sets, allowing the comparison of two non-parametric samples in the event that the data is not normally distributed. The Shapiro Wilk test values are shown in Table 9.

Table 9: Shapiro Wilk-test data

Shapiro-Wilk Test	**leftpeaksag1**	**leftpeaksag2**	**leftpeaksag3**	**rightpeaksag1**	**rightpeaksag2**	**rightpeaksag3**	**leftpeakcor1**	**leftpeakcor2**	**leftpeakcor3**
	0.6505	0.3895	0.3646	0.5724	0.2328	0.7812	0.4368	0.6246	0.0602
	rightpeakcor1	**rightpeakcor2**	**rightpeakcor3**	**leftinitialcor1**	**leftinitialcor2**	**leftinitialcor3**	**rightinitialcor1**	**rightinitialcor2**	**rightinitialcor3**
	0.9341	0.3361	0.0685	0.4781	0.4746	0.7078	0.5873	0.0016	0.9176

The results from the student t-test show that 14 of the 17 data sets have a p-value greater than 0.05 demonstrating that there is no significant difference between the Kinect device and the motion lab. The remaining 2 data sets show a significant difference between these two systems. The student t-test results are illustrated in table 10. Of the non-normally distributed data, the Wilcoxon Signed Rank test shows no significant difference between the motion lab and the Kinect data. This result is presented in Table 10.

Table 10: Student t-test data and Wilcoxon signed rank test data

	leftpeaksag1	**leftpeaksag2**	**leftpeaksag3**	**rightpeaksag1**	**rightpeaksag2**	**rightpeaksag3**	**leftpeakcor1**	**leftpeakcor2**	**leftpeakcor3**
Student t-test	0.0337	0.0418	0.1799	0.0564	0.0956	0.1549	0.6916	0.9767	0.3765
	rightpeakcor1	**rightpeakcor2**	**rightpeakcor3**	**leftinitialcor1**	**leftinitialcor2**	**leftinitialcor3**	**rightinitialcor1**	**rightinitialcor3**	
	0.0338	0.5827	0.6382	0.8105	0.2824	0.8565	0.1506	0.8788	
Wilcoxon Signed Rank Test		**rightinitialcor2**							
		0.2208							

7.2 Results for in-field testing

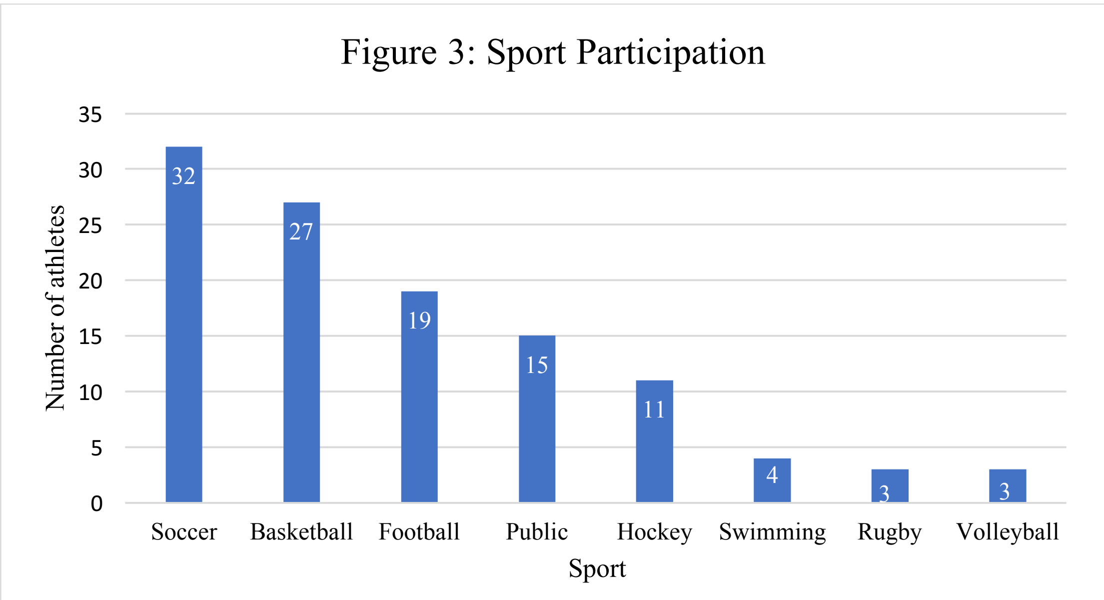
7.2.1 Demographics of in-field testing cohort

A total of 114 participants were recruited; 69 males and 45 female athletes. The average age was 22.02 years (±2.19), the average height was 1.79 meters (±0.12), the average weight 77.90 kilograms (±9.45), and the average BMI 24.23 (±3.76). Demographic distribution of these participants is summarized in table 11.

Table 11: Demographics of McGill Participants (n=114)		
Gender	69 males	45 females
Age	22.02 (± 2.19)	
Height (m)	1.79 (± 0.12)	
Weight (kg)	77.90 (± 16.70)	
BMI (kg/m^2)	24.23 (± 3.76)	
Knee Injuries	5 non-contact	
*Data are shown as mean and standard deviation		

Of the 114 athletes that were recruited, 40 athletes were identified as having a high-risk score (risk score greater than 55%), as determined by the Kinect device (using the methods described above). Of those 114 athletes, five (4.39%) sustained an ACL injury by the end their respective sport seasons. All the injured athletes had previously been identified by the device as having a high-risk score of ACL injury. Two male and two female basketball players along with one male soccer player incurred non-contact ACL injuries.

The breakdown by sport participation can be seen in Figure 3.



Given that all five of the injured athletes were captured in the predicted 40 high risk athletes by the Kinect, this yields a sensitivity of 100% for the device. As for the specificity, the Kinect computed 35 false positives therefore yielding a specificity of 68%. This has been outlined in Table 6.

Table 6: Sensitivity & Specificity Table of Kinect device		
N=114	**ACL tear**	**No ACL tear**
Kinect positive prediction	5	35
Kinect negative prediction	0	74
Sensitivity: 100% Specificity: 68%		

7.3 Medical charts

7.3.1 Results for Comparison with current medical assessment

We compared the pre-season assessment from the Kinect injury score to the pre-season medical assessment (described above). An orthopedic resident reviewed the athletes pre-season medical files for any indications from the primary care physicians that might indicate a concern of injury. Using a full patient history and the physicians notes on the pre-season physical knee exam, it was then determined whether or not each athlete was at an increased risk of an ACL injury before starting their respective seasons. Results from this physician reported activity were then compared to the results from the Kinect system.

For this analysis, only McGill athletes having complete medical records (n=96) were used. The resident identified 36 athletes as being high risk of ACL injury and 60 being low risk of ACL injury. Of the 36, four had an ACL injury identified in their medical charts. Furthermore, four of the total five injured athletes were captured by this assessment method. This yielded a sensitivity of 80% and a specificity of 65%.

7.4 Other data captured

Objective measurements of knee laxity were also captured using a KT-1000 arthrometer in order to compare with the Kinect data (n=25). The laxity results are presented in table 12 of the supplemental materials. We looked to see if those individuals with a difference of greater than 3mm of laxity between left and right leg had any predictive value when it came to injury outcome. No correlation was found between objective measurements of knee laxity and the results from the Kinect or injury outcome.

8.0 Discussion

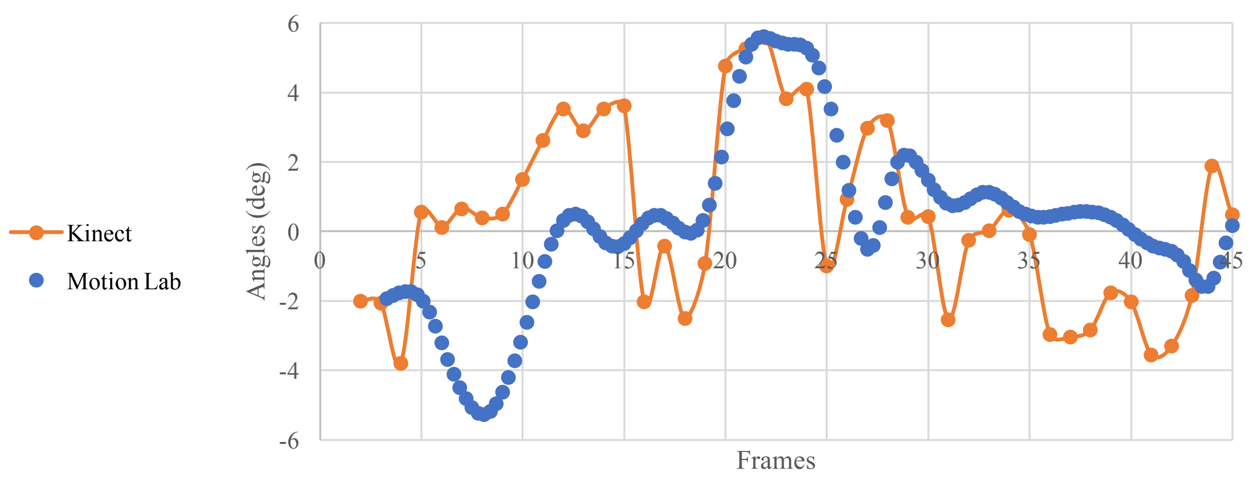
8.1 Kinect device Validation

The identification/development of a system that can be quick, portable and reliable for ACL injury detection is urgently needed. The gold standard, Vicon motion analysis, despite having a high sensitivity and specificity, is not practical for coaches to use on a routine basis for assessing their athletes. The present study compared and validated the Kinect device to the gold standard Vicon motion analysis. Angles at initial and peak points of the drop vertical jump were compared. One data set did not demonstrate normal distribution, and demonstrated high skewness and high kurtosis values. It was noted that one of the collection points from the motion lab was in fact greater than that captured by the Kinect device. The Wilcoxon signed rank test that was performed on this data set yielded a p-value greater than 0.05. This can be due to a number of factors including, light interference or vibration during the jump. Nevertheless, this data point was not excluded.

