The effects of fatigue on consecutive unilateral and bilateral jump task execution

By

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Abstract

PROBLEM: Lower limb injury rates are on the rise in conjunction with increased leisure activity participation. These injuries can occur due to contact, or due to an individual's movement. Injury risk screening has become more prevalent due to this rise in injury rates, but there is no general consensus in the current literature about how an individual's movement will change when performing multiple jumps or landing tasks, as well as when in a fatigued state. This is important as these tests may better correlate with real-life task execution in practice and competition.

PURPOSE: To assess the biomechanics of individuals performing bilateral and unilateral consecutive jump tasks pre- and post-fatigue, and to determine if there are any changes to these movements.

METHODS: A protocol consisting of consecutive bilateral counter movement jumps (CMJ) and consecutive forward moving single foot jumps (FMSFJ) was assessed pre- and post-fatigue in a healthy athletic population.

RESULTS: Main effects of jump type and fatigue were found in 13 and 8 of the 16 variables, respectively. Participants landed in a less flexed position at the trunk, hip, knee, and ankle in the FMSFJ compared to the CMJ, as well as less flexed in both jump protocols post-fatigue, at initial contact and peak flexion. Participants also showed more hip and knee abduction at peak landing in the CMJ protocol, and in pre-fatigue conditions.

CONCLUSIONS: Comparing the CMJ and FMSFJ protocols, data suggest the landings produced in the CMJ are less risky, as these jumps are performed with larger peak joint angles in the sagittal plane. However, due to potential greater risk with the FMSFJ, this jump protocol may be better for assessing future injury risk in an athletic population, while the CMJ protocol may be better for assessing participant sensitivity to fatigue.

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Chapter I: Introduction

In today's society staying active is becoming a top priority for a majority of the population. Levels of leisure time physical activity have been slowly increasing over the past few decades, and are predicted to keep increasing in the future (Borodulin et al., 2016; Carlson, Fulton, Schoenborn, & Loustalot, 2010). Individuals choose to stay active by enjoying the outdoors, working out in a gym, or playing organized sports, to name a few options. Due to this increase in interest in exercise and sport, there is also an increase in incidence of injury, especially in younger populations (10 to 24 years old) (Adirim & Cheng, 2003; Fernandez, Yard, & Comstock, 2007; Finch, Kemp, & Clapperton, 2015). Most injuries are preventable and the high frequency of injury can tend to contribute to overloading of the health care system (Belton, Pike, Heatley, Cloutier, & Skinner, 2015).

A large portion of these exercise and activity related injuries occur to an individual's lower limbs compared to the upper limbs, especially in team court and field sports and gymnastics (Adirim & Cheng, 2003; Fernandez et al., 2007; Harmer, 2005; Maffulli, Bundoc, Chan, & Cheng, 1996; Nicolini, Carvalho, Matsuda, Sayum Filho, & Cohen, 2014; Roos et al., 2015; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, & Comstock, 2013; Sytema, Dekker, Dijkstra, Ten Duis, & Van Der Sluis, 2010). A high proportion of these lower limb injuries are also due to noncontact mechanisms, meaning the individual does not come in contact with another person or object, but they are injured due to their interaction with the playing surface, or due to an incorrect movement which leads to injury (Fernandez et al., 2007; Sentsomedi & Puckree, 2016; Swenson, Collins, Fields, et al., 2013).

Further, the rate of lower extremity injury in the sporting context is usually higher in competition than in practice, (Harmer, 2005; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, et al., 2013; Vincent, Zdziarski, & Vincent, 2015) which could support the notion that the probability of movement error leading to injury increases with increasing intensity and duration of play, leading to an increased volume of work done in the same or similar amount of time. This may lead to an individual being unable to meet these increased demands, or in other words, becoming fatigued. Another cause for this discrepancy in injury rates may be due to the nature of the skills being performed in competition versus practice, with competition tending toward open skills compared to practices being comprised of more closed skills (Schmidt & Lee, 2011b).

