Assessment Tool for Widespread Screening of Anterior Cruciate Ligament Injury Risk

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1.0 Abstract

Knee kinematics during a drop vertical jump (DVJ) were previously shown to be associated with an increased risk of non-contact anterior cruciate ligament (ACL) injury. However, standard motion analysis systems used to quantify knee kinematics are not practical for routine screening. Thus, the present study serves to investigate the predictive capabilities of a portable motion capture tool using initial coronal abduction (IC), peak coronal abduction (PC), and peak flexion (PF) angles during a DVJ to assess for non-contact ACL injury risk.

A total of 405 varsity athletes were recruited. Each participant performed three DVJs at the beginning of their respective seasons and were prospectively followed for non-contact ACL injury until the end of their season. IC, PC, and PF angles during a DVJs were measured using our portable motion capture tool.

The mean difference in PF angles between the injured (86.23±13.60) and uninjured (102.51±17.47) groups was 16.7° ($p \leq 0.05$). Receiver operating characteristic (ROC) analysis found that the area under the curve (AUC) for PF was 0.776 ($P = 0.021$, 95% confidence interval (CI): 0.629-0.923), from which a cut off of 95.17° was obtained with 83% sensitivity and 67% specificity. The AUC for IC was 0.381 ($P = 0.321$, 95% CI: 0.182-0.580), from which a cut off of -1.12° was obtained with 67% sensitivity and 24% specificity. The AUC for PC was 0.401 ($P = 0.408$, 95% CI: 0.244-0.558), from which a cut off of -2.60° was obtained with 67% sensitivity and 25% specificity. When using IC, PC, and PF cut off angles together, all non-contact ACL injuries this season were predicted.

These findings suggest a portable motion capture tool using PF angles alone could effectively predict non-contact ACL injury. Further development of a portable motion capture tool would facilitate widespread screening, thus increasing enrollment in injury prevention programs and ultimately decreasing the incidence of non-contact ACL injuries.

2.0 Résumé

Il a été démontré que des variables biomécaniques du genou lors d'un saut vertical en chute (SVC) sont associée à un risque accru de blessure sans contact du ligament croisé antérieur (LCA). Cependant, les systèmes standard d'analyse de variables utilisés pour quantifier les variables biomécaniques du genou ne sont pas pratiques pour le dépistage de routine. Ainsi, la présente étude sert à examiner les capacités de dépistage d'un outil d'évaluation portable utilisant les angles d'abduction coronale initiale (IC), d'abduction coronale maximale (PC) et de flexion maximale (PF) pendant un SVC pour évaluer le risque de blessure du LCA sans contact.

Au total, 405 athlètes universitaires ont été recrutés. Chaque participant a effectué trois SVC au début de leur saison respective et a été suivi de manière prospective pour les blessures du LCA sans contact jusqu'à la fin de leur saison. Les angles IC, PC et PF pendant un SVC ont été mesurés à l'aide de notre outil d'évaluation portable.

La différence moyenne des angles PF entre les groupes blessés (86,23±13,60) et non blessés (102,51±17,47) était de 16,7 ($p \leq 0,05$). L'analyse de la caractéristique d'exploitation du récepteur (ROC) a révélé que l'aire sous la courbe (AUC) pour PF était de 0,776 ($P = 0,021$, intervalle de confiance de 95 %: 0,629-0,923), à partir de laquelle un seuil de 95,17 a été obtenu avec une sensibilité de 83 % et une spécificité de 67 %. L'AUC pour l'IC était de 0,381 ($P = 0,321$, intervalle de confiance à 95 %: 0,182-0,580), à partir de laquelle un seuil de -1,12 a été obtenu avec une sensibilité de 67 % et une spécificité de 24 %. L'AUC pour la PC était de 0,401 ($P = 0,408$, intervalle de confiance à 95 %: 0,244-0,558), à partir de laquelle un seuil de -2,60 a été obtenu avec une sensibilité de 67 % et une spécificité de 25 %. L'utilisation conjointe des seuils pour les angles IC, PC et PF a permis de prédire toutes les blessures du LCA sans contact de la saison.

Ces résultats suggèrent qu'un outil d'évaluation portable utilisant les angles PF seuls pourraient prédire efficacement les blessures du LCA sans contact. La poursuite du développement d'un outil d'évaluation portable faciliterait un dépistage généralisé. Ceci augmenterait le nombre d'inscriptions aux programmes de prévention des blessures et, finalement, réduirait l'incidence des blessures du LCA sans contact.

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4.0 Contribution of Authors

All chapters were written by Patrik Abdelnour. Dr. Paul Martineau provided advisory feedback for all chapters.

5.0 Introduction

Anterior cruciate ligament (ACL) injuries are becoming increasingly common among athletes, and a source of financial burden and morbidity. In North America, over 250,000 individuals sustain ACL injuries each year (Filbay & Grindem, 2019). The cost associated with ACL reconstruction approaches $1 billion dollars annually in the United States alone, with the total cost associated of the direct and indirect management of ACL injuries exceeding $7 billion dollars per year (Kaeding, Léger-St-Jean, & Magnussen, 2017; Musahl & Karlsson, 2019). In addition, ACL injuries can lead to significant time away from sport participation and physical activity, which may have negative repercussions on an athletes' physical and mental health (Dallinga, Benjaminse, & Lemmink, 2012). Furthermore, the sequelae from these injuries can lead to increased morbidity and osteoarthritis (Keays, Newcombe, Bullock-Saxton, Bullock, & Keays, 2010; Lohmander, Englund, Dahl, & Roos, 2007; Neuman et al., 2008).

Over 70% of ACL injuries occur without physical contact from another athlete or object, which are defined as non-contact ACL injuries (Boden, Dean, Feagin, & Garrett, 2000; Yu & Garrett, 2007). Regardless of performance levels, individuals with poor neuromuscular control of their lower limb biomechanics are at an increased risk for non-contact ACL injuries due to their decreased ability to dynamically stabilize their knee during periods of high stress, such as during pivoting and landing (Hewett et al., 2005; Hewett, Roewer, Ford, & Myer, 2015). Preventative measures to decrease the overall risk of non-contact ACL injury include neuromuscular training and specialized injury prevention programs focused on improving biomechanical variables, where high risk individuals benefit from the largest improvement in biomechanical variables (Hewett, Ford, & Myer, 2006; Hewett, Ford, Xu, Khoury, & Myer, 2017). Two commonly used injury prevention programs are the FIFA11+ and Prevent injury and Enhance Performance (PEP) programs, which were found to decrease the overall risk of non-contact ACL injury by 77% in males and 70% in females, respectively (Gilchrist et al., 2008; H. J. Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2017). However, studies show that compliance rates under 66 to 75% of the program's overall intended volume (session frequencies + durations) result in drastic decreases in the effectiveness of these injury prevention programs (Bisciotti, Chamari, Cena, Carimati, & Volpi, 2016; Dai Sugimoto et al., 2012; D. Sugimoto, Myer, Foss, & Hewett, 2014). Moreover, a meta-analysis conducted by Sugimoto et al. (2012) found that four among the six studies included in their analysis reported compliance rates of less than 50%, which is below the aforementioned 66 to 75% compliance threshold for injury prevention program effectiveness. Given the effectiveness of injury prevention programs, their increased effectiveness for high risk individuals, the importance of compliance on their effectiveness, and their reported lack of compliance, the identification of high-risk individuals for non-contact ACL injury is crucial.

In a prospective cohort study conducted by Hewett et al. (2005) on 205 healthy females, knee kinematics during a drop vertical jump (DVJ) were found to be correlated with non-contact ACL injury, where dynamic knee valgus showed a predictive r^2 of 0.88. Specifically, a greater initial knee coronal abduction angles (IC), greater peak knee coronal abduction angles (PC), and smaller peak knee sagittal flexion angles (PF) were associated to non-contact ACL injury. Although this study demonstrated promising risk factors for non-contact ACL injury risk, the motion analysis labs used to obtain these data have significant barriers to routine use, such as costing $150,000, not being portable, and requiring over 2 hours in testing time by trained personnel (A. D. Gray et al., 2017; Hewett et al., 2005; Hewett et al., 2015). Therefore, a feasible assessment tool to identify individuals with poor neuromuscular control who are at risk for non-contact ACL injury is urgently needed.

Technological advances have resulted in the development of more affordable and portable motion tracking technology. One such device is the Microsoft Xbox Kinect V2 (Microsoft Corporation, Redmond WA), which is equipped with infrared depth sensors and skeletal tracking to allow for accurate and inexpensive kinematic assessment (Livingston, Sebastian, Ai, & Decker, 2012). A recent investigation by Gray et al. (2017) found that the intraclass correlation coefficients (ICC) for the Microsoft Xbox Kinect V2 (Kinect) and the Vicon motion analysis system (Vicon, Denver CO) when measuring the knee ankle separation ratios (KASR) at initial contact and at peak flexion during a DVJ were 0.84 and 0.95 respectively, showing good to excellent agreement between the two system. Furthermore, in a validation study our group previously conducted, we found good to excellent agreement between our Kinect-based tool and a Vicon motion analysis system when measuring IC, PC and PF angles during a DVJ, where ICC values were over 0.77 for all angles (unpublished data, 2022). Using this same Kinect-based tool, our group conducted a subsequent study, where we established cut offs for IC, PC and PF angle with good combined sensitivity and specificity to be used in dichotomizing athletes into high and low risk (unpublished data, 2022). These cut offs were obtained from a cohort of 114 varsity athletes.

The purpose of the present study was to assess the predictive value of knee kinematics for non-contact ACL injury using a practical Kinect-based tool on a larger and more generalized cohort of young varsity athletes. We hypothesize that cut off IC, PC, and PF angles will have good combined specificity and sensitivity, and that athletes who sustain non-contact ACL injury will have more valgus IC, more valgus PC, and smaller PF knee angles during a DVJ compared to uninjured athletes. This hypothesis is consistent with the findings in the literature and in our previous investigation (Hewett et al., 2005).