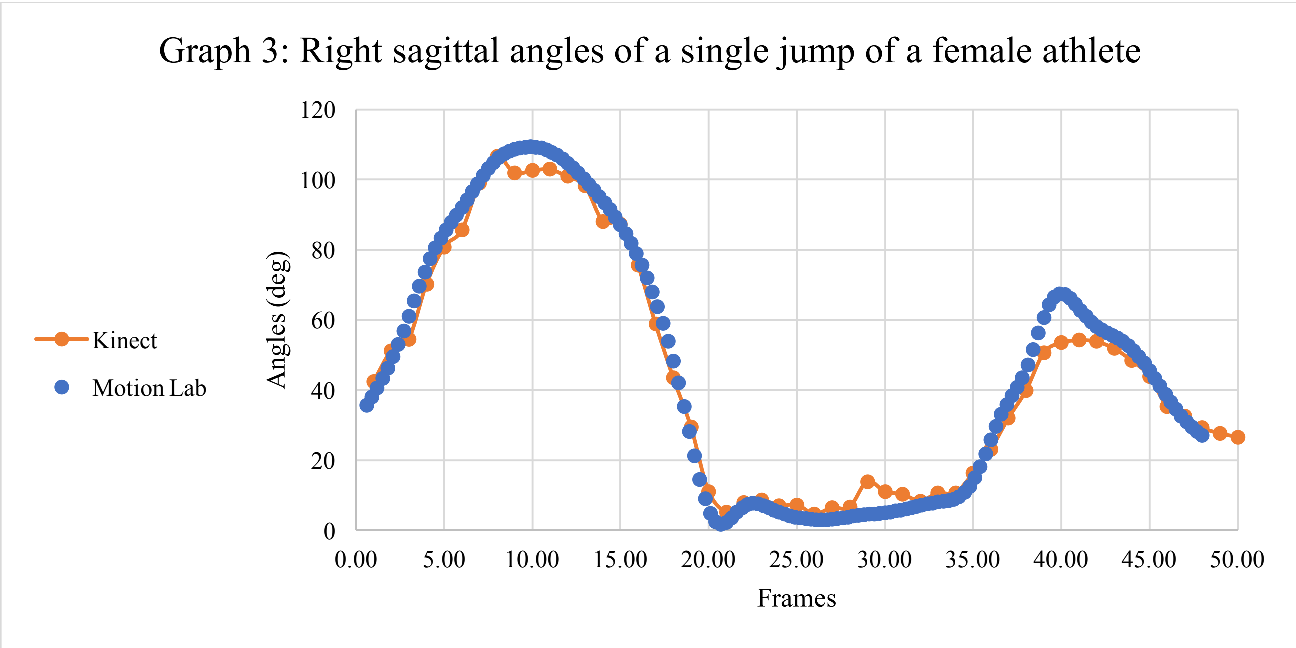
The hypothesis testing for the 18 data sets yielded p-values greater than 0.05 in 15 of 18 situations. The three other data sets had p-values of 0.03, 0.04, and 0.03. These results suggest that the there is no significant difference in the angles that are being measured by the Kinect system and the angles being measured by the Vicon motion analysis system. Two of the three other data sets which yielded significant p-values were in the peak sagittal plane which measures large angle values. It is less surprising that the larger angles yielded significant differences because the angles vary more at the extremes of the jumps. As for the third data set, the significant difference was for the peak coronal angle. Seeing as this is only one of the results, no conclusions could be drawn from this single finding.

Furthermore, as can be seen in Graph 2, the overall pattern between both graphs is quite similar. The Kinect does however, have a less smooth curve than the motion lab in all instances. This is especially obvious in the coronal plane. This can be attributed to the fact that the Kinect is trying to identify relatively small angles of about 4 degrees. It is important to note that these angles are barely noticeable to the naked eye, but are still being picked up by the Kinect system, laying claim to its accuracy. The motion lab is able to confirm these minute angular changes.

Graph 2: Left coronal angles of single jump of a female athlete



Of further interest is the close association of the curves in the sagittal plane (Graph 3). As has been previously mentioned, the Kinect is a front facing single camera system. Nevertheless, it still has the ability to capture sagittal angles quite precisely. The angles of flexion/extension are very similar between both systems. This is likely also attributed to the fact that much larger angles are now being observed and the attention to minute angle changes is not as significant. These data would suggest that the Kinect device is much more valuable when it comes to measuring larger angles. This finding can be used for future studies where this type of device is to be used, for example for rehab where smaller angles may not be captured as precisely as larger ones.



Another reason explaining the difference between the curves is attributed to the rate at which the Kinect captures data as opposed to that of the motion lab. The Kinect has the ability to capture at a maximum of 30 Hz which is the equivalent of 30 frames per second. The motion lab however, record at 100 Hz or 100 frames per second. This creates a much smoother curve as more points are being captured in a given period of time. This precision is something the Kinect device lacks and results in the rough curves that can be observed.

All the above-mentioned findings propose that a portable Kinect system such as the one developed for this study can be used to capture coronal and sagittal angles with sufficient accuracy during a drop vertical jump.

8.2 Injury prediction

The injury prediction component involved testing the device in a cohort of athletes and following-up with the team's strength and conditioning coach as well as therapists throughout their playing season. Their injury status was determined at the end of the season and compared to the pre-season results of the Kinect device. Sensitivity and specificity analysis was performed on this data to determine the predictive strength of the device. Average risk scores were calculated based on the methods described above. Injury risk was stratified as either high risk or low risk. Forty athletes were deemed high risk from the Kinect system, leaving 74 as being low-risk (appendix 5). ACL injuries were determined based on physicians' interpretation and diagnosis from magnetic resonance imaging. Five athletes had a complete ACL tear. All five of these injuries had a non-contact mechanism of injury (appendix 6). The five athletes represent 4.39% of the participant pool. This is in line with the likelihood of injury among competitive athletes present in the literature. Furthermore, the sports which these athletes participated in (basketball and soccer) are not surprising as they are two of the highest risk sports for non-contact ACL injury. Upon confirmation of the injuries, their data was cross-checked to see whether or not the system had predicted these athletes as being high risk. The five injured athletes were captured in the 40 high risk predictions.

In all 40 of the high-risk athletes, the first of three jumps they perform yielded a higher risk score. This is likely attributed to the fact that their jumping mechanics start to improve as they continue jumping. They receive biomechanical feedback from their muscles and make minor adjustments for subsequent jumps. For this reason, their last of three jumps consistently shows a smaller risk score than their first jump. The first jump was mainly used to classify risk score, regardless of their decreasing score due to biomechanical feedback throughout the jumps.

Additionally, 41 athletes from the cohort yielded risk scores of zero in one or more jumps. According to the parameters set for injury risk prediction (table 5), a risk score of 0% was indicative of a result that was off of the measurable charts. Upon investigating the injury history of those 41 athletes, it can be noted that 21 (51.2%) of them have some form of diagnosed knee pathology. Knee pathology refers to previous knee surgery (ACL, PCL, meniscus, or MCL), or other injuries such as patellofemoral syndrome, knee sprains, patellar dislocations etc.. These results are not strong enough to indicate any conclusive evidence. However, what was observed was that these athletes who have knee pathologies seem to be jumping in a way that the Kinect system is identifying them as outlying the set parameters. Further investigation is warranted to make additional conclusions.

8.3 Pre-physical assessment

To date, risk score stratification based on athlete preseason physical assessment and athlete history has never been explicitly studied in order to predict future injury outcome. A review of the literature was conducted to establish a list of risk factors, these are outlined in the methods section above.

The risk factor of family history of ACL injury was excluded from the present analysis as this data was not available from the pre-season assessments provided to us from the McGill Varsity Sports Medicine Clinic. Of the five athletes that had a season ending ACL injury, 4 were captured by this analysis. One athlete who had an ACL injury was not captured as being high risk based on the assessment. Although 1 of the 5 athletes was not captured by the chart analysis it did yield a sensitivity of 80%. When it comes to injury prediction, it is preferred to have a high sensitivity even if the specificity is slightly lower as this ensures that all athletes who are at risk will be captured by the device and none will be missed. The downside to this is that athletes who are at the cutoff of being injured or not, are pooled in the high-risk category. As mentioned above, the chart analysis provided one false negative and led to missing one high-risk athlete who ended up getting injured. For this reason, it can be believed that the Kinect system provides a slightly better predictive analysis than the chart review. Nevertheless, the chart analysis does have an impressive predictive ability however, this is not something that most athletes who are playing sports are privileged to have. A trained orthopaedic surgical resident accessed these charts and each chart analysis took an estimated time of 8-10 minutes per athlete. This makes for a slightly longer analysis process than the Kinect device which takes an average of 5 minutes as mentioned previously.

9.0 Limitations

One of the limitations of this system is that an Xbox Kinect device is not a readily available tool that coaches at all levels have access to. Albeit the low cost of this device, offering this platform on mobile devices would facilitate widespread access of this tool to sport teams that can afford a Kinect device. Furthermore, another limitation to this study is that the evaluation was done using the drop vertical jump which requires the use of a 31-centimeter block. The requirement for extra equipment does not make this test very practical. A future consideration for this would be to test other jumps including a single leg hop jump and/or a tuck jump. These tests have not yet been validated for ACL injury prediction and further research is therefore warranted.

10.0 Conclusion

The results have demonstrated that the Kinect system measures jumping angles comparable to the expensive, technologically advanced gold standard motion analysis systems. The software used has shown to predict those athletes that are at an increased risk of obtaining an ACL injury with a sensitivity of 100%. The Kinect system has the ability to decrease the incidence of noncontact ACL injuries by predicting which athletes are at an increased risk. This would further inform which athletes need further attention with their physiotherapists, strength and conditioning coaches as well as potential assessment at a motion lab.

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12.0 Supplemental Materials

Appendix 1: Protocol
Risk prediction of ACL injuries: A New Model

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<u>Study Purpose and Rationale</u>

Anterior cruciate ligament (ACL) tears are frequent injuries making ACL reconstruction one of the most commonly performed orthopaedic surgeries[(Garrett et al., 2006)]. Despite the significant advances in surgical techniques over the years, it remains fraught with frequent complications such as graft rupture, clinical failure and ultimately osteoarthritis. Risk factors that have been associated with ACL injury include the size of the femoral notch, the diameter of the ACL, the mechanical axis of the lower extremities and other specific anatomical features(Alentorn-Geli et al., 2014). Female athletes are more prone to ACL injuries and tear their ACL two to eight times more frequently than male athletes(Ireland, 2002). Factors associated with a higher risk of ACL injury in women athletes include hormonal status and increased knee laxity. Although many of the aforementioned factors are not modifiable, others like core stability, quadriceps dominance and jumping/landing mechanics are. In fact, neuromuscular training programs have shown decreased injury rates in the order of 39% in female athletes, but their adoption is far from uniform nor widespread in Canada(Sugimoto, Myer, Barber Foss, & Hewett, 2014). The poor natural history of the ACL injured knee and failure of current surgical techniques to overcome long-term deterioration suggest research should be directed at injury prevention for improved long-term patient outcome.

Motion analysis systems have shown that jumping dynamics can reliably predict the risk of knee injury, but such systems are expensive and are only available in well-equipped research centers(Hewett, Roewer, Ford, & Myer, 2015b). The only current method to assess risk of ACL injury is the Gait analysis. This motion analysis system uses a number of high definition motion and infrared cameras to pick up a number of angles and points in space during a biomechanical movement(Arneja & Leith, 2009). A study by Hewett et. al demonstrated that individuals with greater initial knee coronal angle and smaller peak knee sagittal angles when performing a standardized drop vertical jump have a decreased risk of injury(Hewett et al., 2015b). This method requires a unique testing lab with specialized equipment and is very costly. Following analysis and risk of ACL injury the athletes are provided with feedback on exercise and muscle strengthen regimens based on their risk. This is the only currently available prophylactic method.

In the study proposed, we will not be able to predict risk. At the completion of this study, we are establishing which parameters (i.e. angles) could indicate a high risk of ACL injury. Future studies would then be proposed to further validate this system in a predictive fashion.

<u>Hypothesis and Project Objectives:</u>

The goal of this proposal is to create an injury prevention application that is powerful, easy to use and adopt using commercially available motion capture hardware and downloadable on most smartphones.