The mechanism of lower body injury commonly includes excessive knee (Cortes, Greska, Kollock, Ambegaonkar, & Onate, 2013; Dalton et al., 2011) or hip adduction (Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008), stiff legged landings with low angles of knee flexion, hip flexion and ankle dorsiflexion (Bates, Ford, Myer, & Hewett, 2013; Norcross et al., 2013), rapid deceleration, requiring high eccentric forces (Schilaty, Bates, Krych, & Hewett, 2017) and creating higher ground reaction forces (Norcross et al., 2013), or a combination of the above mentioned mechanisms. Neuromuscular fatigue can create a progressive loss of movement variability, which has the ability to negatively impact other physiological processes, and ultimately lead to a decline in overall physical function (Cortes, Onate, & Morrison, 2014). These processes affected by fatigue could then lead to an individual expressing the unwanted and unsafe movement mechanics outlined previously, and possibly leading to an increased chance of injury.

Researchers have been looking into injury causation and prevention for many years, but might not be approaching the problem in the correct manner. Most injury prevention or prediction literature uses a type of jumping, landing, or cutting exercise, and analyzes how the participant moves, categorizing it as a good or bad movement, or above or below a certain threshold. These studies usually only use one repetition of the movement being analyzed, (Augustsson et al., 2006; Ebben, Flanagan, & Jensen, 2009; Gathercole, Sporer, Stellingwerff, & Sleivert, 2015; Heebner et al., 2017; Holden, Boreham, Doherty, Wang, & Delahunt, 2015; Kockum & Heijne, 2015; Taylor, Ford, Nguyen, & Shultz, 2016) and usually do not include or have limited kinematic and kinetic values in the analyses (Gathercole et al., 2015; Kockum & Heijne, 2015; Maulder & Cronin, 2005; Meylan et al., 2009). The author feels it is necessary to quantitatively analyze these movements under conditions when individuals are performing consecutive tasks to properly understand the possible mechanisms related to injury, which will be discussed further throughout this review of literature.

Authors usually choose to analyze unilateral or bilateral jumping or landing tasks, and draw conclusions from those individual movement characteristics. Although unilateral and bilateral movements are both important, few researchers actually compare unilateral and bilateral jumping or landing tasks in the same study, on the same individuals (Ebben et al., 2009; Heebner et al., 2017; Kockum & Heijne, 2015; McCurdy, Walker, Armstrong, & Langford, 2014; Meylan et al., 2009; Pain, 2014; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Taylor et al., 2016; Trzaskoma, Ilnicka, Wiszomirska, Wit, & Wychowanski, 2015). Bilateral tasks have the potential to hide asymmetries between limbs in an individual (Kockum & Heijne, 2015), and unilateral and bilateral movements have the potential to show different results, respectively (Earl, Monteiro, & Snyder, 2007; McCurdy et al., 2014; Pappas, Hagins, et al., 2007; Taylor et al., 2016). This disparity may be due to inherent differences in mechanics required to execute bilateral and unilateral tasks.

Heebner et al. (2017) studied the differences in landing mechanics both unilaterally and bilaterally, and found that one task alone is not likely to represent an individual's performance adequately enough to predict injury risk. This notion is further supported by a study done by Donohue and colleagues in 2015, in which these authors conclude that unilateral tasks are superior to use for observing hip mechanics, where bilateral tasks are superior to use for observing knee mechanics (Donohue et al., 2015). Even though knee injuries are more common than hip and ankle injuries, hip and ankle mechanics may contribute to knee injury, so it is still of importance to study all joints of the lower body to assess possible injury mechanics.

Some researchers do include fatigue, perhaps to address the increased noncontact and competition injuries outlined earlier, but the amount of fatigue can range from muscular-specific fatigue induced by isokinetic protocols to system-based cardiovascular fatigue induced by shuttle run-type protocols (Andrews, Horodyski, Macleod, Whitten, & Behm, 2016; Augustsson et al., 2006; Baghbani, Woodhouse, & Gaeini, 2016; Behrens et al., 2015; Cortes et al., 2013; Dalton et al., 2011; García-Pinillos, Molina-Molina, & Latorre-Román, 2016; Quammen et al., 2012; Rozzi, Lephart, & Fu, 1999). Still, a majority of these investigations do not quantify movement into kinematic and kinetic values in their analyses (Andrews et al., 2016; Baghbani et al., 2016; Behrens et al., 2015; Dalton et al., 2011; Rozzi et al., 1999).