Before diving into the present investigation, it is important to first understand ACL injuries. Therefore, in the next section, the following will be described; 1. the anatomy of the ACL; 2. diagnosis of ACL injury; 3. current treatment and prevention methods, and 4. current challenges with diagnosis and prevention.

6.0 Literature review

6.1 Anatomy of the ACL

6.1.1 Structural Anatomy of the ACL

The knee joint is a modified hinge joint that allows for flexion, extension, as well as slight internal and external rotation. The knee is composed of three primary bones consisting of the femur, tibia and patella. The femur lies above the tibia, while the patella lies anteriorly to both of these structures serving as protection for the knee joint, amongst other functions (A. J. S. B. M. S. M. S. Fox, Wanivenhaus, & Rodeo, 2012). In addition to skeletal structures, the knee consists of four main ligaments that provide stability to the joint; the lateral and medial collateral ligaments (LCL and MCL respectively), the anterior cruciate ligament (ACL), and the posterior cruciate ligament (PCL). The LCL originates on the lateral epicondyle of the femur and inserts on the fibula head. The MCL originates on the medial aspect of the distal femur and inserts on the medial aspect of the proximal tibia. The LCL and MCL together provide protection during sideway knee movements. The ACL originates from the lateral condyle of the femur and inserts into the anterior side of the tibia. There are two major bundles in the ACL; the anteromedial bundle and the posterolateral bundle (Takahashi, Doi, Abe, Suzuki, & Nagano, 2006). The primary function of the ACL is to prevent the tibia from translating in forward relative to the femur. The posterior cruciate ligament (PCL) forms a cross with the ACL in the inner portion of the knee. Finally, the PCL originates in the medial condyle of the femur and inserts into the posterior side of the tibia. The primary function of the PCL is to prevent the tibia from translating backward relative to the femur. Together, the ACL and PCL also serve to stabilize the knee joint during rotational movements, due to the resulting cross structure (Amis & Dawkins, 1991). Although the ACL and PCL have overall similar functions, the PCL is thicker, and therefore stronger, than the ACL. Specifically, the PCL has a cross-sectional area 140% larger than that of the ACL (Trilha Junior, Fancello, Roesler, & More, 2009). Furthermore, these physical differences could explain why we observe a higher incidence of ACL injuries than PCL injuries (Naraghi & White, 2014). In addition, when the ACL ligament tears, it has a very limited capacity to self-regenerate (Fan, Liu, Toh, & Goh, 2009).

6.1.2 Micro Anatomy of the ACL

The ACL is primarily composed of bundles of type I collagen fibers. The bundles of type I collagen fibers are separated by type III collagen fibrils. Between collagen fibrils is a single layer of elongated fibroblast cells. However, the composition of the ACL is not consistent throughout the entirety of the ligament. Approximately 5-10 mm proximal to the tibial ACL insertion in the anterior portion of the ligament lies a fibrocartilaginous zone where cells are arranged into columns and have round to ovoid shapes (Petersen & Tillmann, 1999). This zone corresponds to the area where the ligament impinges on the anterior rim of the femoral intercondylar fossa during knee extension. The compressive force applied during knee extension could explain the emergence of this fibrocartilaginous zone (Petersen & Tillmann, 1999).

Similarly to its composition, the vascularization of the ACL is also not homogenous. The main blood supply for the ACL is from the middle geniculate artery. The distal part of the cruciate ligaments is vascularized by branches of the lateral and medial inferior geniculate artery. However, the fibrocartilaginous zone of the ACL is avascular (Petersen & Tillmann, 1999). A study conducted by Giori et al. found that the avascular regions in ligaments have poor healing abilities (Giori, Beaupre, & Carter, 1993). This would explain why the ACL has a very limited capacity to regenerate on its own and requires more invasive treatments for it to heal, such as ACL reconstruction surgery (Fan et al., 2009).

6.2 Etiology

6.2.1 Types of ACL Injury

There are 2 main types of ACL injury; direct contact and non-contact ACL injury. Direct contact ACL injury refers to when an ACL injury arises due to direct contact with another individual, such as during a collision between two individuals. Non-contact ACL injuries refer to when an ACL injury arises without an external force applied by another individuals, which accounts for 72% of ACL injuries (Boden et al., 2000; Tron Krosshaug et al., 2007).

ACL injuries are also divided into 3 main grades; grade 1, grade 2, and grade 3 ACL sprains (JohnsHopkins, 2022). Grade 1 ACL sprains refers to cases where the ACL is still intact, and functional to a certain degree, but has been stretched beyond its normal range (JohnsHopkins, 2022). Grade 2 ACL sprains refers to cases where the ACL has also been stretched beyond its normal range, but also suffered a partial tear (JohnsHopkins, 2022). Grade 3 ACL sprains refers to cases where the ACL is completely torn and no longer fulfils any of its intended structural functions (JohnsHopkins, 2022).

6.2.2 Mechanism of ACL Injury

ACL injuries occur when excess strain is applied on the ligament. Non-contact ACL injuries typically transpire during sudden deceleration, change in direction or landing maneuvers (Boden et al., 2000; Tron Krosshaug et al., 2007). These movements are often characterized by high amounts of force being applied on the knee joint while it is relatively to fully extended. In this position of the knee joint, the ACL is fully tensed, which would explain why added forces could now strain the ACL beyond its normal capabilities. This mechanism could justify why non-contact ACL injuries typically occur during sudden deceleration, change in direction or landing maneuvers (Boden et al., 2000; Tron Krosshaug et al., 2007).

6.3 ACL Injury Risk

6.3.1 Risk Groups

Between 1985 and 1988, the overall incidence of ACL injury in the United States was 1 for every 3000 individuals, roughly 0.3% (Miyasaka, 1991). Studies have found evidence suggesting that ACL injury incidence rates differ as a function of age. A study conducted by Beck et al. (2017) investigated the ACL injury incidence rates at different ages and found that ACL injury incidence rates were at their highest between the ages of 14 and 18 years old (Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017). As such, the observed increase in incidence rates between the ages of 14 and 18 years old may be explained by an increase in the overall sport participation and the early sport specialisation, which could lead to muscle strength imbalances resulting in decreased stability. Moreover, studies also found that roughly 60% of ACL injury patients were males (Granan, Bahr, Steindal, Furnes, & Engebretsen, 2008; Shea, Pfeiffer, Wang, Curtin, & Apel, 2004). However, when injury rates are normalized to sport exposure, females demonstrated higher rates of ACL injury than males (Shea et al., 2004). Similarly, studies have found that females are three to six times more at risk for non-contact ACL injury than males (Arendt & Dick, 1995; Ferretti, Papandrea, Conteduca, & Mariani, 1992; J. Gray et al., 1985; Hewett, Myer, & Ford, 2006; Malone, 1992; Myklebust, Maehlum, Holm, & Bahr, 2007; Voskanian, 2013). Although multifactorial, one justification for the sex differences seen in ACL injuries is the increase in estradiol levels in females during the menstrual cycle which increases the elasticity of the ACL, thus increasing the risk of ACL injury (Lee et al., 2013; Sandra J Shultz, 2008; S. J. Shultz, Sander, Kirk, & Perrin, 2005). Another explanation lies in the findings of a review conducted by Dai et al. (2012) which found that females tend to restrict sagittal plane motion (less knee flexion) and increase coronal plane motion (more knee valgus) during athletic tasks, thus increasing the load applied on the knee and the ACL.

Rates of ACL injury have also been shown to fluctuate across different sports. A meta-analysis conducted by Prodromos et al. (2007) investigated the incidence of ACL injuries as a function of sport. The study showed that the ACL injury incidence rates, reported as "injuries per 1000 exposures", were 0.17 in collegiate basketball, 0.21 in collegiate soccer, 0.18 in collegiate lacrosse, 0.25 in collegiate wrestling, 0.22 in collegiate rugby, 0.33 in elite handball, and 0.49 in general population alpine skiing, where "exposures" are defined as practice or games (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). These relatively high incidence rates can be justified by the involvement of sudden deceleration, change in direction or landing maneuvers in these sports. Therefore, although not explicit risk factors, taking part in these sports regularly would entail performing these high-risk movements, thus increasing the chances of ACL injury.

Another potential factor affecting ACL injury risk is the level of competition. A study conducted by Uhorchak et al. (2003) investigated the differences in non-contact ACL injury incidence rates between intramural sports and varsity and club sports. The study found that the incidence rate for non-contact ACL injury was five times higher in intramural sports than in varsity and club sports (Uhorchak et al., 2003). Although speculative, this could be due to the fact that athletes in intramural sports are less familiar with the sport-specific movements and are less likely to be doing comprehensive injury prevention programs, compared to higher level athletes.

6.3.2 Risk Factors

Studies show that there are multiple non-modifiable risk factors for ACL injury, such as the size of the femoral notch, the posterior tibial plateau slope, lower extremity alignment and being female (Simon, Everhart, Nagaraja, & Chaudhari, 2010; Tillman, Bauer, Cauraugh, & Trimble, 2005; Whitney et al., 2014; Zebis et al., 2016). However, there are also modifiable risk factors, such as greater quadricep-to-hamstring activation ratio, poor core stability, and poor joint alignment (example: knee valgus) during athletic tasks, all of which contribute to increased loading on the ACL (Jonathan D. Chappell, Yu, Kirkendall, & Garrett, 2002; Dai, Herman, Liu, Garrett, & Yu, 2012; Myer et al., 2009; Nessler, Denney, & Sampley, 2017; Raschner et al., 2012). However, it is important to note that these are but risk factors and will not determine with certainty whether an individual will eventually be diagnosed with an ACL injury, they simply increase or decrease the risk of suffering a non-contact ACL injury.