Our proposed system is based on the Xbox Kinect system that has infrared depth sensors with the ability to measure joint angles, similar to those detected and measured with the Gait analysis. We have created an algorithm to pick up these angles with our Xbox Kinect system. This low-cost tracking program records, identifies and analyzes individual's angles of jumps at many time points. The specific angles focused on are initial knee coronal angle and peak knee sagittal angles during a standardized vertical jump. It then computes the data of a patient's jump and calculates a risk score for ACL injury. This proposed research project will focus on establishing accurate parameters for analysis, the validation and implementation of this system.

The overall objective of our research is organized into two phases:

- Phase 1: Pilot study to establish parameters. Participants will perform both the Gait analysis (Gold Standard) and then tested using our single camera kinect system. We will test different movement parameters (i.e. jumping, lunging, drop and jump etc.), measure the different angles of these jumps at multiple time points and then we will calculate a risk score for ACL injury. Upon establishing the most relevant parameters (peak vs initial sagittal and coronal knee angles) the next step will be to determine a risk score threshold that we can dichotomize into categories that will be useful to the end users (patients, athletes, etc.). The two categories will be based on high risk or low risk depending on the peak vs initial sagittal and coronal knee angles. Based on the literature[5] we will set a low risk if there is greater initial knee coronal angle and smaller peak knee sagittal angles and a high risk reflecting the opposite. The parameters for our risk prediction tool are: peak sagittal knee angle, peak coronal knee angle, initial sagittal knee angle, initial coronal knee angle. The gait analysis will generate a series of angles which we will then extrapolate to determine the risk score. Similarly, the Kinect device will generate a series of angles which we will also extrapolate to determine the risk score. Our data will then be compared to the angles calculated by the Gait analysis in order to refine out high and low risk score angles and establish the most sensitive and specific parameters. We will then perform a chi squared test to determine whether there are significant differences between the Kinect system and the gait analysis.
- Phase 2: Validation phase. This phase will be a head to head comparison of our Kinect system to the Gait analysis. Once again, a chi squared test will be performed to establish the difference between the two systems. In this phase, we will also validate our system with both injured and healthy patients.

- Phase 3: Mobile application phase. This phase will involve moving the Kinect based system to a mobile device.

Furthermore, participants recruited to this study will be re-analyzed at a later time point, to reassess their performance. This will allow us to follow participants should they incur an ACL injury and calculate accuracy and sensitivity of this method. For those participants that had previous ACL injuries we will follow them to assess the method as well.
Our research is built on the hypothesis that a prophylactic approach, through the identification of individuals predisposed to ACL injury will reduce the number of ACL procedures and mitigate long term joint destruction.
We hypothesize that our Kinect/mobile application will be comparable to the gait analysis as an effective early screening tool to help identify athletes at risk for ACL injury.

<u>Clinical outcomes/potentials:</u>

A successful outcome of the proposed research will lead to a decrease in the deleterious effects of ACL injury through injury prevention by creating an easy to use smartphone app to identify patients at risk of injury. The mobile application would serve as a screening tool for therapists, coaches, medical professionals, even parents to identify individuals with specific imbalances predisposing them to ACL injury. This low-cost tracking program will record, identify and analyze individual's angles of jumps at multiple time points. It will then compute the data of a patient's jump and calculate a risk score for ACL injury. The development of novel Canadian health care technology can have an important economic impact for Canada through the training of the next generation of health prevention researchers.

<u>Study Design</u>

This is a prospective unblinded non-randomized clinical trial that will recruit participants from McGill University's student body. The project consists of two phases: Phase 1: referred to our pilot phase for the establishment of optimal parameters (i.e. jumps, lunges, angle calculations) to assess the ACL risk score and benchmark it to the gold standard (gait analysis). Phase 2: Once completed a power analysis will be performed to assess the number of participants required for validation of our system on a larger cohort of participants for the direct comparison of the performance of this to test the gold standard: Gait analysis.

<u>Study Population</u>

The participating population will include active individuals between the ages of 18 and 30. We propose to recruit individuals who are at high risk of ACL injury (varsity athletes). Phase 1: The pilot study will consist of 10-20 students, which will help establish baseline parameters and logistics. Phase 2: Once the pilot study is completed a power analysis will be performed, taking all the parameters in consideration at which time we may need to increase our participants. All participants will be approached by the study coordinator who will present the research initiative. A consent form will be provided to them outlining the research project as well as what they need to do in order to participate. Should the participants wish to explore this, they will then meet with the graduate student working on this project.

- Inclusion:
  - Individuals competing in sports (years of participation will be noted)
- Exclusion:
  - Ages less than 18 and greater than 30,
  - lower limb injury at time of consent
  - non-athletic (less than 150 minutes of exercise/week)

Methodology

The ideal time for recruitment and testing will be determined with the coaching staff of McGill University's varsity teams so as to not interfere with their training schedule. We will first approach the head coach and/or strength and conditioning coach of the teams to receive their approval, prior to approaching the athletes. As part of the pilot study, 10-20 participants will be chosen to test out the Kinect/mobile application as well as perform a gait analysis in order to compare results and calibrate the application. In order to reach 10-20 participants for the pilot we will be contacting individuals by word of mouth through personal networks. The research component will include about 200 athletes being tested with the Kinect/mobile application. This is determined using 95% confidence level with a confidence interval of 5 and estimating a population of 400 McGill Varsity athletes. Due to the mobility of the system, the tests will be done at the McGill Currie Gymnasium where the athletes train.

Study Procedures/Schedule

i. Participants will be presented with study and consented as soon as ethics approval has been granted from the McGill Research Ethics Board (REB). Estimated date of February 2018.

ii. Basic data will be collected (see CRF attached) to allow for statistical analysis. Data will also be obtained from their pre-season assessments that were completed by the trained strength and conditioning coach. This is to happen immediately following REB approval.

iii. Ten to twenty participants will be asked to attend a 1 hour session where they will come to the Shriners Lab for testing using 3-dimensional optical motion capture (Qualisys) sampled at 100 Hz and floor mounted and step mounted force plates (AMTI) sampled at 2000. Reflective markers will be attached to participants over anatomic landmarks according to previous guidelines(Collins, Ghoussayni, Ewins, & Kent, 2009). Data collection will begin with a static trial. The static trial will be used to determine joint centres and as an anatomic calibration. This is a non-invasive test with no discomfort. They will perform 1-2 dynamic knee assessments (drop jump test, or single leg hop test) while being monitored by the gait analysis system followed by our novel low-cost tracking application. A drop jump test is a standardised test where individuals leap down from a 31cm block and then proceed to jump as high as they can while reaching up with their arms. A single leg hop test consists of standing on one leg and attempting to jump to a maximum forward distance. The remainder of the participants (about 180 individuals) will only be assessed on the Kinect/mobile application. For all trials, they will perform 2 practice trials of each activity. Testing will proceed until 5 successful trials of each activity are collected. The timeline for this pilot testing period is anywhere between 3-5 weeks depending on athletes' availability. The timeline for the participants that are only part of the Kinect/mobile application testing will be between 2-3 months given the large number of participants. Estimated date for pilot study is March 2018 followed by mobile application study May 2018.

iv. After 6 months, the research team will contact the medical staff from the teams to confirm if any injuries have occurred. This long-term tracking will be made clear to the team staff at the initiation of the study. Should our tool prove to be effective we will be contacting the strength and conditioning coaches to inform them of our findings. They will then use their judgment and expertise to determine the appropriate exercise prevention program for that specific athlete. The athletes will not be contacted directly by our research team.

Measurements

Joint laxity will be measured with a non-invasive KT 1000 device. This is an arthrometer that was developed to measure anterior tibial motion relative to the femur in millimeters(Arneja & Leith, 2009). This will provide us with objective data for our analysis. Basic demographic and clinical data such as age, sex, health status, height, weight, previous knee injuries, smoking habits will be collected. Health status will be determined based on participants disclosure of previous health issues preventing them from exercise. This information will be collected in order to determine other possible links between injured and un-injured athletes throughout our study. See table attached.

Data analysis plan

The results from the Kinect software testing will be compared to the gait analysis. This will give grounds to calibrating our Kinect software and application. Furthermore, data collected during the validation phase will establish the accuracy of ACL risk prevention by performing statistical analysis on the different parameters captured as described above. The Kinect system records a video of the movements which it then uses measure joint angles. Following a jump, the only data that is captured is the vectors moving in space.

Confidentiality

In order to maintain confidentiality while still being able to compare individual's longitudinally, participants will be given a unique code (double coding system) in order to track whether or not they had an injury and go back to their baseline measures to determine biomechanical discrepancies. We will use a double coding system where each participant is given a random 4 digit number and only the director of the study will hold the key. The data will be password-protected and maintained on an external hard drive in the lab of Dr Martineau. Data will be stored for 25 years after study closure should further analysis be required. For example, if the participant has consented to having his data accessible for future studies they will then be used to any follow up studies.

Ethical considerations

This study will be conducted according to ethical principles stated in the Declaration of Helsinki (2013), ethics approval will be obtained before initiating study, consent forms will take into consideration the well-being, free-will and respect of the participants, including respect of privacy, etc. It will be conducted in accordance with the policies and procedures governing the ethical conduct of research involving human participants at McGill University.

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Appendix 2: Informed Consent Form

McGill *Division of Experimental Medicine – Department of Medicine*

Participant Consent Form

Risk prediction of ACL injuries: A New Model

Researchers: Dr. Paul-André Martineau - Associate Member - Division of Experimental Medicine
Dr. Thomas Fevens - Associate Professor, Computer Science and Software Engineering Concordia University
Dr. Hassan Rivaz - Assistant Professor, Electrical and Computer Engineering Concordia University
Dr. Louis-Nicolas Veilleux Department of Surgery McGill University; Shriners Hospital for Children
Nicolaos Karatzas MSc Candidate, Department of Experimental Medicine McGill University

Purpose of the Study: You are being invited to participate in our Anterior Cruciate Ligament (ACL) injury prevention research project. The purpose of this study is to evaluate an Xbox Kinect or smartphone application as a tool to assess your jumping technique. This information will then be analyzed in order to determine if you are at a higher risk of having an ACL injury

Study Procedures*:* You will be asked to spend an hour session with a representative from our research team in order to perform a few jumping exercises while being recorded by our Kinect system. If you are part of the pilot study you will be asked to do so at the Shriners Hospital of where two systems will assess your jumps. If you are not part of the pilot study the jumping tests can be done at the McGill Currie Gymnasium at a time which will be arranged with our research team. Both these systems will be recording your jump and collecting other information about the location of your joints. The jumps you will have to perform are a vertical drop jump where you will drop down from a 31cm block and then jump up as high as you can and a single leg hop test where you will stand on one leg and jump forward as far as you can. This will be performed 1-5 times while being recorded by our systems.

Voluntary Participation*:* Participating in this study is completely voluntary. You may withdraw from the study at any time, for any reason. Should you withdraw from the study your data will be destroyed unless you specify otherwise. Your choice to participate will not result in any loss or benefit from the McGill Sports team you are a part of.