Although a prolonged running protocol may be more representative of the duration of field and court sport activities, it would be unrealistic to say a prolonged running protocol is similar to how the athlete would be performing throughout the full duration of these activities, especially when considering a variety of sports. Court and field sports usually consist of jogging interspersed with sprints or bursts of anaerobic activity, and gymnastic competitions consist of short sprints into a movement or set of movements, followed by a pause or break before continuing. Also, as mentioned previously, sports such as gymnastics have a high incidence of injury as well, and bouts of competition are not long in duration, but do involve running, sprinting, and jumping. With this in mind, a sprint running protocol may be more representative of these types of activities. Repeat sprint literature shows similar HR and heart rate recovery (HRR) responses (Abrantes, Sampaio, Reis, Sousa, & Duarte, 2012; Danieli et al., 2014; Taskin, Erkmen, & Cieioglu, 2014), and also produce similar ratings of perceived exertion (RPE) values as prolonged protocols (Girard, Mendez-Villanueva, & Bishop, 2011; Keir, Thériault, & Serresse, 2012; Selmi, Haj Sassi, Haj Yahmed, Moalla, & Elloumi, 2016).

The current study aims to address the gaps in the literature including the use of a consecutive protocol, comparing unilateral and bilateral tasks, and a competition-equivalent fatiguing protocol. This study investigated the kinematics and kinetics of both a bilateral and unilateral consecutive jump procedure, before and after fatigue. Fatigue was induced by a treadmill sprint protocol to understand how an individual's mechanics may change with fatigue, such as would occur in a court, field, or gymnastic sport scenario.

Literature Review

Epidemiology and Incidence of Injury

An abundance of research has been conducted looking at incidence rate of injury in sport. With the push to have a healthier and more active population, participation in all levels of activity, ranging from leisure walking to professional sport has increased (Borodulin et al., 2016; Carlson et al., 2010; Costa E Silva, Fragoso, & Teles, 2017). With this increase, there is a corresponding increase in injury rates as well. In Canada specifically, the 2009-2010 Community Health Survey listed sports and physical exercise as the most frequent activity when a serious injury occurred, totalling 34.9% of all serious injuries (Statistics Canada, 2016). Sprains and strains, and broken bones were the top injuries that were reported in this survey (51.1% and

16.9%, respectively), with the ankle, wrist, and knee being most commonly affected (22.8%, 17.3% and 15.0%, respectively) (Statistics Canada, 2016).

Further, injury in Canadian school-aged children involves fractures, sprains and strains in up to 47% of cases, with 12% of these injuries resulting from organized sport (Josse, MacKay, Osmond, & MacPherson, 2009). The total cost of sport related injuries in Canada across all ages in 2010 amounted to $187 million and over 68,000 emergency room visits (Belton et al., 2015). Although these injuries only account for 0.7% of injury costs and 2.0% of all emergency room visits, these numbers are a controllable contribution to the overload of the Canadian health care system that can potentially be reduced. Further, this number is most likely greatly underestimating the amount of musculoskeletal injuries that occur, as many cities across Canada have specialized orthopaedic trauma centers that most likely take the majority of musculoskeletal injury cases.