6.4 Diagnosis

There are multiple steps involved in the diagnosis of ACL injury. As part of standard care, physicians will typically first consider the mechanism of injury and inquire about relevant information the patient may provide. For example, there is a well-known "pop" sound that is commonly heard during an ACL tear. Physical knee exams will follow, which are aimed toward identifying signs of injury in the knee joint. Such signs of injury could be tenderness or swelling in certain areas, or even differences with the contralateral uninjured knee. Several physical tests designed to isolate the ACL and investigate its integrity are then conducted. A study conducted by Cimino et al. (2010) found that the Lachman test was the most effective at diagnosing ACL injuries. While the patient is flat on their back with their affected knee slightly flexed, force is applied with one hand to the posterior side of the tibia while holding the femur in place with the other hand, in an attempt to translate the tibia anteriorly and assess the ACL's capacity to restrict that movement (Cimino, Volk, & Setter, 2010). There are other similar tests such as the anterior drawer test and the pivot shift test, which also look to investigate the integrity of ACL through its present performance (Cimino et al., 2010).

Although fairly accurate, there are limitations with physical knee exams. A study showed that an orthopaedic surgeon and a primary care physician failed to diagnose 7% and 38% of ACL tears respectively, using physical knee exams and medical history (Geraets et al., 2015). This margin of error could largely be due to the difficulty of the assessments as well as the skill and experience required to perform them appropriately. Therefore, there is a need for slightly more invasive tests to either confirm ACL injuries or effectively rule out other possible injuries. Magnetic resonance imaging (MRI) can be used to confirm ACL injury diagnoses, and help select the appropriate treatment (Wang et al., 2018).

6.5 Current Treatment

Treatment for ACL injuries varies depending on the patient's physical activity aspirations and the grade of the injury. Individuals who are relatively sedentary, engage solely in moderate intensity exercise, and do not take part in sports involving high stress on the knee joint, may be counseled by their physician away from surgical intervention and towards physical therapy. Conversely, for competitive athletes or for individuals taking in part in sports involving sudden deceleration, change in direction or landing maneuvers, treatment will vary based on the grade of the injury. Grade 1 and Grade 2 ACL sprains could be treated by immobilizing of the knee joint, followed by rigorous physical therapy and a gradual return back to sports (JohnsHopkins, 2022). Grade 2 ACL sprains, where there is a significant amount of tear, and Grade 3 ACL sprains may require surgical intervention, followed by rigorous physical therapy and a gradual return back to sports (JohnsHopkins, 2022). Moreover, it is possible to suffer damage to other structures in addition to the ACL, in which case there is more important need for surgery (JohnsHopkins, 2022).

6.5.1 Challenges with Current Treatment

ACL injuries can lead to significant time away from sport participation and physical activity, which has negative health repercussions and may be a source of personal suffering (Dallinga et al., 2012). Furthermore, the sequelae from these injuries leads to increased morbidity and osteoarthritis (Keays et al., 2010; Lohmander et al., 2007). A literature review conducted by Delincé et al. (2012) found that regardless of the treatment, whether it was surgical or non-surgical, completely normal knee kinematics are not restored and the risk of subsequent ACL injuries remains high. Moreover, studies also found that neuromuscular deficiencies are present in both the injured and uninjured limbs following ACL reconstruction surgery, further increasing the risk of subsequent ACL injuries (Delincé & Ghafil, 2012; Nyland, Burden, Krupp, & Caborn, 2011; Paterno et al., 2010; Stasi, Myer, & Hewett, 2013; Vairo et al., 2008). These findings emphasize the importance of developing ACL injury prevention methods.

6.6 Prevention

6.6.1 Prevention Programs

There are ACL injury prevention programs aimed at improving the aforementioned modifiable risk factors, and ultimately decreasing the risk of non-contact ACL injury. These injury prevention programs can be general or sport specific. One such intervention is neuromuscular training which focuses on learning to perform tasks with safer biomechanics. Neuromuscular training employs exercises aimed at improving the aforementioned biomechanical factors associated to non-contact ACL injury, such as increasing core strength and stability, increasing hamstring strength and activation, and decreasing knee valgus during athletic tasks (Jonathan D Chappell & Limpisvasti, 2008; Gilchrist et al., 2008; Hewett et al., 2017; Mandelbaum et al., 2005; Myer, Ford, Palumbo, & Hewett, 2005; H. Silvers-Granelli et al., 2015; H. J. Silvers-Granelli et al., 2017). Moreover, a study that implemented targeted neuromuscular training (TNMT) on 624 female athletes found that high risk individuals had the largest improvement in biomechanical factors associated to non-contact ACL injury (Hewett et al., 2017). Furthermore, a study conducted by Stasi at al. (2013) reports that TNMT have the greatest potential to address the neuromuscular deficiencies observed in individuals with prior ACL injuries.

One of the more commonly used neuromuscular training programs is the FIFA 11+, which is a soccer specific injury prevention program designed by the Fédération Internationale de Football Association (FIFA) in response to the increasing injury rates in 2009. This program consists of a 20-minute warm up to be performed two to three times a week and is comprised of dynamic exercises that are time efficient and require no extra equipment (H. J. Silvers-Granelli et al., 2017). This injury prevention program employs exercises focusing on improving the aforementioned modifiable risk factors and overall neuromuscular control (see Figure 1 for breakdown by exercise). Studies show that while FIFA 11+ was not solely designed for ACL injury prevention, implementation of this prevention program decreases the risk of non-contact ACL injuries by up to 77% in males (H. Silvers-Granelli et al., 2015; H. J. Silvers-Granelli et al., 2017; Steffen et al., 2013). In addition, studies implementing a similar injury prevention program called the Prevent injury and Enhance Performance (PEP) program found between 70% and 88% decreases in non-contact ACL injury risk in females (Gilchrist et al., 2008; Mandelbaum et al., 2005). Although these studies suggest that ACL injury prevention programs decrease the risk of non-contact ACL injury, investigations found that this effectiveness is dependent on compliance, where compliance rates under 66 to 75% of the program's overall intended volume (session frequencies + durations) results in drastic decreases in their effectiveness (Bisciotti et al., 2016; Dai Sugimoto et al., 2012; D. Sugimoto et al., 2014). Moreover, a meta-analysis conducted by

Sugimoto et al. (2012) found that four among the six studies included in their analysis reported compliance rates of less than 50%. Similarly, a cross-sectional survey study reporting on a home-based ACL injury prevention program for female high school athletes found that only 26% of athletes participated in over 46% of the required injury prevention program sessions (Thein-Nissenbaum & Brooks, 2016). As such, up to at least 74% of the athletes in the aforementioned investigations were under the 66 to 75% compliance cut off for injury prevention program effectiveness. An important factor that may explain these observed low compliance rates is the lack of perceived need for these injury prevention programs. Taken together, these findings on the effectiveness of injury prevention programs, their increased benefits for high risk individuals, and the importance of adherence on their effectiveness reinforce the need to identify high risk individuals for non-contact ACL injury, thus motivating them to enroll in injury prevention programs.

Figure 1. Poster breakdown of FIFA 11+ injury prevention program by exercise. Freely available at extranet.fifa.com/medical (Kirkendall, Junge, & Dvorak, 2010).

6.6.2 ACL Injury Risk Assessment

In recent years, efforts focused towards creating effective non-contact ACL injury risk assessments have significantly increased. Beyond general risk factors, assessment methods have been developed around biomechanical concepts, where visual review of 2D recordings is performed to investigate for specific or overall kinematics related to ACL injury risk during certain tasks, such as knee valgus during drop vertical jumps (DVJ) or tuck jumps (Padua et al., 2009). Such an assessment method called the Landing Error Scoring System (LESS) showed predictive validity when measurements were compared with that of laboratory-based 3-dimensional motion analysis systems (gold standard for biomechanical assessments related to non-contact ACL injury risk) and are relatively practical for widespread use (A. S. Fox, Bonacci, McLean, Spittle, & Saunders, 2016; Padua et al., 2009). However, these biomechanical assessments require raters to subjectively assess 2D recordings of the jumps, and thus, introduce rater bias (Padua et al., 2009). A study investigating the intra– and interrater reliability of subjective assessments of filmed DVJs (Figure 2) found that assessments differed more based on the rater, than the actual DVJ performed (Lindblom, Hägglund, & Sonesson, 2021). These results emphasize that perhaps objective assessments are necessary to insure internal and external validity.

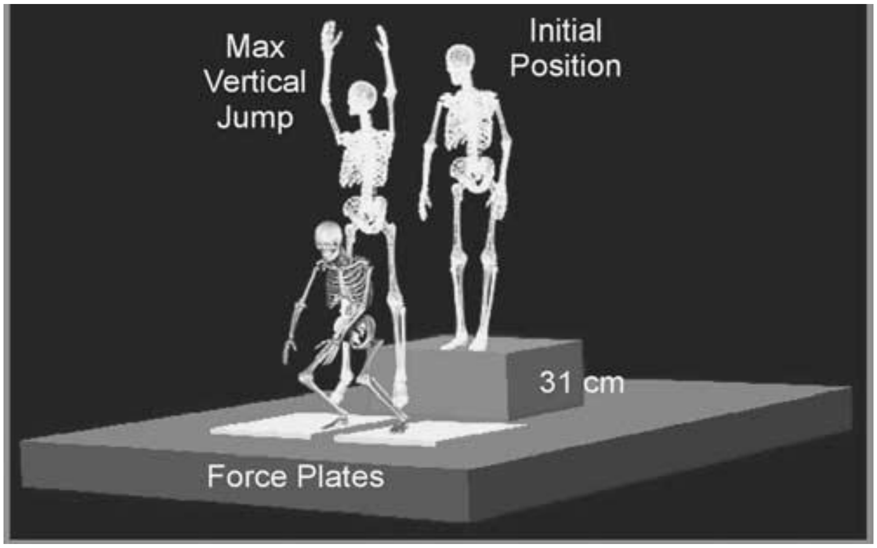

Figure 2. Biomechanical representation of a DVJ (Hewett et al., 2005).