Potential Risks: There are no potential risks to participating in this study.

Potential Benefits: Participating in the study might not benefit you directly but you will have the opportunity to be a part of a new system that could help prevent ACL injury. Furthermore, there is the potential to see certain issues with your jumping mechanics which could be improved to improve your athletic performance.

Compensation: There will be no compensation for participation in this study.

Confidentiality: We will be collecting personal information such as your date of birth, email address and other data (height, weight, past ACL injury, years of competition etc.). This data will be linked to a unique code that is non-identifiable. We will use a double coding system where each participant is given a random 4 digit number and only the director of the study will hold the key. This unique identifier with your data and recordings will be kept on an external drive that will be password protected and only accessible by Dr. Martineau and his graduate student. Data will be stored for 25 years after study closure should further analysis be required. Video taping of the testing session may be used to show the system during conferences or thesis presentations. You have the right to ask that your session not be videotaped. A member of the McGill Institutional Review Board, or a person designated by this Board, may access the study data to verify the ethical conduct of this study.

If you have any questions or comments about this study, please do not hesitate to contact Nick Karatzas at **nicolaos.karatzas@mail.mcgill.ca.**

If you have any ethical concerns or complaints about your participation in this study, and want to speak with someone not on the research team, please contact Ms. Ilde Lepore, Ethics Officer, McGill Institutional Review Board, at 514-398-8302 or ilde.lepore@mcgill.ca.

I have read this consent form, or I have had the purpose of the study, the activities, and risks and benefits of the study explained to me. Any questions that I had were answered. I am aware that I can stop being in this study at any time. I agree to take part in this study. I do not give up any of my rights by taking part in this study. I will receive a signed and dated copy of this consent form.

PLEASE WRITE YOUR INITIALS NEXT TO THE YES OR NO OPTION OF YOUR CHOICE

Yes:____No:____You consent to be video- taped.

Yes:____No:____You consent for the video-tape to be played publically during the dissemination of results.

Yes: ____No: ____You can identify me in the video-tape if shown publically

Yes:_____ No:____ You consent to have your data accessible following study closure for future studies.

Participant's Name: (please print) ____

Participant's Signature:

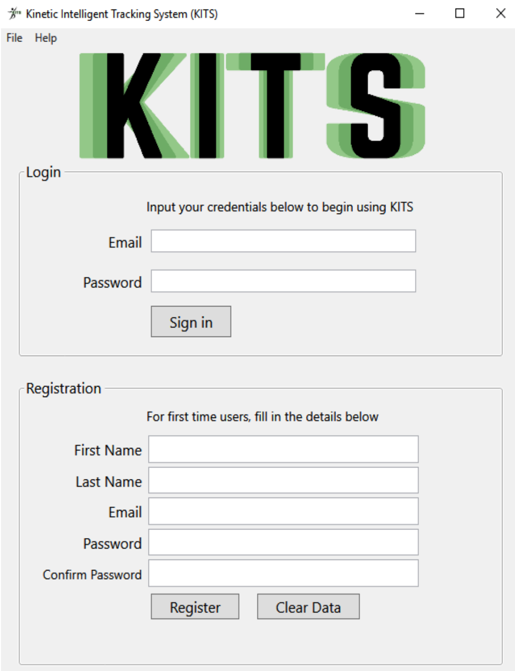
Date:

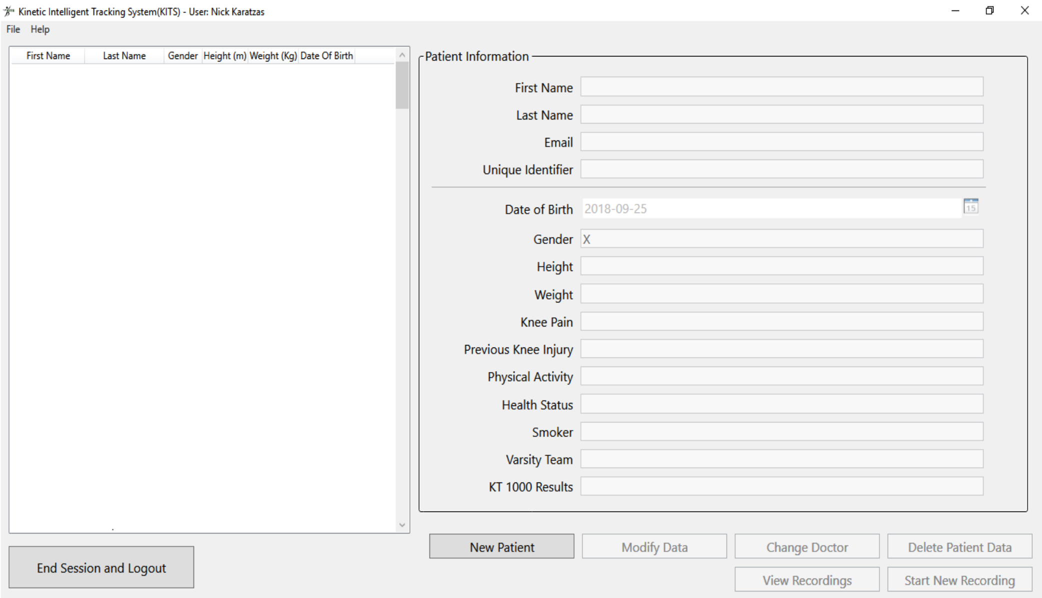
Please save or print a copy of this document to keep for your reference.

Appendix 3: Specifications of software

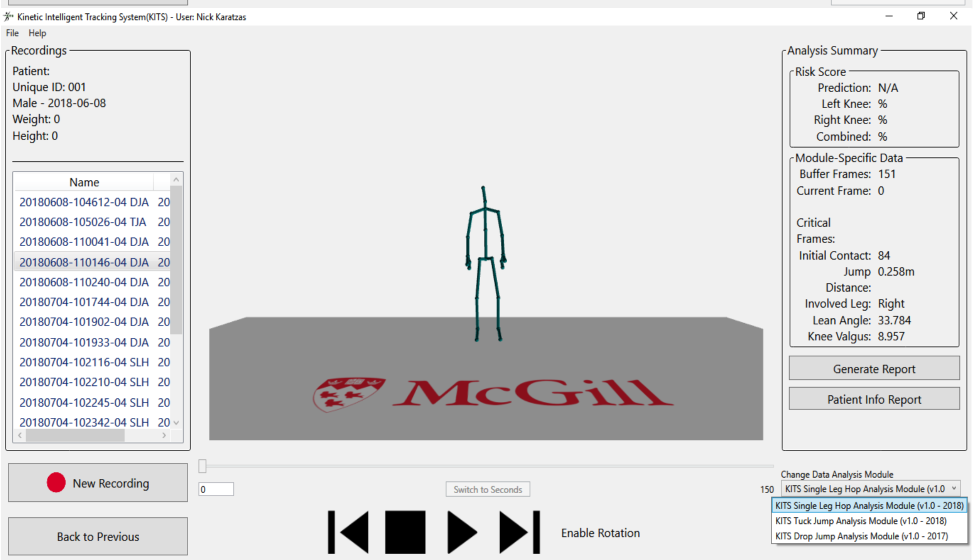
	Minimum	Ideal	Maximum
User Distance from Device	2m	2.5m	5m
User Distance from surrounding objects	0.5m	1m	N/A
User height	0.5	N/A	2.2m
Device height with respect to ground	1m	0.6m	1.5m
Software Analysis Latency	< 1 minute		
Frames Captured per Second	30 Hz		

Appendix 4: Screenshots of system




Kinetic Intelligent Tracking System(KITS) - User: Nick Karatzas
File Help
First Name Last Name Gender Height (m) Weight (Kg) Date Of Birth
Patient Information
First Name
Last Name
Email
Unique Identifier
Date of Birth 2018-09-25
Gender X
Height
Weight
Knee Pain
Previous Knee Injury
Physical Activity
Health Status
Smoker
Varsity Team
KT 1000 Results
End Session and Logout
New Patient
Modify Data
Change Doctor
Delete Patient Data
View Recordings
Start New Recording


Kinetic Intelligent Tracking System(KITS) - User: Nick Karatzas
File Help
New Recording
Select who to record
If no selection is available, ensure that your recording device is on and is streaming
Capture Device
MS Kinect for Xbox One (2014
Analysis Module
Body #1
Body #2
Body #3
Body #4
Body #5
Body #6
Recording for Patient: TEST (X, 2018-07-05)
Back
Waiting for Selection
Start Recording


Kinetic Intelligent Tracking System(KITS) - User: Nick Karatzas
File Help
Recordings
Patient:
Unique ID: 001
Male - 2018-06-08
Weight: 0
Height: 0
Name
20180608-104612-04 DJA 20
20180608-105026-04 TJA 20
20180608-110041-04 DJA 20
20180608-110146-04 DJA 20
20180608-110240-04 DJA 20
20180704-101744-04 DJA 20
20180704-101902-04 DJA 20
20180704-101933-04 DJA 20
20180704-102116-04 SLH 20
20180704-102210-04 SLH 20
20180704-102245-04 SLH 20
20180704-102342-04 SLH 20
McGill
Analysis Summary
Risk Score
Prediction: N/A
Left Knee: %
Right Knee: %
Combined: %
Module-Specific Data
Buffer Frames: 151
Current Frame: 0
Critical Frames:
Initial Contact: 84
Jump Distance: 0.258m
Involved Leg: Right
Lean Angle: 33.784
Knee Valgus: 8.957
Generate Report
Patient Info Report
New Recording
Back to Previous
0
Switch to Seconds
150
Enable Rotation
Change Data Analysis Module
KITS Single Leg Hop Analysis Module (v1.0
KITS Single Leg Hop Analysis Module (v1.0 - 2018)
KITS Tuck Jump Analysis Module (v1.0 - 2018)
KITS Drop Jump Analysis Module (v1.0 - 2017)

Appendix 5: Athlete Injury Prediction

Identification	Left	Right	Combined	Risk
97VR	32.91	38.28	35.595	Low
58DE/004	93.65	55.19	74.42	High
41KU	28.9	40.65	34.775	Low
39MA	4.49	33.79	19.14	Low
49AL	26.4	37.89	32.145	Low
55CA	23.33	59.77	41.55	High
69SO	7.04	3.61	5.325	Low
75CO	6.86	7.97	7.415	Low
81PA	12.16	0	6.08	Low
82ND	54.73	30.59	42.66	Low
AE_f14	27.72	31.16	29.44	Low
AM_f04	23.33	30.76	27.045	Low
AP_f21	24.87	21.72	23.295	Low
AM_f05	23.33	95.5	59.415	High
DM_f15	40.23	41.89	41.06	Low
AS_f06	6	39.33	22.665	Low
FP_f23	0	48.46	24.23	Low
FB_b01	23.33	26.57	24.95	Low
JH_f12	29.84	37.15	33.495	Low
GB_f07	51.7	23.98	37.84	Low
VD_f16	33.56	39.88	36.72	Low