Further, once an injury has occurred, especially in a younger individual, there is an increased potential for that individual to incur a secondary health condition, such as osteoarthritis, joint pain, or a mobility disability (Whittaker, Woodhouse, Nettel-Aguirre, & Emery, 2015). Osteoarthritis (OA) alone, for example, is estimated to account for up to 85.5% of all societal costs related to arthritis worldwide (Whittaker et al., 2015). The cost of arthritic disease exceeds $24 billion annually in Australia, and OA related medical costs exceed $185 billion per year in the United States (Finch et al., 2015). In Canada, costs related directly to productive work hours lost, specifically in those with OA, are predicted to increase 46% by 2031 up to $17.5 billion annually from $12 billion in 2010 (Sharif et al., 2017). A study out of Australia displayed increasing trends in the number of all sports injuries, with increases in occurrence of lower limb injuries in a particularly young portion of the population (15 years old and older) (Finch et al., 2015). This may be due to increasing levels of participation, or participation in more competitive or higher-level sports. This increased number of injuries could mean that injuries occurring to younger individuals could lead to progression of OA in this population starting as young as 25 to 45 years old. Theoretically, this increased incidence of lower body injury can then lead to increased secondary joint disease, OA or otherwise, and therefore an increase in direct costs to the public health care system, with a decrease in quality of life and physical activity in these populations. This again could compound the public health burden if these individuals were to develop obesity or diabetes from lack of exercise (Finch et al., 2015). OA is just one possible path of lower limb health post-injury, to show the impact a seemingly benign event can have economically.

Subsequent to overall injury incidence, the specific joint or muscle that has been injured, the activity or sport in which the individual injured themselves, and the exact mechanism of injury has also been extensively investigated. Lower extremity injuries in adults account for up to 36% of all hospital-treated physical activity related injuries (Finch et al., 2015) and up to 90% of musculoskeletal sport injuries (Nicolini et al., 2014). In adolescents, musculoskeletal injuries to the lower extremities can account for as much as 58% of all reported injuries (Maffulli et al., 1996). More specifically, it has been reported in many studies and systematic reviews that up to 66% of these lower extremity injuries, across younger and older age groups, involve the knee and ankle joints (Bleakley, Tully, & O’Connor, 2011; Ekegren, Gabbe, & Finch, 2015; Fernandez et al., 2007; Finch et al., 2015; Harmer, 2005; Leppänen, Pasanen, Kujala, & Parkkari, 2015; Maffulli et al., 1996; Majewski, Susanne, & Klaus, 2006; Roos et al., 2015; Sentsomedi & Puckree, 2016; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, et al., 2013; Vincent et al., 2015).

Injuries can be classified as a contact or a noncontact mechanism, especially when referring to the lower body. A contact mechanism of injury means that the individual who was injured was injured by contact with another person or object, where a noncontact mechanism of injury means individuals injured themselves by interaction with the playing surface only, or in midair. Twenty-five percent of all lower limb injuries in high-school aged populations occur in a noncontact injury scenario (Fernandez et al., 2007; Sentsomedi & Puckree, 2016). Twenty-six percent of all ankle injuries are reported to be due to a noncontact mechanism (Swenson, Collins, Fields, et al., 2013), and up to 80% of all anterior cruciate ligament (ACL) injuries of the knee occur by noncontact mechanisms (Bates et al., 2013; Harmer, 2005; Morgan, Donnelly, & Reinbolt, 2014).

ACL injuries are of heightened interest recently, as injury occurrence seems to be increasing at a high rate compared to active populations of the past, with a jump in incidence from 1% of athletic injuries in 1997 (Parkkari, Pasanen, Mattila, Kannus, & Rimpelä, 2008) to 37% of athletic injuries in 2008 (Nicolini et al., 2014). This may be due to an increase in reporting of injuries, better record keeping of injuries, or an increased interest in sport participation. It is also suggested that females are, at best, at a three-fold higher risk of noncontact mechanism of ACL rupture compared to males playing the same sport or activity (Russell, Palmieri, Zinder, & Ingersoll, 2006). Overuse injuries are another type of injury that most likely occur in a noncontact scenario, and can be due to repetitive, improper movement execution. Overuse can also lead someone with proper movement execution to use poor or improper mechanics as they begin to fatigue, leading to subsequent injury. Seventy percent of all overuse injuries in high school and collegiate age athletes occur to the lower limb (Roos et al., 2015).