A study conducted by Hewett et al. (2005) included 205 female athletes and used an optoelectronic motion analysis system to measure their initial knee coronal abduction angles (IC), peak knee coronal abduction angles (PC), and peak knee sagittal flexion angles (PF) angles during a standardized DVJ (Figure 3). This investigation found that greater IC, greater PC, and smaller PF knee angles during a DVJ were statistically associated with an increased risk of non-contact ACL injury (Hewett et al., 2005). These findings propose that using motion analysis to measure IC, PC, and PF knee angles during a DVJ could provide objective measurements to assess for non-contact ACL injury risk.

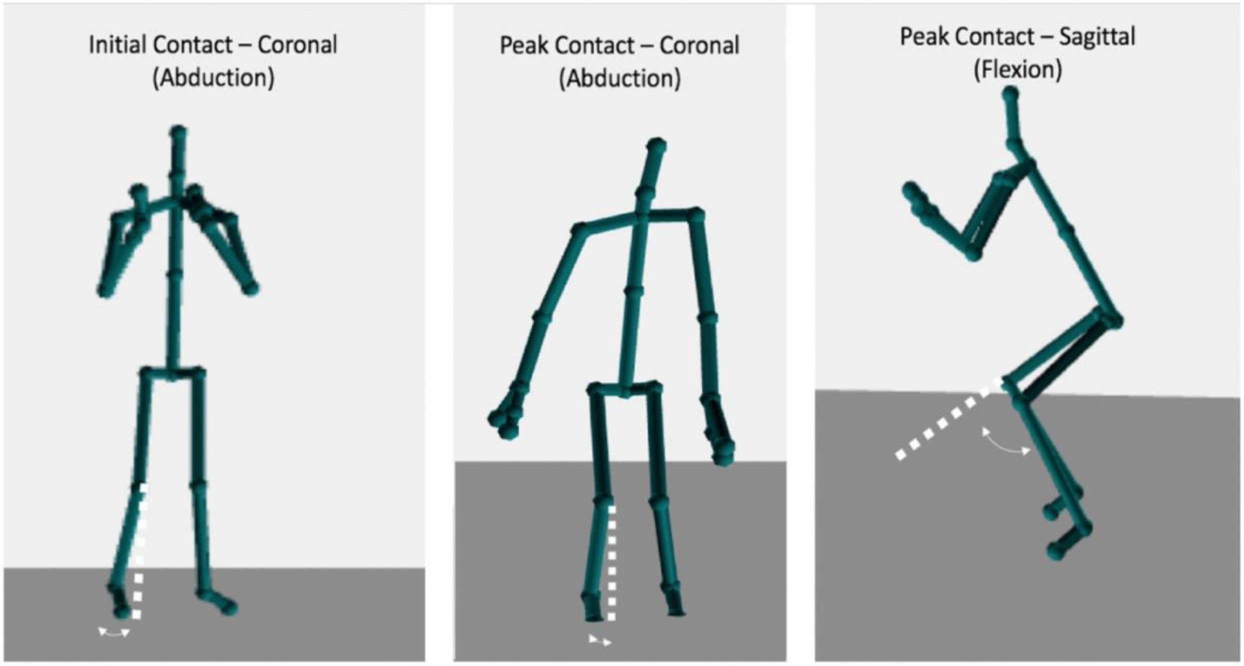

Figure 3. Biomechanical illustrations of IC (left image), PC (middle image), and PF (right image) angles during a DVJ (unpublished data, 2022). IC is measured at first contact with the floor during a DVJ. PC is measured at the point of largest coronal knee angle (or most valgus knee angle) during a DVJ. PF is measured at the point of largest sagittal knee angle (or most knee flexion angle) during a DVJ.

6.7 Motion Analysis

Motion analysis systems are used to accurately capture and either evaluate or quantify human locomotion. There are several types of motion analysis systems, each with their own strengths and weaknesses.

6.7.1 Optoelectronic Systems

The current gold standard motion analysis systems are optoelectronic systems, such as the Vicon Motion analysis system (Vicon, Denver CO) (Merriaux, Dupuis, Boutteau, Vasseur, & Savatier, 2017). Optoelectronic motion analysis systems emit and detect optical power (light) in order to capture movement. These motion analysis systems usually consist of multiple high-speed digital cameras set up around a specific area designated for the task to be performed and captured. Markers are then placed on the participant's joints to be identified by the high-speed digital cameras during their task. Based on the spatial identification of the markers, various measurements can be extracted, such as coronal and sagittal knee angles.

Although optoelectronic systems are extremely accurate, they also have their weaknesses. These marker-based motion capture systems require specialized motion labs, which employ costly, high speed motion analysis cameras that can cost up to $150,000 (A. D. Gray et al., 2017). In addition, the specific software and trained technicians needed to conduct the assessment could cost an athlete over $400 and could require up to 4 hours of analysis to obtain meaningful results (Merriaux et al., 2017). Thus, although these motion analysis systems are capable of highly accurate biomechanical measurements, they also have many barriers for widespread screening of non-contact ACL injury risk (Merriaux et al., 2017).

6.7.2 Alternative Motion Analysis System

Technological advancements have resulted in the development of more affordable and portable motion tracking technology. One such alternative device is the Microsoft Xbox Kinect V2 (Microsoft Corporation, Redmond WA), which is equipped with infrared depth sensors and skeletal tracking to allow for accurate and inexpensive kinematic assessment (Livingston et al., 2012). The Microsoft Xbox Kinect V2 (Kinect) emits fields of infrared light and uses the refraction of this infrared light to identify an individual's joints. With Kinect-based portable systems already being employed in health care applications, such as in targeted rehabilitation programs for stroke patients and those suffering from Parkinson's disease, the development of a Kinect-based tool for accurate biomechanical assessment is a logical extension of this concept (A. D. Gray et al., 2017; Park, Lee, Lee, & Lee, 2017; Shih, Wang, Cheng, & Yang, 2016; Vieira, Gabriel, Melo, & Machado, 2017).

A recent investigation by Gray et al. (2017) demonstrated that a Kinect-based portable system could be used to measure knee ankle separation ratios (KASR), as proxy for knee valgus, with a similar degree of accuracy as the Vicon motion analysis system (or Vicon system). Our group has devised a Kinect-based tool to screen individuals for non-contact ACL injury risk based on their IC, PC, and PF angles, building upon the findings of the study conducted by Hewett et al. (2005). In a validation study, we found good agreement between our Kinect-based tool and the Vicon system when measuring IC, PC, and PF knee angles during a DVJ, where ICC values were over 0.77 for all angles (unpublished data, 2022). Furthermore, our Kinect-based tool was then used in a prospective style study with 114 varsity athletes, where statistically significant IC, PC, and PF cut offs were obtained (unpublished data, 2022). Although promising, the sample size of our previous investigation was relatively low, thus a subsequent study with a larger sample size was needed (Karatzas, 2019).

The purpose of the present study was to assess the predictive value of IC, PC, and PF angles during a DVJ for non-contact ACL injury risk using a practical Kinect-based tool on a larger and more generalized cohort of young varsity athletes. We hypothesize that cut off IC, PC, and PF angles will have good combined specificity and sensitivity, and that athletes who sustain non-contact ACL injury will have more valgus IC, more valgus PC, and smaller PF knee angles during a DVJ compared to uninjured athletes.

Development of a portable, practical, and accurate tool for widespread screening of non-contact ACL injury risk is imperative. Such a tool could identify and motivate high risk individuals to be enrolled in injury prevention programs, thus ultimately decreasing the incidence of ACL injuries.

7.0 Methods

This investigation was a prospective cohort study. McGill University varsity athletes from Football, Soccer, Rugby, and Cross Country were assessed with the Kinect-based assessment tool before their season commenced. The same varsity athletes were then followed throughout their seasons and monitored for non-contact ACL injuries. The resulting injured (IN) group consisted of athletes who suffered non-contact ACL injuries this season, while the uninjured (UN) group consisted of the individuals who did not suffer non-contact ACL injuries this season. The IC, PC, and PF angles during a DVJ were compared between the two groups.

7.1 Ethics Approval

Ethics approval for the study was obtained by McGill University's Ethics Board in 2018. Research resumption application was accepted, rendering the study valid until February 8th, 2023. Written and informed consent was obtained by all participants prior to their involvement in the study.

7.2 Participants

The Kinect-based assessment was performed on 405 athletes before the start of the varsity season. Amongst this sample, 383 athletes went on to be selected as part of the official varsity rosters, and therefore, were considered eligible to be followed prospectively throughout the 2021-2022 varsity season. Within this group, 156 athletes' seasons were delayed due to the Covid-19 pandemic, leaving 227 athletes who have completed a full varsity season. Of the 227 athletes, 21 individuals with previous lower limb injuries potentially affecting their jumping mechanics were excluded. Thus, this analysis will be conducted on the resulting cohort of 206 McGill varsity athletes.

The inclusion criteria consisted of being selected as part of an official McGill Varsity roster for the 2021-2022 season, having been cleared by Varsity team's medical staff to return to play, and having completed a full Varsity season. The exclusion criteria, assessed on a case by case basis by a staff orthopaedic surgeon, consisted of current or previous serious injuries possibly affecting jumping mechanics, such as a recent concussion, any lower limb ligament injuries, or any bone fractures.

7.3 Kinect-Based Assessment

Knee kinematics were measured using the Kinect-based tool during a standardized DVJ off a 31 cm box (Figure 4). In keeping with the same protocol as the study conducted by Hewett et al. (2005), each participant performed three DVJs while IC, PC and PF were captured. IC was defined as the coronal knee angle when the participant's feet first make contact with the floor during the DVJ. PC was defined as the largest coronal knee angle (most valgus knee angle) throughout the entire DVJ after IC. PF was defined as the largest knee flexion angle throughout the entire DVJ.