YR_f13	45.3	48.16	46.73	Low
MP_f18	7.69	41.7	24.695	Low
TT_f22	19.74	18.5	19.12	Low
ML_f20	20.56	41.13	30.845	Low
KB_f03	20.86	11.54	16.2	Low
KK_f09	32.08	25.12	28.6	Low
JW_f08	37.96	38.94	38.45	Low
JH_f19	0	0	0	Low
JS_f17	23.33	23.44	23.385	Low
GQ_SF02	50.79	48.39	49.59	Low
NB_SF04	91.77	15.26	53.515	High
ED_SF02	70.14	92.35	81.245	High
OL_SF06	35.77	84.51	60.14	High
RZ_SF07	16.79	22.55	19.67	Low
RS_SM01	2.29	18	10.145	Low
MM_SM02	23.33	32.96	28.145	Low
SV_SM03	18.68	59.36	39.02	High
TM_SM04	47.07	72.17	59.62	High
NC_RW02	6.8	21.45	14.125	Low
CW_RW03	86.73	63.83	75.28	High
MM_RM01	0	0	0	Low
CC_WH01	76.19	100	88.095	High
ND_MB02	53.42	35	44.21	Low
IC_MB03	23.33	35.33	29.33	Low
AB_MB04	14.1	75.81	44.955	High
AC_MB05	73	63.5	68.25	High
SJ_MB06	23.33	85.04	54.185	High
BL_MB08	26.23	56.82	41.525	High
KL_MB09	25.52	81.96	53.74	High
GT_MB10	45.21	60.82	53.015	High
QW_MB14	72.8	56.98	64.89	High
JD_MB17	12.28	26.98	19.63	Low
RO_MB18	36.95	31.33	34.14	Low
GH_BW01	13.18	35	24.09	Low
GC_BW05	37.25	61.74	49.495	High
RT_BW07	73.57	72.91	73.24	High
CC_BW08	23.12	48.7	35.91	Low
KO_BW09	17.14	10.85	13.995	Low
SM_BW12	7.48	35	21.24	Low
SD_BW13	33.49	78.7	56.095	High
ER_BW14	59.5	20.2	39.85	High
SL_BW15	16.89	87.73	52.31	High

NH_BW16	0	0	0	Low
DS_BW16	50.1	66.42	58.26	High
TV_BW17	0	14.87	7.435	Low
GD_SW03	4.94	36.18	20.56	Low
IP_SW15	17.8	19.21	18.505	Low
MC_SW25	12.83	31.77	22.3	Low
AG_SW29	37.18	56.8	46.99	High
LD_WH10	34.13	56.41	45.27	High
SC_WH12	39.83	28.93	34.38	Low
KD_WH16	15.4	5.02	10.21	Low
NH_WH17	45.79	90.2	67.995	High
LJ_WH22	53.62	62.85	58.235	High
TF_MH02	47.57	35.65	41.61	Low
AP_MH06	23.33	45.18	34.255	Low
FG_MH07	0	0	0	Low
JF_MH11	35.34	23.33	29.335	Low
NP_MH23	4.59	19.17	11.88	Low
BJ_SM07	1.35	77.21	39.28	High
CF_SM08	0	6.27	3.135	Low
RT_SM09	37.41	67.1	52.255	High
CB_SM10	60.2	37.27	48.735	High
DS_SM12	43.3	59.56	51.43	High
JL_SM14	24.84	39.65	32.245	Low
SC_SM16	16.22	15.2	15.71	Low
ME_SM17	3.82	48.84	26.33	Low
JM_SM18	34.19	32.66	33.425	Low
JE_SM19	25.21	47.46	36.335	Low
JM_SM21	46.91	100	73.455	High
FB_SM22	74.73	62.23	68.48	High
AW_SM24	35	35	35	Low
TF_SM25	25.07	32.6	28.835	Low
CC_SM26	7.72	11.78	9.75	Low
SB_SF18	10.14	26.96	18.55	Low
OT_SF19	16.26	17.16	16.71	Low
TL_SF03	55.56	78.51	67.035	High
KV_GP02	84.98	69.78	77.38	High
013	36.46	47.9	42.18	Low
014	44.48	36.36	40.42	Low
KV_GP01	37.15	23.72	30.435	Low
011	54.31	28.28	41.295	Low
012	NA	NA	NA	NA
GH_GP04	7.24	22.85	15.045	Low

CM_GP05	0	14.45	7.225	Low
JA_SM15	0	0	0	Low
010	47.5	91.5	69.5	High
009	79.07	13.25	46.16	High
003	47.77	61.69	54.73	High
005	84.3	54.46	69.38	High
008	26.36	32.81	29.585	Low
006	25.73	60.76	43.245	High
001	23.33	39.17	31.25	Low

Appendix 6: Injured athlete information

ID	Gender	Height (m)	Weight (kg)	BMI (kg/m^2)	Sports Played
BL_MB08	M	1.98	86.18	21.98	Basketball
GT_MB10	M	1.88	82.55	23.25	Basketball
RT_BW07	F	1.8	78.02	24.08	Basketball
ER_BW14	F	1.88	91.63	25.92	Basketball
FB_SM22	M	1.82	82	24.75	Soccer

Table 2: Vicon Lab Data Example (Single jump for 1 participant)

Frames	Time (s)	X	Y	Z	X	Y	Z	DEG to RAD	Left adjusted angle		DEG to RAD	Right adjusted angle	
0.30	2.75	27.173	-24.3125	0.223028	9.53205	-26.5241	16.7217	0.424333174	-0.034969087	-2.003581119	0.462932876	0.016443005	0.942114779
0.60	2.76	24.6819	-24.3802	-0.111233	10.8908	-26.2547	17.8463	0.425514762	-0.033784225	-1.935693504	0.458230959	0.012635144	0.723940422
0.9	2.77	23.247	-24.4729	-0.311663	13.2749	-25.7973	19.2502	0.427132683	-0.032159607	-1.842609744	0.450247823	0.00620941	0.355772963
1.20	2.78	22.9811	-24.5532	-0.326396	16.7704	-25.2261	20.7117	0.428534182	-0.030750233	-1.761858551	0.440278502	-0.001746478	-0.10006583
1.5	2.79	23.9317	-24.5956	-0.188822	21.3784	-24.6441	21.9423	0.429274202	-0.030005277	-1.719175755	0.430120686	-0.009776072	-0.560127677
1.80	2.8	26.075	-24.5841	-0.0236997	27.0194	-24.1294	22.6933	0.429073489	-0.030207382	-1.730755503	0.421137477	-0.016814001	-0.963371299
2.1	2.81	29.32	-24.4995	-0.00213665	33.5267	-23.6942	22.8323	0.42759694	-0.031692954	-1.815872507	0.413541804	-0.022719513	-1.301732218
2.40	2.82	33.5234	-24.3136	-0.261581	40.6053	-23.276	22.3621	0.424352373	-0.034949846	-2.002478695	0.406242837	-0.028355885	-1.62467251
2.70	2.83	38.498	-24.004	-0.848716	47.7777	-22.7587	21.4365	0.418948834	-0.040351136	-2.311949768	0.397214248	-0.035276677	-2.021204721
3	2.84	43.9962	-23.5819	-1.72214	54.4076	-22.0268	20.3584	0.411581799	-0.047669603	-2.731267061	0.384440184	-0.044973873	-2.576813126
3.30	2.85	49.6856	-23.0978	-2.77796	59.878	-21.0401	19.4865	0.40313266	-0.055999087	-3.208511366	0.36721902	-0.057876574	-3.316083417

3.6	2.86	55.1586	-22.6143	-3.87166	63.8315	-19.8663	19.074	0.394693993	-0.064250872	-3.681303807	0.346732345	-0.072980759	-4.181489494
3.90	2.87	60.0094	-22.1713	-4.84762	66.29	-18.6497	19.1572	0.386962184	-0.071753081	-4.111148705	0.32549867	-0.088367229	-5.063069246
4.2	2.88	63.9441	-21.7803	-5.57736	67.5897	-17.5531	19.5684	0.380137947	-0.078328843	-4.487912099	0.306359389	-0.102012956	-5.844911854
4.50	2.89	66.8541	-21.4441	-5.98912	68.22	-16.7112	20.0372	0.37427015	-0.083948998	-4.809923264	0.291665462	-0.112352012	-6.437296094
4.80	2.9	68.8136	-21.1772	-6.08303	68.6543	-16.2	20.3082	0.369611866	-0.088388511	-5.064288664	0.282743339	-0.118573696	-6.793772322
5.1	2.91	70.021	-21.0085	-5.93171	69.2151	-16.0172	20.2299	0.366667496	-0.091184553	-5.22449007	0.279552877	-0.120788433	-6.920667398
5.40	2.92	70.7229	-20.9668	-5.66298	70.0061	-16.0855	19.7953	0.365939694	-0.091874497	-5.264020909	0.280744937	-0.119961551	-6.873290549
5.7	2.93	71.1485	-21.0657	-5.42624	70.9358	-16.2883	19.1281	0.367665824	-0.090237387	-5.17022143	0.284284465	-0.117501996	-6.732368471
6.00	2.94	71.4663	-21.2986	-5.3497	71.8123	-16.5228	18.4224	0.371730696	-0.086371612	-4.94872884	0.288377262	-0.114649845	-6.568952243
6.3	2.95	71.7643	-21.6442	-5.50453	72.4513	-16.7454	17.8606	0.377762554	-0.080607754	-4.618484079	0.292262365	-0.111934275	-6.413361557
6.60	2.96	72.0541	-22.0757	-5.88953	72.7439	-16.9765	17.5507	0.38529365	-0.073364812	-4.203494107	0.29629582	-0.109106524	-6.251343354
6.90	2.97	72.2959	-22.5711	-6.44033	72.6747	-17.2712	17.5042	0.393940011	-0.064984909	-3.723361031	0.301439306	-0.105487882	-6.044010407
7.2	2.98	72.431	-23.1153	-7.05557	72.3022	-17.6756	17.6529	0.403438093	-0.055699161	-3.191326872	0.308497417	-0.100498781	-5.758156017
7.50	2.99	72.409	-23.6959	-7.62835	71.7233	-18.1993	17.8839	0.413571474	-0.045698192	-2.618313508	0.317637707	-0.093996858	-5.385623251
7.8	3	72.2032	-24.2957	-8.07173	71.0447	-18.8158	18.0754	0.424039959	-0.035262904	-2.020415583	0.328397661	-0.086282161	-4.943603701
8.10	3.01	71.8123	-24.8884	-8.33458	70.3575	-19.4723	18.1311	0.434384526	-0.024846147	-1.423579342	0.339855748	-0.077992993	-4.468669346
8.4	3.02	71.2548	-25.4416	-8.40804	69.7132	-20.0974	18.0079	0.444039687	-0.015028054	-0.861044056	0.350765801	-0.070027531	-4.012281958
8.70	3.03	70.5609	-25.9234	-8.32211	69.1141	-20.6143	17.7241	0.452448683	-0.006400985	-0.366749447	0.359787408	-0.06338587	-3.631742829
9.00	3.04	69.7657	-26.3091	-8.1336	68.5281	-20.9618	17.3403	0.459180418	0.000557016	0.03191466	0.365852427	-0.058892292	-3.37427798
9.3	3.05	68.9046	-26.5825	-7.90886	67.9189	-21.1142	16.9246	0.463952148	0.005517221	0.316113472	0.368512309	-0.056914244	-3.260945983
9.60	3.06	68.0107	-26.7362	-7.70639	67.274	-21.092	16.5234	0.466634719	0.008316045	0.476474294	0.368124846	-0.057202665	-3.277471298
9.9	3.07	67.1124	-26.7722	-7.56429	66.6131	-20.9563	16.1534	0.467263038	0.008972668	0.514095999	0.365756434	-0.058963595	-3.378365115
10.20	3.08	66.2304	-26.7026	-7.49634	65.9711	-20.7861	15.8155	0.466048289	0.007703566	0.441381813	0.362785884	-0.061167192	-3.50462195
10.5	3.09	65.3766	-26.5504	-7.49579	65.3742	-20.6515	15.5097	0.463391898	0.004933628	0.282676068	0.36043667	-0.062905936	-3.604244637