The effects of fatigue, the duration of activity and the type of activity have also been examined with respect to injury rate. The rate of lower extremity injury in the sporting context is usually higher in competition than in practice (Harmer, 2005; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, et al., 2013; Vincent et al., 2015). Activities utilizing a ball, such as football, soccer, volleyball, handball, and basketball, as well as gymnastics have shown higher rates of lower body injury in relation to all other forms of physical activity (Adirim & Cheng, 2003; Fernandez et al., 2007; Harmer, 2005; Maffulli et al., 1996; Nicolini et al., 2014; Roos et al., 2015; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, et al., 2013; Sytema et al., 2010). This may be due to more jumps, sudden stops, or changes of direction commonly observed in activities utilizing a ball and gymnastic events compared to other forms of physical activity. Another cause for this discrepancy in injury rates may be due to the nature of the skills being performed in competition versus practice, with competition tending toward open skills compared to practices being comprised of more closed skills (Schmidt & Lee, 2011b). An open skill is performed in an environment that is constantly changing, and that change may be unpredictable, such as in a game or competition. A closed skill is performed in a predictable and perhaps stable environment, such as drills in practice (Schmidt & Lee, 2011b). This change in the environment may have different impacts on an individual's attention, which will be explained in more detail later (Schmidt & Lee, 2011a).

Further, the impact of sex on rate of injury has been debated in literature surrounding lower extremity injury. The current North American viewpoint is that females are at higher risk of knee injury, specifically injury to the ligaments of the knee, especially in the activities utilizing a ball mentioned previously (Fernandez et al., 2007; Parkkari et al., 2008; Swenson, Collins, Best, et al., 2013). However, literature from European countries reports similar or higher incidence of all knee injuries in males, including ligaments such as the medial collateral ligament (MCL) and ACL, even when corrected for athletic exposure rates (Clayton & Court-Brown, 2008; Maffulli et al., 1996; Majewski et al., 2006; Vincent et al., 2015). Two other studies did not have the common consensus on which sex had higher incidence of lower extremity injury, and injury risk seemed to be sport dependent (Bleakley et al., 2011; Nicolini et al., 2014). It is unclear as to why there is a difference in incidence across continents, but this discrepancy in the literature makes it apparent that it cannot assumed males are less likely to incur a knee injury, so both sexes should be investigated separately in risk analyses.

Some of the reasons proposed for the sex-based discrepancy in injury incidence include hormonal, neuromuscular, and anatomical differences between males and females (Gehring, Melnyk, & Gollhofer, 2009; Stroube et al., 2013; Weeks, Carty, & Horan, 2015; Weinhandl, Irmischer, & Sievert, 2015), as well as possible training differences.

Anatomy, and Mechanism and Incidence of Injury of the Joints of the Lower Extremity

The lower limb attaches to the trunk via the pelvis. The pelvis' bony structure is comprised of three bones; the left and right innominate bones and the sacrum. These bones are joined at the pubic symphysis anteriorly, and the sacroiliac joints posteriorly (Moore, Agur, & Dalley, 2015b). Collectively, this structure is referred to as the pelvic girdle. The main role of the pelvic girdle is to transfer weight from the upper body received from the trunk, into the legs during gait, stance, and all other weight bearing activities (Moore et al., 2015b). The pelvic girdle is held together as one structure and strengthened by multiple ligaments. Many muscles cross and attach to the pelvic girdle from both the upper and lower body, allowing energy transfer to occur from the upper to the lower limbs and vice versa.

The pelvic girdle is shaped differently for males and females, so this is one of the main anatomical differences that is said to contribute to differences in movement execution and injury risk. The male pelvic girdle is generally thicker, heavier, and has more prominent bony markings, whereas the female pelvis is generally wider, shallower, and has a larger pelvic inlet and outlet (Moore et al., 2015b). The male pelvis also has larger acetabula, which can contribute to a more secure hip joint in males, jointly with males having larger muscle mass generally than females (Moore et al., 2015b).