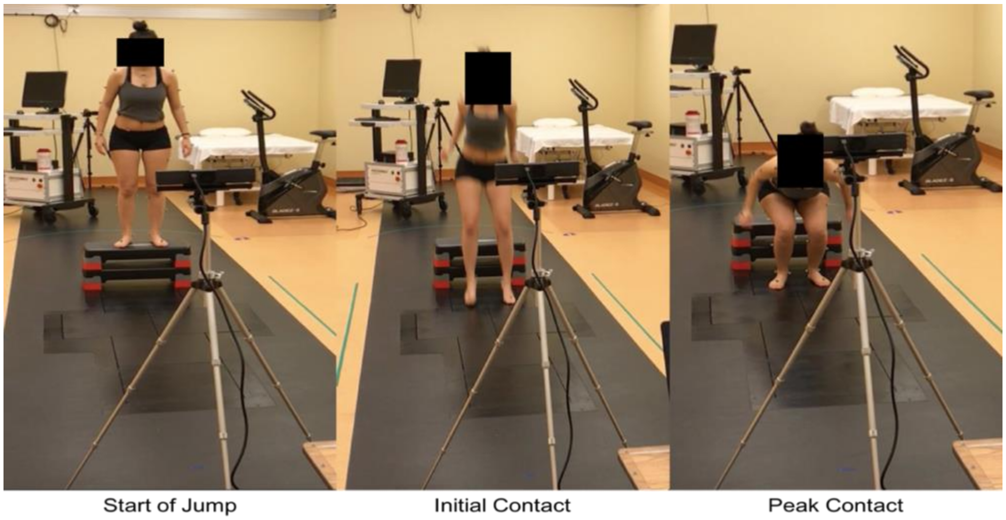

Figure 4. Images of the Kinect-based portable system setup with freeze frames from the beginning of the Drop Vertical Jump (DVJ) as well as the two significant time points: initial and peak contact (unpublished data, 2022). The Kinect-based portable system is mounted on a tripod at a distance of 2.5 meters from the participant for optimal accuracy.

The Kinect (Microsoft, Redmond WA), programmed using Microsoft's open source Kinect V2 software development kit, was mounted on a tripod 2.5 m away from the athletes performing a DVJ (Figure 4). The Kinect-based tool is capable of 3-dimensional tracking by using an infrared depth sensor with a capture rate of 30 frames per second (A. D. Gray et al., 2017). Our proprietary software was programmed to use formulas to calculate the angles of interest. These formulas utilize force vectors from the knee to the hip (femur) and the knee to the ankle (tibia; Equation 1) to calculate the knee abduction in the coronal plane and knee flexion in the sagittal plane at every frame throughout the DVJ. The coronal knee abduction angles were calculated using Equation 2, while sagittal knee flexion angles were calculated using Equation 3. Once the knee angles during a DVJ are calculated at every frame, our software identifies pertinent jump frames from which the IC, PC and PF angles are extracted. In order to identify these pertinent jump frames, our software used kinematic triggers. Kinematic triggers are specific movements throughout a DVJ our software is designed to recognize and use to identify pertinent jump frame. The kinematic trigger our software uses to detect the initial landing frame is when the foot joint stops travelling in a downward direction, indicating that the subject has made contact with the floor. Subsequently, the kinematic trigger our software uses to detect the peak landing frame is 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 selects the frame with the smallest distance as the peak landing frame. Our software then generates an excel file with the initial knee coronal abduction, peak knee coronal abduction, and peak knee sagittal flexion angles for further analysis.

Equation 1: Vector definition of tibia and femur

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

Equation 2: Formula for calculating coronal knee abduction angles

$$x = RotationAxis.x * sin(RotationAngle / 2)$$
$$y = RotationAxis.y * sin(RotationAngle / 2)$$
$$z = RotationAxis.z * sin(RotationAngle / 2)$$
$$w = cos(RotationAngle / 2)$$

Equation 3: Formula for calculating sagittal knee flexion angles

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

7.4 Statistical Analysis

The statistical analysis was run using SPSS Version 27 statistics software (IBM, Armonk NY). A Shapiro-Wilk test for normality was performed on the data set for each variable. The difference was calculated for the mean knee angles during a DVJ between the resulting IN group and the UN group. Normally distributed data sets were compared using a two-tailed independent-samples t-test, while non-normally distributed data was compared using the Wilcoxon Signed Rank test. Statistical significance was set at $P<0.05$. Receiver operating characteristic (ROC) analysis was then performed on IC, PC, and PF angles for the whole cohort and then for males only, where resulting area under the curve (AUC) outcomes are either excellent (0.90-1), good (0.80-0.89), fair (0.70-0.79), poor (0.60-0.69), or fail (0.50-0.59). Cut offs were then obtained from the ROC curves with the highest combination of sensitivity and specificity, while slightly prioritising sensitivity as appropriate in this context. Although there are no specific criteria for minimum specificity and sensitivity as different screening tools can accept different levels of inaccuracy depending on their use, the aforementioned AUC indicates the predictive validity of the combined sensitivity and specificity for a cut off. ROC analysis was not performed on females exclusively as no female non-contact ACL injury was reported this season.

Different sets of cut off values were applied to the cohort to dichotomize participants into high and low risk groups in order to investigate the cut offs' capacity to identify participants from the IN group. The sets of cut offs used were: 1) Hewett: the mean knee angles obtained from the injured group in the study conducted by Hewett et al. (2005), 2) Previous ROC: cut off knee angles obtained from the ROC analysis performed by our group on a previous cohort of 114 athletes (unpublished data, 2022), 3) Current ROC: cut off knee angles obtained from the ROC analysis performed in this study, and 4) Current Male ROC: cut off knee angles obtained from the ROC analysis performed only on the males in this study.

Secondary analysis was performed where mean differences were calculated for IC, PC, and PF angles between injured and uninjured males, as well as between uninjured males and females. A Shapiro-Wilk test for normality was performed on each variable. Normally distributed data sets were compared using a two-tailed independent-samples t-test, while non-normally distributed data was compared using the Wilcoxon Signed Rank test. Statistical significance was set at $P<0.05$.

Recordings of jumps were reviewed and verified by a researcher blinded to injury outcomes. Jumps were considered faulty and were excluded if not performed with proper technique or if knee angles measured by the Kinect-based tool were not biomechanically possible and/or were inconsistent with the visual recordings. Six jumps in the entire cohort were considered faulty and were excluded. Outliers were then identified for exclusion as values more than 1.5 times the interquartile range (IQR) above the third quartile or less than 1.5 times the IQR below the first quartile (Walfish, 2006). The remaining knee angles for each athlete's eligible jumps (ranging between one and three jumps) were averaged into one IC, one PC, and one PF angle. These mean knee angles were used for statistical analysis.

8.0 Results

The demographic data breakdown by sex is summarised in table 1. The demographic data breakdown by sport and sex is summarised in table 2.

Table 1. Mean demographic data breakdown by sex with standard deviations (N=206).

Gender	**Male (N=141)**	**Female (N=65)**
Age	20.80±1.7	20.18±1.91
Height (m)	1.81±0.08	1.66±0.06
Weight (Kg)	88.07±18.59	62.43±7.17
BMI (Kg/m^2)	26.73±4.43	22.63±2.35

Table 2. Mean demographic data breakdown by sport and sex with standard deviations. P values were obtained from two-tailed independent-samples t-tests performed for male to female comparisons. **(Bold** indicates statistical significance)

		Gender			**Height (m)**			**Weight (Kg)**			**BMI (Kg/m^2)**		
Varsity Sport	**N**	**Male**	**Female**	**Age**	**Male**	**Female**	**P value**	**Male**	**Female**	**P value**	**Male**	**Female**	**P value**
Football	75	75 (100%)	0 (0%)	21.49±1.53	1.83±0.07	N/A	N/A	95.15±20.39	N/A	N/A	28.33±4.55	N/A	N/A
Soccer	44	21 (48%)	23 (52%)	19.39±1.66	1.77±0.07	1.68±0.6	**<0.000**	70.56±6.84	63.00±7.56	**<0.000**	22.44±1.20	22.34±1.63	0.829
Rugby	63	36 (57%)	27 (43%)	20.32±1.61	1.82±0.7	1.64±0.05	**<0.000**	87.43±10.26	64.28±5.91	**0.001**	26.42±2.56	23.80±2.33	**<0.000**
Cross Country	24	9 (38%)	15 (62%)	20.42±1.84	1.76±0.06	1.670.07	**0.002**	73.21±23.32	56.64±6.30	**<0.000**	23.47±6.76	20.36±1.47	0.096
Total	206	141 (68%)	65 (32%)	20.56±1.80	1.81±0.07	1.66±0.06	**<0.000**	88.12±19.26	62.07±7.20	**<0.000**	26.66±4.50	22.49±2.32	**<0.000**

8.1 Injured Athletes

Out of the 206 participants in the cohort, 6 participants suffered non-contact ACL injuries during the 2021-2022 season. All 6 injured participants were male varsity football athletes. Resulting injured (IN) and uninjured (UN) groups consisted of 6 and 200 participants respectively. When comparing age between IN (20.83±0.75) and UN (20.55±1.76), there was no significant difference found. Similarly, there was also no significant difference found for height

(H), weight (W), and BMI between IN (H: 1.84±0.07m, W: 84.32±14.60Kg, BMI: 24.88±3.00 kg/m^2) and UN (H: 1.76±0.10m, W: 79.76±20.58Kg, BMI: 25.36±4.43 kg/m^2) groups.

8.2 Quantitative Results

All statistical analyses were conducted with an alpha level of 0.05. Angles are reported in degrees, where negative (-) angles indicate valgus angles. The number of participants in each group of the analysis below is indicated by "N=". Out of 3666 data points, 34 IC angle outliers, 22 PC angle outliers, and 31 PF angle outliers were identified and excluded. All outliers were in the uninjured group.