10.80	3.1	64.5556	-26.3493	-7.54268	64.8287	-20.593	15.241	0.459882041	0.001284885	0.073618489	0.359415653	-0.063660552	-3.647480961
11.10	3.11	63.7682	-26.1407	-7.61117	64.3171	-20.6178	15.0259	0.456241284	-0.002486593	-0.142471273	0.359848495	-0.063340726	-3.629156277
11.4	3.12	63.0154	-25.968	-7.67336	63.8082	-20.7078	14.8912	0.45322771	-0.005598764	-0.320785575	0.361419291	-0.062179082	-3.562598974
11.70	3.13	62.302	-25.8682	-7.70206	63.2748	-20.833	14.8633	0.451485262	-0.007393017	-0.423588673	0.363604443	-0.060560529	-3.469862718
12	3.14	61.6375	-25.863	-7.67435	62.7149	-20.9653	14.9518	0.451394504	-0.007486421	-0.428940313	0.365913514	-0.058846915	-3.371679879
12.30	3.15	61.0381	-25.9523	-7.57753	62.1618	-21.0867	15.1373	0.452953083	-0.005881231	-0.336969704	0.368032343	-0.057271508	-3.28141572
12.6	3.16	60.5261	-26.114	-7.41321	61.6665	-21.1904	15.3821	0.455775281	-0.00296835	-0.170073917	0.36984225	-0.055923529	-3.204182168
12.90	3.17	60.1267	-26.3111	-7.19482	61.2734	-21.2752	15.651	0.459215325	0.000593216	0.033988794	0.371322289	-0.054819669	-3.140935663
13.20	3.18	59.8634	-26.5021	-6.94171	61.003	-21.3373	15.9238	0.462548904	0.004056121	0.232398613	0.372406138	-0.054010408	-3.094568411
13.5	3.19	59.7549	-26.6496	-6.67432	60.8497	-21.3644	16.2015	0.465123264	0.006738175	0.386068995	0.372879123	-0.053657015	-3.074320494
13.80	3.2	59.8101	-26.7276	-6.4075	60.7907	-21.3358	16.5019	0.466484621	0.008159246	0.46749035	0.372379959	-0.054029964	-3.095688904
14.1	3.21	60.0288	-26.7251	-6.14665	60.8028	-21.2303	16.8527	0.466440988	0.008113669	0.464878989	0.370538636	-0.055404317	-3.174433518
14.40	3.22	60.4034	-26.6486	-5.88646	60.8781	-21.0387	17.2783	0.465105811	0.006719969	0.385025843	0.367194585	-0.057894745	-3.317124562
14.7	3.23	60.9204	-26.5208	-5.61411	61.036	-20.7725	17.7864	0.46287528	0.004395773	0.251859239	0.362548519	-0.061343032	-3.514696862
15.00	3.24	61.5609	-26.3781	-5.31493	61.324	-20.4672	18.3582	0.460384695	0.001806654	0.103513636	0.357220029	-0.065281095	-3.740331247
15.30	3.25	62.3033	-26.2664	-4.97762	61.8013	-20.1746	18.9544	0.458435163	-0.000215566	-0.01235105	0.352113195	-0.069038777	-3.955630536
15.6	3.26	63.1248	-26.2349	-4.59677	62.5098	-19.9436	19.5343	0.457885384	-0.00078514	-0.044985208	0.348081485	-0.071994045	-4.124954909
15.90	3.27	64.0027	-26.3291	-4.17307	63.4475	-19.7997	20.0767	0.459529484	0.000919077	0.05265922	0.345569956	-0.073830006	-4.230147743
16.2	3.28	64.9131	-26.5835	-3.71285	64.5606	-19.7351	20.5888	0.463969602	0.005535407	0.317155433	0.344442473	-0.074652969	-4.277300058
16.50	3.29	65.8333	-27.0121	-3.23158	65.7666	-19.7205	21.09	0.471450083	0.01335878	0.765401728	0.344187655	-0.074838858	-4.287950683
16.8	3.3	66.7411	-27.6018	-2.75431	66.9825	-19.7233	21.5894	0.481742289	0.024218072	1.387593292	0.344236524	-0.074803211	-4.285908271
17.10	3.31	67.6115	-28.31	-2.31188	68.137	-19.7185	22.0711	0.494102711	0.037407274	2.143278943	0.344152749	-0.074864319	-4.289409498
17.40	3.32	68.4118	-29.0701	-1.93356	69.1709	-19.6918	22.4953	0.507368959	0.051745048	2.964772854	0.343686746	-0.075204154	-4.308880651
17.7	3.33	69.0992	-29.8047	-1.63702	70.0321	-19.6385	22.8173	0.520190148	0.065783561	3.76912038	0.342756485	-0.075882162	-4.34772764

18.00	3.34	69.6197	-30.4425	-1.41931	70.6706	-19.5609	23.0149	0.531321858	0.078119068	4.475892889	0.34140211	-0.076868352	-4.404232128
18.3	3.35	69.9112	-30.933	-1.25371	71.0354	-19.4645	23.1067	0.539882698	0.08769962	5.024818074	0.339719612	-0.078091934	-4.47433823
18.60	3.36	69.9096	-31.2549	-1.0941	71.0741	-19.3558	23.1498	0.545500912	0.094031803	5.387625428	0.337822439	-0.079469613	-4.553273402
18.9	3.37	69.5557	-31.4169	-0.885606	70.7459	-19.2479	23.2128	0.548328346	0.097232041	5.570985577	0.335939229	-0.080835039	-4.631506555
19.20	3.38	68.8007	-31.4533	-0.578909	70.0363	-19.1671	23.3416	0.548963646	0.097952353	5.612256438	0.334529003	-0.081856154	-4.690012124
19.50	3.39	67.6083	-31.4131	-0.144012	68.9572	-19.1534	23.5396	0.548262023	0.09715687	5.566678593	0.334289893	-0.082029172	-4.699925344
19.8	3.4	65.9496	-31.3472	0.420693	67.5239	-19.2483	23.7726	0.547111851	0.095854038	5.492031854	0.33594621	-0.080829981	-4.631216757
20.10	3.41	63.7907	-31.294	1.08765	65.7255	-19.4765	23.9884	0.546183336	0.094803377	5.43183339	0.339929052	-0.077939713	-4.465616608
20.4	3.42	61.0797	-31.2692	1.80937	63.5182	-19.8418	24.129	0.545750494	0.094313929	5.403790056	0.34630474	-0.073293265	-4.199394751
20.70	3.43	57.7382	-31.2635	2.53428	60.8342	-20.3323	24.1362	0.545651011	0.094201464	5.397346329	0.35486558	-0.067015535	-3.839707323
21	3.44	53.6649	-31.2449	3.2217	57.5852	-20.9255	23.9563	0.545326379	0.093834554	5.376323891	0.365218873	-0.059362779	-3.401236695
21.30	3.45	48.7509	-31.1667	3.84831	53.6621	-21.589	23.5438	0.543961532	0.092293254	5.288013909	0.376799132	-0.050722592	-2.906190463
21.60	3.46	42.9117	-30.9809	4.40247	48.9414	-22.2863	22.8648	0.54071871	0.08863962	5.078676141	0.388969313	-0.041548194	-2.380536189
21.9	3.47	36.1323	-30.6539	4.86788	43.31	-22.9923	21.9069	0.535011484	0.082238114	4.711896836	0.401291338	-0.032158366	-1.84253867
22.20	3.48	28.5179	-30.1792	5.20649	36.7144	-23.717	20.6969	0.526726406	0.073009997	4.183164704	0.413939739	-0.022411144	-1.284063974
22.5	3.49	20.347	-29.5813	5.35802	29.2467	-24.5163	19.3137	0.516291082	0.061495233	3.52341731	0.427890155	-0.011529072	-0.660567144
22.80	3.5	12.1054	-28.9008	5.26076	21.2452	-25.459	17.8873	0.504414116	0.048535083	2.780855415	0.444343374	0.00148834	0.085275592
23.1	3.51	4.45947	-28.1706	4.8854	13.3427	-26.5291	16.5661	0.491669722	0.0347983	1.993795735	0.463020143	0.016513842	0.946173454
23.40	3.52	-1.86703	-27.4143	4.26665	6.39248	-27.5331	15.4513	0.478469797	0.020753227	1.189072324	0.480543248	0.030861192	1.768216031
23.70	3.53	-6.28847	-26.6813	3.51659	1.26134	-28.1562	14.5449	0.465676534	0.007315482	0.419146235	0.491418395	0.039891275	2.285601721
24	3.54	-8.54061	-26.0856	2.80493	-1.44152	-28.1862	13.7935	0.455279607	-0.003480538	-0.199420109	0.491941994	0.040328524	2.310654208
24.30	3.55	-8.75811	-25.7867	2.29483	-1.58865	-27.6964	13.1955	0.450062818	-0.008855982	-0.507410365	0.483393371	0.033218309	1.90326893
24.6	3.56	-7.41751	-25.8971	2.06532	0.404757	-26.9873	12.8265	0.451989662	-0.006873756	-0.393837184	0.471017241	0.023031008	1.319579561
24.90	3.57	-5.18641	-26.3861	2.08711	3.71279	-26.3468	12.7725	0.460524322	0.001951636	0.111820479	0.459838407	0.01393499	0.798416126