The female pelvic girdle typically has a larger width, which can create a larger quadriceps angle, more commonly referred to as the Q-angle. The Q-angle is measured as the angle found between the femoral axis relative to the tibial axis measured at the knee in the frontal plane (Kernozek, Torry, & Iwasaki, 2008; Pantano, White, Gilchrist, & Leddy, 2005). It is suggested that because of this larger Q-angle, that females will inherently exhibit larger values of knee adduction or valgus, and because of this are at a higher risk of injuries with a mechanism related to valgus collapse, such as ACL and MCL injuries (Pantano et al., 2005). Although this is thought to be likely, the specific combination of anatomical and muscle strength characteristics that may influence knee joint biomechanics and injury is not well understood (Ireland, 2002; Nilstad, Krosshaug, Mok, Bahr, & Andersen, 2015). It is suggested that instead of Q-angle being considered as the anatomical game-changer, that perhaps the ratio of pelvic width to femoral length may be more informative (Ireland, 2002).

The sacroiliac joints on the posterior aspect of the pelvic girdle, mentioned previously, are the joints specifically in which forces from the upper body are transferred to the lower body. The sacrum receives forces from the vertebral column, and transfers these forces to the pelvic bones via the sacroiliac joints and indirectly to the legs through the hip joints(Moore et al., 2015b). When the forces are transmitted through this joint, such as in jumping and landing, the sacrum tends to rotate anteriorly and superiorly, when usually there is only slight gliding and rotation occurring at the sacroiliac joint (Moore et al., 2015b). These unwanted movements are resisted by ligaments of the pelvic girdle, namely the sacrotuberous, sacrospinous, and anterior, interosseus and posterior sacroiliac ligaments. The muscles of the thigh, buttock, and back help to control movement of the entire pelvic girdle during weight acceptance. When these muscles are not working together in the proper order, or are not strong enough to control the increased momentum of the body, this is when unwanted or excessive movements can occur (Moore, Agur, & Dalley, 2015a; Moore et al., 2015b).

The most proximal joint of the lower limb is the hip joint. The hip joint is a multiaxial ball and socket joint and is the point of connection between the pelvic girdle and the lower limb. Due to this socket formation, the hip joint relies mostly on ligaments and muscles to keep it in its correct articulation. The head of the femur is secured in the acetabulum of the hip bone by the fibrocartilage labrum of the acetabulum and four broad ligaments that almost entirely encapsulate the head and neck of the femur, which help to control abnormal motion at the hip joint (Moore et al., 2015a). The hip joint also has many muscles crossing it, including medial and lateral rotators, hip flexors and extensors, and hip adductors and abductors. In total, 21 muscles cross the hip joint, from all sides, creating superb stability (Moore et al., 2015a). This is most likely why hip injuries are not very common, and the injuries in the upper leg are usually muscular in nature, not ligamentous or bony.

Hamstring and quadriceps muscle group strains, as well as adductor group strains (also known as groin strains) are frequent injuries to the upper leg. Hamstring strains can account for 12 to 26% of all injuries, in sports such as track and field, soccer, football, and rugby (Opar, Williams, & Shield, 2012). The mechanism of hamstring and groin strains usually involves high eccentric forces and high muscle strain (Opar et al., 2012; Van Der Horst, Smits, Petersen, Goedhart, & Backx, 2015; Worrell & Perrin, 1992). Other possible contributors to upper leg muscle injury are large imbalances in quadriceps and hamstring strength ratios, and imbalances between limbs (Worrell & Perrin, 1992). However, if an individual is strong and stable through the hip joint, excessive applied forces may then be transferred to the lower limb to the next joint distally; the knee joint.

The knee joint is a modified hinge joint, rotating about the left-right axis primarily, with the ability to rotate about the longitudinal axis when the knee is flexed (Moore et al., 2015a). The knee joint's articular surfaces are large in size but mostly incongruent in shape. This makes the stability of the knee joint highly dependent on the strength and actions of the surrounding muscles, their associated tendons, and the ligaments that connect the femur and the tibia (Moore et al., 2015a). Because of this relationship between stability and muscular strength and action, most injuries to the knee are preventable through strengthening and proper movement execution. Injuries to the knee usually occur due to excessive valgus motion created by increased external knee abduction moments, greater hip internal rotation, and greater hip adduction (Lawrence et al., 2008). Knee injury also commonly occurs in rapid deceleration and planting (Schilaty et al., 2017), as is common in ball sports and gymnastic sports.