8.2.1 Initial Analysis: Injured vs Uninjured

The Shapiro-Wilk test concluded that the data for initial coronal abduction (IC) and peak coronal abduction (PC) angles was normally distributed. The data for peak flexion (PF) angles ($W=0.98$; $p \leq 0.05$) was found to have a non-normal distribution. In light of this, a two-tailed independent-samples t-test was performed to compare the mean IC and PC angles, while the Mann-Whitney U test was performed to compare the PF angles. Mean comparisons for IC, PC, and PF angles between IN and UN groups are shown in table 3. The mean differences for IC and PC angles were both less than 1.2° ($p>0.05$), no statistical significance was found. The mean difference for PF angles between the IN and UN groups was 16.28° ($p \leq 0.05$), where the IN group had a smaller mean PF angle.

Table 3. Mean initial coronal abduction (IC), peak coronal abduction (PC), and peak flexion (PF) angles for injured (IN) and uninjured (UN)groups. (*= Mann-Whitney U test, **Bold** indicates statistical significance) All angles are reporter in degrees ± standard deviation.

	Groups (N=206)			T-Test or Mann-Whitney U test (*)
Knee Angles	IN (N=6) M=6 F=0	UN (N=200) M=135 F=65	Mean difference	Significance
IC	-1.99±1.83	-3.01±2.52	1.02	0.337
PC	-3.67±1.44	-4.33±2.49	0.66	0.517
PF	86.23±13.60	102.51±17.47	16.28	**0.021***

8.2.2 ROC Analysis Results

The plotted ROC curves for IC, PC, and PF angles obtained from the entire cohort are shown in figure 5. The area under the curve (AUC) for IC was 0.381 (*P* = 0.321, 95% confidence interval (CI): 0.182-0.580). From which, a cut off of -1.12° was obtained with 67% sensitivity and 24% specificity. The area under the curve (AUC) for PC was 0.401 (*P* = 0.408, 95% CI: 0.244-0.558). From which, a cut off of -2.60° was obtained with 67% sensitivity and 25% specificity. The area under the curve (AUC) for PF was 0.776 (*P* = 0.021, 95% CI: 0.629-0.923). From which, a cut off of 95.17° was obtained with 83% sensitivity and 67% specificity. Statistical significance was only found for the PF plotted ROC curve.

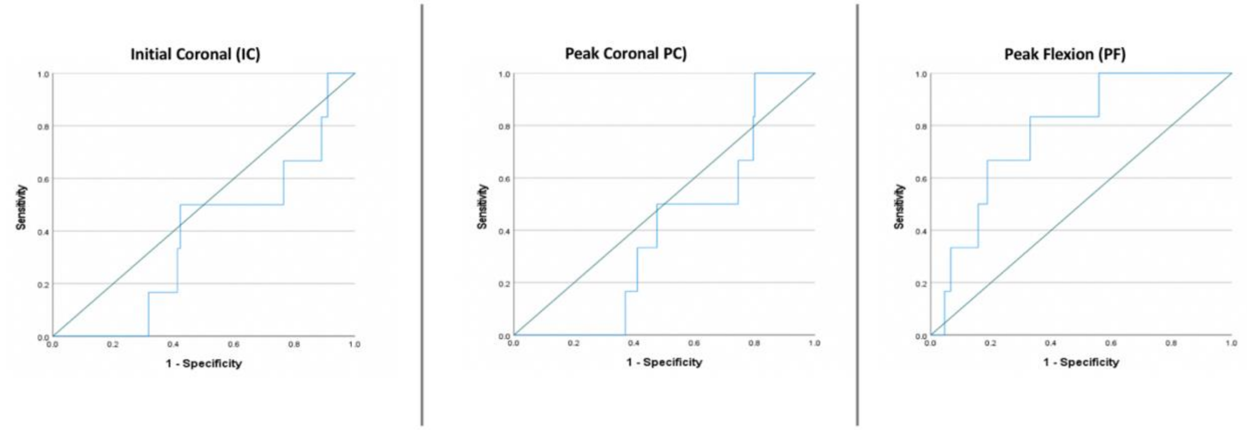

Figure 5. Plotted receiver operating characteristic (ROC) curve for initial coronal (IC), peak coronal (PC), and peak flexion (PF) angles. The area under the curve (AUC) for IC was 0.381 (*P* = 0.321). The AUC for PC was 0.401 (*P* = 0.408). The AUC for PF was 0.776 **(*P* = 0.021)**.

The second plotted ROC curves for IC, PC, and PF angles obtained from only males are shown in figure 6. The area under the curve (AUC) for IC was 0.474 (*P* = 0.830, 95% CI: 0.245-0.703). From which, a cut off of -1.12° was obtained with 67% sensitivity and 33% specificity. The area under the curve (AUC) for PC was 0.501 (*P* = 0.992, 95% CI: 0.332-0.671). From which, a cut off of -2.60° was obtained with 67% sensitivity and 36% specificity. The area under the curve (AUC) for PF was 0.745 (*P* = 0.043, 95% CI: 0.591-0.899). From which, a cut off of 95.33° was obtained with 83% sensitivity and 65% specificity. Statistical significance was only found for the PF plotted ROC curve.

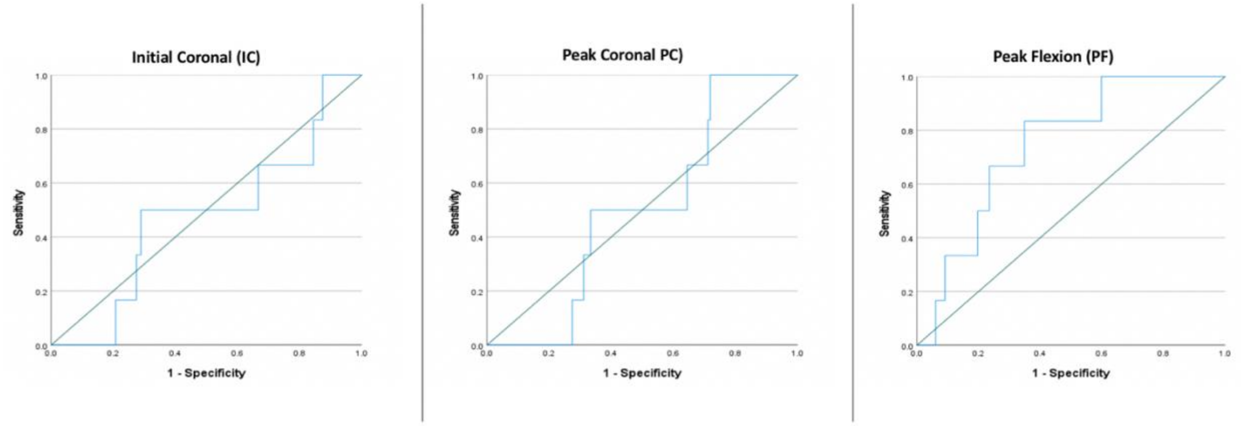

Figure 6. Plotted receiver operating characteristic (ROC) curve for initial coronal (IC), peak coronal (PC), and peak flexion (PF) angles from male participants (N=135). The area under the curve (AUC) for IC was 0.474 (P = 0.830). The AUC for PC was 0.501 (P = 0.992). The AUC for PF was 0.745 **(P = 0.043)**.

8.2.3 Application of Cut Off Angles

The Hewett cut off knee angles used were -5° for IC, -9° for PC, and 71.9° for PF. The Previous ROC cut off knee angles used were -2.96° for IC, -6.16° for PC, and 93.82° for PF. The Current ROC cut off knee angles used were -1.12° for IC, -2.60° for PC, and 95.17° for PF. The Current Male ROC cut off knee angles used were -1.12° for IC, -2.60° for PC, and 95.33° for PF. Individuals were classified as high risk if their knee angles were smaller (meaning more valgus for IC and PC angles, and less flexion for PF angles) than the cut offs used. The resulting number of participants classified as “high risk” per cut off angle is shown in table 4. Hewett cut off knee angles classified 1 individual from the injured group as “high risk”. Previous ROC cut off knee angles classified 5 individuals from the injured group as “high risk”. Finally, Current ROC and Current Male ROC cut off knee angles classified all 6 individuals from the injured group as “high risk”.

Table 4. Application of cut offs to whole cohort (Cohort N=206, Injured (IN) group N=6, Uninjured (UN) group N=200). With the exception of the Current Male ROC cut offs, which were solely applied to males (N=141)

	# Of classified high-risk participants per knee angle cut off (% = percentage of cohort)					
Source of Cut offs	IC cut off	# of IN classified as high risk	PC cut off	# of IN classified as high risk	PF cut off	# of IN classified as high risk
Hewett	42 (20%)	0	4 (2%)	0	13 (6%)	1
Previous ROC	99 (48%)	3	47 (23%)	0	71 (34%)	4
Current ROC	156 (76%)	4	153 (74%)	4	73 (35%)	5
Current Male ROC	94 (67%)	4	91 (64%)	4	54 (38%)	5

8.2.4 Secondary Analysis

A secondary analysis was also conducted. Mean comparisons were performed for male vs female and for injured male vs uninjured male.

8.2.4.1 Male vs Female

The Shapiro-Wilk test concluded that the data for IC and PC angles was normally distributed. The data for PF angles ($W=0.98$; $p \leq 0.05$) was found to have a non-normal distribution. In light of this, a two-tailed independent-samples t-test was performed to compare the mean IC and PC angles, while the Mann-Whitney U test was performed to compare the PF angles. Mean comparisons for IC, PC, and PF angles between males and females of the uninjured group are shown in table 5. Mean differences for IC and PC angles between males and females were over 2.2° ($p \leq 0.05$), where females had on average more valgus mean IC and PC angles than males. Both mean differences for IC and PC angles were statistically significant. The mean difference for PF angles between males and females was 4.76° ($p > 0.05$), where males had a smaller mean PF angle.