25.2	3.58	-2.74261	-27.0737	2.27084	7.3699	-25.8714	13.0826	0.472525206	0.014487959	0.830098887	0.451541112	0.007247054	0.415225623
25.50	3.59	-0.62874	-27.7264	2.53026	10.5688	-25.5003	13.7437	0.48391697	0.026526819	1.519874761	0.445064195	0.002063271	0.118216721
25.80	3.6	0.820276	-28.1747	2.8067	12.8458	-25.1674	14.6367	0.491741281	0.034874944	1.998187128	0.439253994	-0.002559819	-0.146666821
26.1	3.61	1.48236	-28.3659	3.05887	14.0928	-24.8869	15.5255	0.49507835	0.038455263	2.203324271	0.434358346	-0.006435574	-0.368731225
26.40	3.62	1.40984	-28.3411	3.24684	14.449	-24.7211	16.1402	0.494645509	0.037990198	2.17667799	0.43146459	-0.008718122	-0.499511568
26.7	3.63	0.76889	-28.1777	3.32818	14.1615	-24.7101	16.307	0.491793641	0.034931029	2.001400541	0.431272603	-0.008869339	-0.508175671
27.00	3.64	-0.225146	-27.9441	3.26288	13.4762	-24.8373	16.0175	0.487716552	0.030572649	1.751683754	0.433492662	-0.007119059	-0.407892058
27.3	3.65	-1.36303	-27.6859	3.02267	12.5819	-25.0445	15.4027	0.483210111	0.025775835	1.476846587	0.437108985	-0.004260164	-0.244089421
27.60	3.66	-2.47756	-27.4353	2.59976	11.6026	-25.2661	14.6551	0.478836316	0.02114073	1.211274581	0.440976634	-0.001191791	-0.068284616
27.90	3.67	-3.45606	-27.2213	2.01177	10.6149	-25.4539	13.9517	0.475101312	0.017198492	0.985401031	0.444254362	0.001417371	0.081209366
28.2	3.68	-4.23525	-27.0707	1.30123	9.67186	-25.5837	13.4063	0.472472846	0.014432938	0.826946453	0.44465198	0.003225472	0.184805942
28.50	3.69	-4.7885	-27.0009	0.531771	8.8198	-25.6502	13.0552	0.471254606	0.013153604	0.753646017	0.447680444	0.004153322	0.237967845
28.8	3.7	-5.11474	-27.0128	-0.218403	8.10696	-25.658	12.8676	0.47146223	0.013371605	0.766136536	0.447816579	0.00426222	0.244207231
29.10	3.71	-5.23319	-27.0881	-0.86591	7.58195	-25.6167	12.7776	0.472776533	0.014752096	0.845232849	0.447095758	0.003685781	0.211179686
29.4	3.72	-5.18039	-27.1943	-1.33436	7.28328	-25.5415	12.7224	0.474630073	0.016702145	0.956962426	0.445783271	0.002637203	0.151100589
29.70	3.73	-5.00517	-27.2941	-1.5684	7.2263	-25.453	12.6732	0.476371911	0.018537949	1.062146256	0.444238655	0.001404847	0.080491833
30.00	3.74	-4.75973	-27.3551	-1.5475	7.39453	-25.3772	12.6504	0.477436562	0.019661598	1.126526601	0.442915695	0.000350775	0.020097933
30.3	3.75	-4.49008	-27.359	-1.29231	7.73995	-25.3421	12.7157	0.47750463	0.019733479	1.130645037	0.442303084	-0.000136877	-0.007842448
30.60	3.76	-4.22817	-27.3048	-0.862036	8.19345	-25.3707	12.9451	0.476558662	0.018734962	1.07343428	0.442802249	0.000260448	0.014922565
30.9	3.77	-3.99007	-27.205	-0.343118	8.68149	-25.4727	13.3937	0.474816823	0.016898818	0.968230949	0.444582484	0.001679012	0.096200294
31.20	3.78	-3.77999	-27.0804	0.168889	9.14272	-25.6403	14.0678	0.472642143	0.014610848	0.837139914	0.447507656	0.004015126	0.23004979
31.5	3.79	-3.59552	-26.9534	0.587274	9.53859	-25.8494	14.9116	0.470425575	0.012283881	0.703814519	0.45115714	0.006938847	0.397566675
31.80	3.8	-3.4318	-26.8421	0.848211	9.85502	-26.0652	15.8159	0.468483023	0.010248778	0.58721417	0.45492356	0.009966987	0.571066291
32.10	3.81	-3.28255	-26.7575	0.918667	10.0951	-26.2519	16.6448	0.467006475	0.008704498	0.498730976	0.45818209	0.012595658	0.721678043

32.4	3.82	-3.14048	-26.7033	0.796251	10.268	-26.3813	17.2709	0.466060506	0.007716322	0.442112699	0.460440546	0.014422424	0.826344025
32.70	3.83	-2.99707	-26.6784	0.50384	10.3803	-26.44	17.6066	0.465625919	0.007262655	0.416119489	0.461465054	0.015252422	0.873899388
33	3.84	-2.84198	-26.6781	0.0814226	10.4331	-26.4317	17.6209	0.465620683	0.00725719	0.415806386	0.461320192	0.015135012	0.867172338
33.30	3.85	-2.66397	-26.6962	-0.421441	10.4246	-26.3759	17.342	0.465936588	0.007586943	0.434699841	0.460346298	0.014346111	0.821971627
33.6	3.86	-2.45288	-26.7253	-0.952823	10.3515	-26.3036	16.8474	0.466444479	0.008117315	0.465087894	0.459084425	0.013325039	0.763468481
33.90	3.87	-2.20266	-26.7584	-1.46379	10.2108	-26.2477	16.2441	0.467022183	0.008720914	0.499671579	0.458108786	0.012536433	0.718284676
34.20	3.88	-1.91525	-26.7895	-1.91218	9.99854	-26.2332	15.6454	0.46756498	0.009288357	0.532183647	0.457855713	0.012331996	0.706571324
34.5	3.89	-1.60246	-26.8143	-2.26608	9.70865	-26.272	15.1505	0.467997822	0.00974107	0.558122198	0.458532901	0.012879152	0.737921059
34.80	3.9	-1.28572	-26.8294	-2.50557	9.33186	-26.3639	14.8302	0.468261366	0.010016809	0.573920876	0.460136859	0.014176552	0.812256615
35.1	3.91	-0.99218	-26.8319	-2.62385	8.8568	-26.5007	14.7219	0.468305	0.010062468	0.57653695	0.462524469	0.016111566	0.923124754
35.40	3.92	-0.748073	-26.8203	-2.62679	8.27492	-26.6706	14.8315	0.468102541	0.009850627	0.564399325	0.465489783	0.01852103	1.061176871
35.7	3.93	-0.570207	-26.7924	-2.53281	7.58688	-26.8617	15.1423	0.467615595	0.009341285	0.53521621	0.468825108	0.021239479	1.216932533
36.00	3.94	-0.459364	-26.7448	-2.36835	6.81068	-27.0628	15.6256	0.466784818	0.008472868	0.485459574	0.472334965	0.024109777	1.381388445
36.30	3.95	-0.394175	-26.6746	-2.15942	5.99082	-27.2628	16.2492	0.465559597	0.007193438	0.412153637	0.475825623	0.026974205	1.54550812
36.6	3.96	-0.325551	-26.5811	-1.92383	5.20687	-27.4499	16.9829	0.463927714	0.005491762	0.314654756	0.479091134	0.02966282	1.699554407
36.90	3.97	-0.173222	-26.4665	-1.66648	4.58116	-27.6101	17.7981	0.461927566	0.003409814	0.195367931	0.481887152	0.0319718	1.831849192
37.2	3.98	0.174955	-26.3366	-1.37779	4.28186	-27.7237	18.6588	0.459660384	0.001054882	0.060440275	0.483869846	0.033613017	1.925884014
37.50	3.99	0.860095	-26.2011	-1.03724	4.51686	-27.7621	19.5134	0.457295463	-0.001395958	-0.079982484	0.484540052	0.034168527	1.957712403
37.8	4	2.03995	-26.0718	-0.620709	5.512	-27.6864	20.2925	0.455038752	-0.003729327	-0.2136747	0.483218838	0.033073775	1.894987699
38.10	4.01	3.8667	-25.9609	-0.112124	7.47291	-27.454	20.9166	0.453103182	-0.005726513	-0.328105053	0.479162693	0.029721834	1.702935659
38.40	4.02	6.45772	-25.8774	0.482939	10.5319	-27.0318	21.3134	0.451645832	-0.007227744	-0.414119215	0.471793913	0.02366667	1.356000288
38.7	4.03	9.86606	-25.8212	1.12426	14.6825	-26.4105	21.4387	0.450664957	-0.00823694	-0.471941893	0.460950182	0.014835199	0.849994283
39.00	4.04	14.0585	-25.7785	1.73083	19.7224	-25.6058	21.2937	0.449919701	-0.009003062	-0.51583746	0.446905518	0.003533712	0.202466758
39.3	4.05	18.9096	-25.7226	2.19351	25.2465	-24.6413	20.9361	0.448944062	-0.010005169	-0.573253965	0.430071817	-0.009814518	-0.562330467

39.60	4.06	24.2239	-25.6203	2.41788	30.7331	-23.5298	20.498	0.44715859	-0.011836589	-0.678186622	0.410672482	-0.024939707	-1.428939944
39.9	4.07	29.7913	-25.4436	2.37395	35.7159	-22.2854	20.1838	0.444074594	-0.014992389	-0.859000625	0.388953605	-0.041560099	-2.381218273
40.20	4.08	35.4426	-25.1925	2.09377	39.9633	-20.9742	20.1776	0.439692072	-0.019460538	-1.115006686	0.366068848	-0.058731517	-3.365068042
40.50	4.09	41.0693	-24.9202	1.62829	43.5715	-19.7516	20.51	0.43493954	-0.024284278	-1.391386649	0.344730453	-0.074442843	-4.265260691
40.8	4.1	46.6027	-24.7302	1.0269	46.904	-18.8271	21.0253	0.431623415	-0.027636827	-1.583473523	0.328594884	-0.086140135	-4.935466173
41.10	4.11	51.9708	-24.732	0.347688	50.3834	-18.3625	21.4689	0.431654831	-0.027605117	-1.581656672	0.320486084	-0.091961065	-5.26898088
41.4	4.12	57.0655	-24.9785	-0.334422	54.2415	-18.3742	21.6209	0.435957067	-0.023253393	-1.332321284	0.320690287	-0.091814939	-5.260608504
41.70	4.13	61.7421	-25.4311	-0.935366	58.3816	-18.7084	21.409	0.443856427	-0.015215273	-0.871770917	0.326523178	-0.087630918	-5.020881745
42	4.14	65.85	-25.9702	-1.38018	62.4373	-19.1023	20.9533	0.453265497	-0.005559177	-0.318517386	0.33339803	-0.082674221	-4.736883926
42.30	4.15	69.2679	-26.4414	-1.62215	65.9672	-19.3034	20.5076	0.461489489	0.002954369	0.169272889	0.336907887	-0.080132973	-4.59128118
42.60	4.16	71.9262	-26.7067	-1.65567	68.6576	-19.1793	20.3155	0.466119847	0.007778284	0.44566284	0.334741933	-0.08170205	-4.68118267
42.9	4.17	73.8139	-26.6815	-1.51985	70.4236	-18.7464	20.4775	0.465680024	0.007319125	0.419354982	0.327186403	-0.087153937	-4.993552745
43.20	4.18	74.9801	-26.3509	-1.28892	71.3874	-18.124	20.9198	0.459909966	0.001313865	0.075278941	0.316323474	-0.094934618	-5.439352958
43.5	4.19	75.5295	-25.7671	-1.0485	71.7825	-17.4641	21.4641	0.449720734	-0.009207506	-0.527551205	0.304806046	-0.103111473	-5.907852206
43.80	4.2	75.6041	-25.0327	-0.867027	71.8536	-16.8963	21.9283	0.436903036	-0.022294085	-1.27735695	0.294896066	-0.11008884	-6.30762592
44.1	4.21	75.3549	-24.2737	-0.775191	71.7962	-16.5037	22.1947	0.423655987	-0.035647537	-2.042453448	0.288043904	-0.114882481	-6.582281303
44.40	4.22	74.9126	-23.6086	-0.762876	71.7317	-16.3214	22.2332	0.412047802	-0.047208218	-2.704831653	0.284862169	-0.117099942	-6.709332467
44.70	4.23	74.3691	-23.1244	-0.793003	71.7036	-16.3468	22.0924	0.403596918	-0.055543165	-3.182388938	0.285305482	-0.116791299	-6.691648528
45	4.24	73.7745	-22.8645	-0.823841	71.692	-16.552	21.8716	0.399060807	-0.059989119	-3.43712332	0.288886898	-0.114294079	-6.548568355
45.30	4.25	73.1465	-22.8292	-0.825814	71.6377	-16.8949	21.683	0.398444706	-0.06059148	-3.471636095	0.294871632	-0.110105979	-6.308607875
45.6	4.26	72.4837	-22.9849	-0.78721	71.4677	-17.3273	21.615	0.401162183	-0.05793192	-3.319254519	0.302418435	-0.104797402	-6.004448834
45.90	4.27	71.7757	-23.2745	-0.710417	71.1189	-17.7991	21.7022	0.406216657	-0.052966634	-3.034764563	0.310652899	-0.098969686	-5.670545333
46.2	4.28	71.0071	-23.6284	-0.603002	70.5649	-18.2648	21.9081	0.412393377	-0.046865933	-2.685220169	0.318780897	-0.093180349	-5.338840748
46.50	4.29	70.1592	-23.9749	-0.472479	69.8198	-18.6891	22.1438	0.418440943	-0.040857358	-2.340954177	0.326186329	-0.087873077	-5.034756423