Table 5. Mean initial coronal abduction (IC), peak coronal abduction (PC), and peak flexion (PF) angles for males and females within UN group. (*= Mann-Whitney U test, **Bold** indicates statistical significance) All angles are reporter in degrees ± standard deviation.

	Groups (N=200)			T-Test or Mann-Whitney U test (*)
Knee Angles	Female UN (N=65)	Male UN (N=135)	Mean difference	Significance
IC	-4.57±2.08	-2.28±2.46	2.29	**<0.000**
PC	-5.87±1.95	-3.59±2.38	2.28	**<0.000**
PF	106.12±15.99	100.73±17.94	5.39	0.057*

8.2.4.2 Male Injured vs Male Uninjured

The Shapiro-Wilk test concluded that the data for IC and PC angles was normally distributed. The data for PF angles ($W=0.98$; $p \leq 0.05$) was found to have a non-normal distribution. In light of this, a two-tailed independent-samples t-test was performed to compare the mean IC and PC angles, while the Mann-Whitney U test was performed to compare the PF angles. Mean comparisons for IC, PC, and PF angles between injured group and males of the uninjured group are shown in table 6. Mean differences for IC and PC angles were less than 0.80° ($p>0.05$), where the injured group had on average slightly less valgus mean IC and PC angles than males of the uninjured group. The mean difference for PF was 14.50° ($p>0.05$), where the injured group had a smaller mean PF angle. Only the mean PF comparison was statistically significant.

Table 6. Mean initial coronal abduction (IC), peak coronal abduction (PC), and peak flexion (PF) angles for males in IN group and males in UN group. (*= Mann-Whitney U test, **Bold** indicates statistical significance) All angles are reporter in degrees ± standard deviation.

	Groups (N=141)			T-Test or Mann-Whitney U test (*)
Knee Angles	IN (N=6)	Male UN (N=135)	Mean difference	Significance
IC	-1.99±1.83	-2.28±2.46	0.28	0.782
PC	-3.67±1.44	-3.59±2.38	0.78	0.937
PF	86.23±13.60	100.73±17.94	14.50	**0.043***

8.3 Summarizing Figures

Mean IC and PC angles for each group statistically analyzed in this investigation are graphically represented in figure 7. Visual inspection of the data reveals a trend of increasingly valgus IC and PC angles from predominantly male groups to predominantly female groups. In addition, visual inspection of the data reveals a trend of increasingly valgus IC angles with increasingly valgus PC angles across all groups.

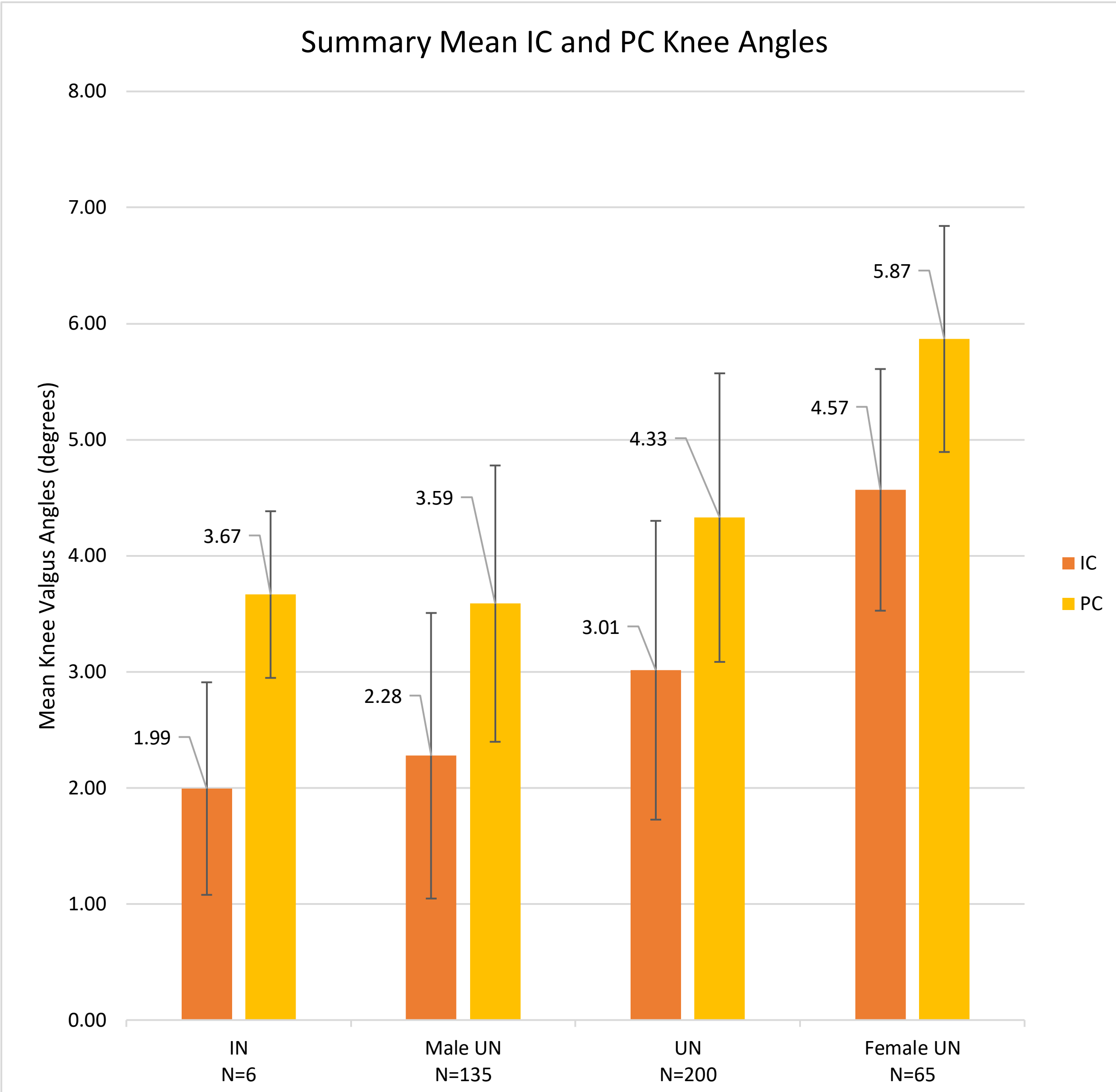

Figure 7. Summary graph of mean IC and PC angles per group. All knee angles are reported in degrees as knee valgus angles (absolute value) with standard deviation bars. IN=injured (all male), Male UN= male uninjured, UN=uninjured, and Female UN=female uninjured.

Mean PF angles for each group statistically analyzed in this investigation are graphically represented in figure 8. Visual inspection of the data reveals a clear separation between the injured group and all the other groups, where the mean PF angle in the injured group is much smaller.

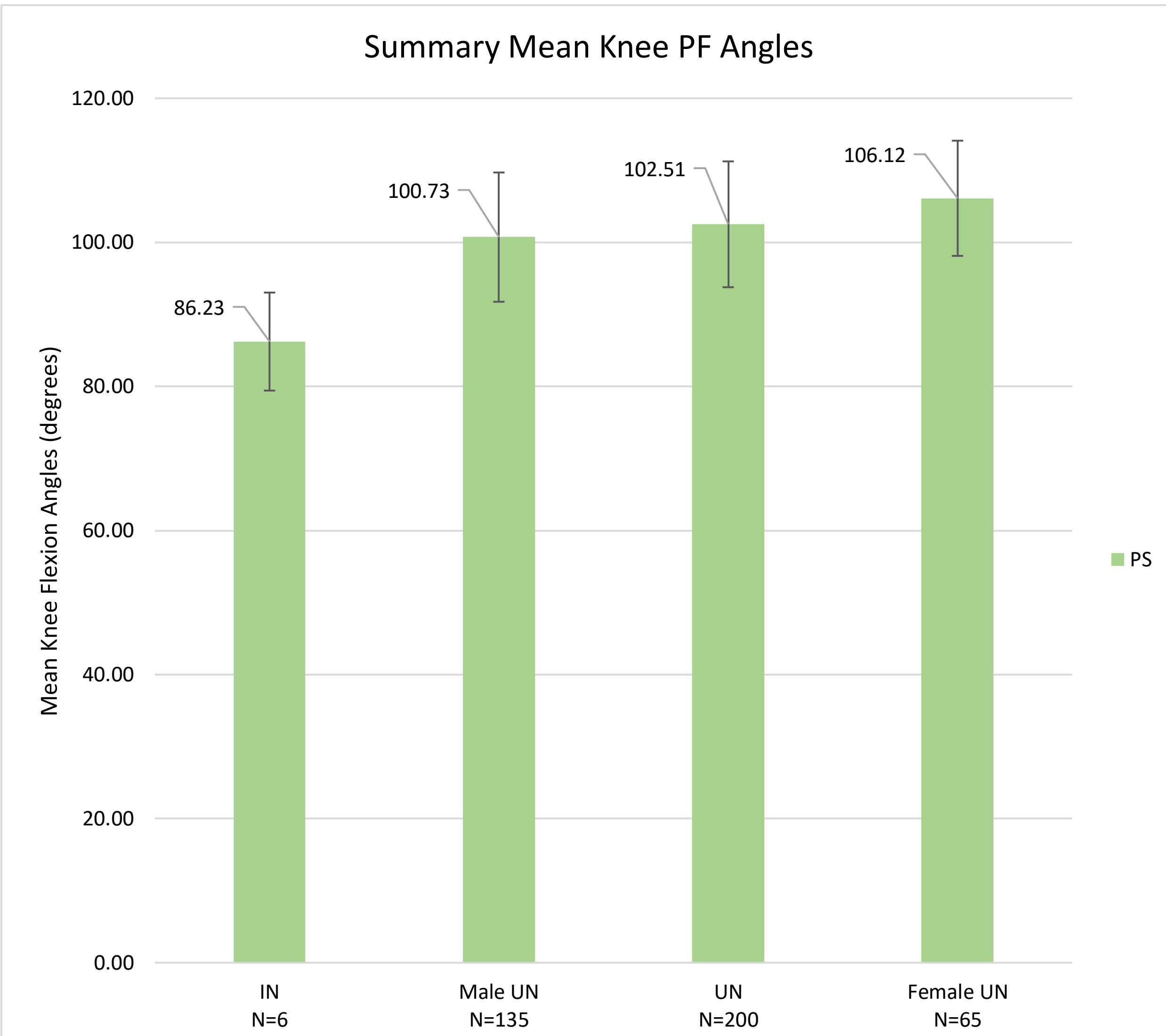

Figure 8. Summary graph of mean PF angles per group. All angles are reported in degrees with standard deviation bars. IN=injured (all male), Male UN= male uninjured, UN=uninjured, and Female UN=female uninjured.

9.0 Discussion

The development of non-contact ACL injury risk assessments tailored for widespread use is essential for targeted injury prevention programs. Our group has developed and validated a practical Kinect-based tool to measure IC, PC, and PF angles during DVJ. However, there is conflicting evidence regarding the reliability of these knee angles to predict non-contact ACL injury risk (T. Krosshaug et al., 2016). Further understanding of these knee angles would facilitate the development of a Kinect-based tool to assess individuals for non-contact ACL injury risk based on their IC, PC, and PF angles.

In the present investigation, we prospectively followed male and female varsity athletes during one season to determine whether IC, PC, and PF knee angles measured using our Kinect-based assessment could predict non-contact ACL injuries. When using the three knee angles together, all non-contact ACL injuries this season were predicted. However, we found that when using the three knee angles individually, PF angle was the only variable with good predictive capabilities for non-contact ACL injury risk assessment, which is not surprising as PF angle was also the only variable significantly different between injured and uninjured groups. Together, these data suggest that our Kinect-based tool using PF angles alone could predict non-contact ACL injury. Furthermore, the Kinect-based tool is agnostic to demographic data, and therefore, more knee extension during landing seems predictive of biomechanical deficiencies for all individuals regardless of sex.

The observed overall effectiveness of IC, PC, and PF knee angles as predictors for non-contact ACL injury is consistant with the findings of Hewett et al. (2005). However, contrary to Hewett's investigation, we found that IC and PC angles individually had "failed" AUCs, which is indicative of poor combined sensitivity and specificity when used to screen for non-contact

ACL injury. These data could possibly be due to IC and PC angles being weaker predictors for non-contact ACL injury. Such a notion is also observed in a study conducted by Krosshaug et al. (2016) who prospectively followed 710 females and found that IC angles and medial knee displacement during a DVJ were not good predictors for non-contact ACL injury risk. Similarly, a prospective study conducted on 880 females also found no correlation between subjectively assessed control during a DVJ and non-contact ACL injury risk (Petushek, Nilstad, Bahr, & Krosshaug, 2021). Despite these findings, IC and PC angles were not explicitly measured in this investigation (Petushek et al., 2021). Therefore, the lack of predictive capability of IC and PC angles may be due to our relatively small sample size compared to the two aformentioned prospective studies (T. Krosshaug et al., 2016; Petushek et al., 2021). Moreover, considering our previous investigation found that injured females had more valgus knee angles than injured males, and that our current study compared injured males to an uninjured group comprised of both males and females, sex differences may also contribute to the lack of predictive capability we found for IC and PC angles (unpublished data, 2022).

When comparing uninjured males and females, we found that females had more valgus IC and PC angles than males, but no significant difference was found for PF angles. Our finding on PF angles between uninjured males and females is inconsistent with the literature, where a review conducted by Dai et al. (2012) demonstrated that females have smaller PF angles than males. It is possible that the lack of significant difference we found for PF angles between uninjured males and females could be due to our relatively small sample size. However, our findings on IC and PC angles between uninjured males and females are in line with the current literature, where females are well documented to have more valgus IC and PC angles during a DVJ and more overall valgus knee kinematics compared to males (Dai et al., 2012; Ford, Myer,

& Hewett, 2003; Tillman et al., 2005; Willis et al., 2019). Given that females have more valgus knee angles than males, the inclusion of females in the uninjured group may explain the observed lack of differences in IC and PC angles with the injured group comprised solely of males. More valgus knee angles in females may also explain why cut offs previously established from cohorts with a higher percentage of females were too valgus and not sensitive enough to predict all 6 injured males from this investigation. Such a concept may also justify why we found that the set of IC, PC, and PF angle cut offs obtained from a male-only ROC analysis had more predictive value overall than the other sets of cut offs used in this investigation. Moreover, due to the well-established evidence suggesting females are more at risk for non-contact ACL injuries, studies have focused heavily on comparing movement patterns between males and females (Dai et al., 2012). Consequently, there is limited research prospectively examining males based on knee angles during a DVJ associated to non-contact ACL injury. In summary, the above-mentioned findings suggest that future studies should investigate knee angles in males in order to establish sex-specific cut offs to optimally assess non-contact ACL injury risk.

Visual inspection of the data revealed a close association between IC and PC angles, where their valgus IC angles were positively correlated with valgus PC angles across all groups. Moreover, findings between groups in this investigation have been consistent in IC and PC angles. The close link between IC and PC angles observed in our investigation is in line with a prospective cohort study conducted on 740 females, where they found a strong correlation between IC and PC angles ($r>0.80$) (T. Krosshaug et al., 2016). These findings suggest that including both IC and PC angles may be redundant, and that future studies should look to identify the most effective variable between the two knee angles for assessment of non-contact ACL injury risk.

9.1 Methodological Considerations

One of the limitations of this study is the narrow age group of the participants included. Since non-contact ACL injury risk has been shown to vary based on age, the fact that our participants are young varsity athletes may decrease the generalizability of our findings to older and younger populations (Beck et al., 2017). Secondly, the overall sample size was relatively small compared to other prospective investigations (T. Krosshaug et al., 2016; Petushek et al., 2021). Therefore, this cohort may have been underpowered to detect differences in IC and PC angles between injured and uninjured groups. Furthermore, this investigation followed participants for only one season that was also cut short due to the Covid-19 pandemic, which is a shorter period of time than in other investigations. The resulting uninjured group could very well be also comprised of high-risk individuals who have not yet had enough sport exposure to suffer a non-contact ACL injury. It is also possible that the shorter season is a contributing factor as to why we did not observe any female non-contact ACL injuries this season. In addition, female participants' phase of the menstrual cycle was not recorded at the time of assessment. Therefore, it is possible that the increase in ACL elasticity observed during the menstrual cycle could be a contributing factor to the increased knee valgus seen in Females (Lee et al., 2013; Sandra J Shultz, 2008; S. J. Shultz et al., 2005). Moreover, the participants' sport and respective sport positions were not considered in this investigation. As a result, a given knee angle may predict a different ACL injury risk depending on the sport and respective sport positions due to the differences in physical and biomechanical demands. Finally, the Kinect-based tool is not as overall accurate as the optoelectronic motion analysis systems used in similar investigations. However, our group conducted a validation study where we found excellent agreement between our Kinect-based tool and an optoelectronic motion analysis system when measuring IC, PC and

PF during a DVJ (Karatzas, 2019). It is also important to note that the goal of this investigation is not to produce indisputably accurate IC, PC, and PF angles, as an optoelectronic motion analysis system would be better suited for the task (Merriaux et al., 2017). Rather, the goal is to investigate if a Kinect-based assessment can be used as a screening tool to dichotomize individuals in high and low risk groups for non-contact ACL injury using IC, PC, and PF angles.

9.2 Future Directions

Future studies should test the cut off IC, PC, and PF angles obtaining from this cohort on a new cohort, in order to further investigation of the association between kinematic factors during a DVJ and non-contact ACL injury risk. Future efforts will also be aimed at translating this tool onto a platform for mobile phones. As mobile phone camera technologies are rapidly advancing, a phone application for non-contact ACL injury risk assessment would facilitate widespread screening. Moreover, further research should investigate more practical tasks not requiring a box (ex: Tuck jump) and its association with non-contact ACL injury risk. Implementing such a task would promote widespread screening by gradually removing barriers from conventional non-contact ACL injury risk assessment.

10.0 Conclusion

Our group has developed a portable and practical Kinect-based tool to predict non-contact ACL injuries by measuring IC, PC, and PF angles during DVJ. The findings in this investigation propose that such a Kinect-based tool can predict non-contact ACL injury. Specifically, all non-contact ACL injuries this season were predicted when all three knee angles were utilized. However, when used individually, PF angle was the only variable with good predictive capabilities for non-contact ACL injury risk assessment. We found no significant difference for IC and PC angles between injured and uninjured individuals. Taken together, these findings suggest a portable Kinect-based assessment using only PF angles would effectively assess non-contact ACL injury risk. Furthermore, PF angles would intuitively be a good screening measurement as an increase in knee flexion during landing tasks protects against non-contact ACL injuries, thus suggesting that individuals who exhibit an increase in knee flexion during landing tasks have a decreased risk of suffering a non-contact ACL injury. Moreover, considering the Kinect-based tool is agnostic to demographic data, more knee extension during landing seems predictive of biomechanical deficiencies regardless of sex. Future studies are needed to further investigate the association of IC and PC angles with non-contact ACL injury before including these knee angles in the proposed Kinect-based assessment. Development of a portable Kinect-based tool would facilitate widespread screening, thus increasing the number of identified high risk individuals and increase enrollment in injury prevention programs, ultimately improving athlete care and decreasing the incidence of non-contact ACL injuries.

11.0 References

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