46.80	4.3	69.2123	-24.2514	-0.327085	68.915	-19.0503	22.3158	0.423266778	-0.036037269	-2.064783425	0.332490458	-0.083330151	-4.77446596
47.1	4.31	68.1475	-24.4148	-0.177182	67.8798	-19.3445	22.3646	0.426118646	-0.033178141	-1.900967433	0.337625217	-0.079612708	-4.56147214
47.40	4.32	66.9508	-24.4467	-0.032212	66.7353	-19.584	22.2748	0.426675406	-0.032619036	-1.868933089	0.341805281	-0.076574897	-4.387418436
47.7	4.33	65.6167	-24.3546	0.104697	65.4912	-19.7903	22.0703	0.425067958	-0.034232428	-1.961373635	0.345405895	-0.073949804	-4.237011651
48.00	4.34	64.1502	-24.1667	0.237379	64.1455	-19.9877	21.8026	0.421788484	-0.037516206	-2.14952027	0.348851175	-0.071430624	-4.092673266
48.3	4.35	62.567	-23.9255	0.371262	62.6944	-20.1978	21.5313	0.41757875	-0.041716147	-2.390159167	0.352518112	-0.068741421	-3.938593283
48.60	4.36	60.89	-23.6802	0.506312	61.1446	-20.4384	21.3057	0.413297458	-0.045969918	-2.633882314	0.356717374	-0.065651672	-3.761563729
48.9	4.37	59.1447	-23.4794	0.63449	59.512	-20.7229	21.1624	0.409792836	-0.049438907	-2.8326407	0.361682836	-0.061984032	-3.551423454
49.20	4.38	57.3512	-23.3663	0.7434	57.8144	-21.0577	21.1248	0.407818869	-0.051387636	-2.944294635	0.367526198	-0.057648101	-3.302992874
49.5	4.39	55.5163	-23.376	0.823656	56.0648	-21.4391	21.2021	0.407988166	-0.051220649	-2.934727	0.374182884	-0.052682155	-3.018465161
49.80	4.4	53.6333	-23.5343	0.875893	54.2698	-21.8543	21.3875	0.410751022	-0.048491631	-2.778365801	0.381429491	-0.047243535	-2.706855177
50.1	4.41	51.6904	-23.8553	0.914595	52.4341	-22.2871	21.6587	0.416353529	-0.042935296	-2.460011267	0.388983276	-0.041537612	-2.379929885
50.40	4.42	49.677	-24.339	0.966991	50.5674	-22.724	21.9811	0.424795687	-0.034505456	-1.977016985	0.396608619	-0.035738916	-2.047689054
50.7	4.43	47.5878	-24.9698	1.06812	48.6839	-23.1562	22.3158	0.435805224	-0.023407295	-1.341139232	0.404151932	-0.029963655	-1.716790981
51.00	4.44	45.4246	-25.7164	1.25155	46.7959	-23.5771	22.63	0.448835852	-0.010116256	-0.579618768	0.411498023	-0.024301523	-1.392374703
51.3	4.45	43.1978	-26.5344	1.54079	44.9107	-23.9797	22.9016	0.463112645	0.004642861	0.266016367	0.418524719	-0.018850026	-1.08002691
51.60	4.46	40.9259	-27.3716	1.94386	43.0324	-24.357	23.1203	0.477724542	0.01996574	1.143952656	0.425109846	-0.013709063	-0.78547145
51.9	4.47	38.633	-28.1744	2.4519	41.1622	-24.7004	23.2851	0.491736045	0.034869336	1.997865796	0.431103307	-0.009002662	-0.515814545
52.20	4.48	36.3448	-28.8946	3.0411	39.3032	-25.001	23.3997	0.504305906	0.048417709	2.774130402	0.436349766	-0.004861172	-0.278524659
52.50	4.49	34.0869	-29.4947	3.67818	37.4656	-25.2521	23.4662	0.514779627	0.059837375	3.428429041	0.440732288	-0.001385973	-0.079410427
52.8	4.5	31.8833	-29.9514	4.32579	35.6637	-25.4507	23.4842	0.522750546	0.068608687	3.930988225	0.444198512	0.001372844	0.078658184
53.10	4.51	29.7564	-30.2566	4.94697	33.9096	-25.6009	23.453	0.52807729	0.074509428	4.269075775	0.446819996	0.003465359	0.198550452
53.4	4.52	27.7276	-30.4158	5.50702	32.2105	-25.7124	23.3728	0.530855855	0.07759991	4.446147335	0.448766039	0.005022106	0.2877455
53.70	4.53	25.8157	-30.4451	5.97369	30.5705	-25.7982	23.2432	0.531367236	0.078169636	4.478790201	0.450263531	0.006222005	0.356494619

54	4.54	24.0379	-30.3684	6.31676	28.9911	-25.8731	23.0643	0.530028569	0.076678855	4.393374787	0.451570783	0.007270875	0.416590448
54.30	4.55	22.4075	-30.215	6.50991	27.4664	-25.9499	22.8398	0.527351233	0.073703281	4.222886912	0.452911196	0.008347717	0.478288963
54.6	4.56	20.9255	-30.0142	6.53827	25.9793	-26.0369	22.5789	0.523846612	0.069820295	4.000408201	0.454429632	0.009569253	0.548277784

Table 4: Kinect Data Example

Frame	Left Coronal:	Right Coronal:	Left Sagittal:	Right Sagittal:
1	-2	17.04	27.5	35.94
2	-2.05	16.92	32.23	50.56
3	-3.79	16.88	56.67	68.95
4	0.57	15.91	62.94	87.18
5	0.12	14.41	94.35	93.57
6	0.66	-7.2	101.18	100.47
7	0.4	-5.7	102.4	102.55
8	0.5	-4.65	101.96	102.04
9	1.5	-4.74	101.25	101.14
10	2.62	-2.4	93.72	98.78
11	3.54	-2.61	87.58	94.31
12	2.9	-2.62	89.49	96.79
13	3.54	-1.88	49.15	105.31
14	3.62	-2.56	51.56	102.69
15	-2.02	-2.39	98.78	99.53
16	-0.41	-2.54	95.51	99.97
17	-2.51	-0.91	97.89	99.93
18	-0.92	-2.52	102.81	98.25
19	4.76	0.98	75.04	92.57
20	5.27	-0.91	91.28	92.1
21	5.57	0.13	73.2	72.65
22	3.83	-0.86	57.28	50.57
23	4.1	-2.18	25.87	36.24
24	-0.99	2.57	11.15	9.22
25	0.93	2.16	6.83	4.87
26	2.98	-0.71	4.93	10.05
27	3.19	-1.64	3.08	12.87
28	0.41	-2.74	6.81	9.08
29	0.43	-1.79	13.22	7.04
30	-2.53	-1.81	12.19	7.01
31	-0.26	0.3	4.82	4.73
32	0.02	0.55	3.69	6.24
33	0.62	0.24	5.3	4.49
34	-0.08	0.65	4.3	5.75
35	-2.97	0.33	6.89	5.57
36	-3.04	2.13	8.34	4.85
37	-2.83	2.54	6.25	3.73
38	-1.76	1.78	5.96	5.07
39	-2.03	1.16	15.32	15.77

40	-3.55	-0.52	35.03	33.87
41	-3.3	-3.36	59.67	53.02
42	-1.83	-0.94	59	71.33
43	1.89	-0.23	87.58	84.21
44	0.49	-4.23	102.1	102.42
45	0.24	-5.08	103.25	102.78
46	-1.04	-4.99	87.03	102.18
47	-1.2	-4.29	102.87	101.99
48	-0.94	-3.39	101.98	99.71
49	-1.77	-2.02	94.48	92.02
50	-1.58	-1.33	90.56	89.07
51	-0.95	-2.29	81.89	80.87
52	-0.25	-1.61	77.16	75.44
53	0.72	-1.98	69.79	68.78
54	1.23	-2.52	63.74	62.33
55	-4.09	-0.66	58.94	47.6
56	-0.26	-0.24	32	32.14
57	-1.2	0.06	20.5	19.68
58	-1.27	-0.21	18.86	16.4
59	-0.35	0.3	14.96	9.53
60	-0.85	-0.16	13.02	7.26
61	-1.44	-0.62	8.81	6.64
62	-2.22	-0.68	7.22	5.68
63	-2.29	-0.85	6.15	5.43
64	-2.25	-0.83	4.79	5.24
65	-2.06	-0.78	4.64	5.23

Table 12: Knee laxity data

Identification	KT 1000 Results (mm)	
97VR	R: 6.5	L: 7
58DE/004	R: 4	L: 3
41KU	R: 6	L: 5.5
39MA	R:2	L:2.5
49AL	R:2	L:2
55CA	R:5	L:5
69SO	R:2	L:5
75CO	R:2	L:6
81PA	R:8	L:5
82ND	R:3	L:6
AP_f21	R:5	L:8
AM_f05	R:7	L:6.5
AS_f06	R:10	L:4
FP_f23	R:3	L:6
GB_f07	R:5	L:3
VD_f16	R:6	L:6
YR_f13	R:2	L:2

MP_f18	R:1	L:6
TT_f22	R:3	L:3
ML_f20	R:8	L:5
KB_f03	R:4	L:1
KK_f09	R:4	L:5
JW_f08	R:6	L:4
JH_f19	R:3	L:6
JS_f17	R:4	L:3