There are four capsular ligaments and one extracapsular ligament of the knee that help to strengthen the joint capsule of the knee itself (Moore et al., 2015a). The four capsular ligaments include the patellar ligament (or tendon), which joins the patella to the tibial plateau, the oblique popliteal ligament which strengthens the posterior joint capsule, the arcuate popliteal ligament which traverses the popliteus muscle and covers the posterior knee joint, and the medial collateral ligament (MCL) which attaches from the medial epicondyle of the femur to the medial condyle of the tibia. The MCL also has deep fibers that firmly attach to the medial meniscus, which is described in greater detail later. The one extracapsular ligament is known more commonly as the lateral collateral ligament (LCL), which attaches from the lateral epicondyle of the femur to the lateral surface of the head of the fibula.

The MCL and LCL are known collectively as the ‘collateral’ ligaments, and are taut when the knee is in full extension, but slack when the knee is moving through its range of motion, which helps permit some transverse rotation at the knee joint. The LCL is rounded and cord-like, while the MCL is a flat band, making the LCL stronger than the MCL, and thus more difficult to injure (Moore et al., 2015a). It is also more common for the knee to collapse into the medial side, as mentioned previously, due to this relationship. This knee adduction, when excessive and chronic, can predispose an individual to patellofemoral pain syndrome (PFPS) (Cronström, Creaby, Nae, & Ageberg, 2016). It is suggested that females are at a higher risk of PFPS, which can be due to insufficient neuromuscular control or pelvic anatomical differences mentioned prior (Cronström et al., 2016; Galloway et al., 2018; Moore et al., 2015b).

In addition to the ligaments mentioned already, there are also two intercapsular ligaments, the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL), which both help to control rotation and translation of the knee joint. The ACL runs from the anterior intercondylar area of the tibia to the posterior-medial part of the lateral condyle of the femur. The ACL is the weaker ligament of the two, and its role is to limit posterior rolling and displacement of the femur on the tibia as well as hyperextension and internal rotation of the knee joint. With the knee at 90 degrees of flexion, the ACL is taut and prevents anterior translation of the tibia on the femur (Moore et al., 2015a). The second cruciate ligament, the PCL, is the strongest ligament of the knee and runs from the posterior intercondylar area of the tibia to the anterior part of the medial condyle of the femur. The PCL limits anterior rolling and displacement of the femur on the tibia and helps prevent hyper flexion and internal rotation of the knee joint. In weight bearing, the PCL is the main stabilizer for the femur during flexion activities, such as walking downhill, or slowing to a stop from a sprint (Moore et al., 2015a). It has been suggested that the size and shape of the femoral notch that these two ligaments reside in can be different in males and females, or can predispose an individual for injury to one of these ligaments. The literature states that females have an increased posterior tibial slope, a smaller femoral notch size, a smaller ligament diameter, and a more defined edge to the femoral notch itself (Sutton & Bullock, 2013). These anatomical factors could potentially place a female at higher risk of cruciate ligament injury.

The tibia and femur are separated by a medial and lateral plate of fibrocartilage on the superior articular surface of the tibia, which help with shock absorption and proper tracking of the knee joint (Moore et al., 2015a). The medial plate, also referred to as a meniscus, is the larger of the two, and is firmly attached to the tibial plateau. This is due to the fact that the medial meniscus, being a c-shaped structure, shares its three external facing borders with the attachment of ligaments of the knee, namely, the ACL anteriorly, the PCL posteriorly and the MCL on the medial side of the knee joint (Moore et al., 2015a). The lateral meniscus is smaller, almost circular, and more moveable than the medial meniscus. The lateral meniscus only shares an attachment with one of the major ligaments of the knee, the PCL. Due to the more intrinsic nature of the medial meniscus' attachments, it is more likely to be injured than the lateral meniscus, along with the ligaments it associates with. Out of all internal knee traumas, Majewski et al. (2006) reported a frequency of medial meniscus injury up to 25%, and only 8.7% injury for the lateral meniscus. This disparity in injury rate may be due to different rotational forces in common mechanisms of injury affecting the menisci differently, which will be briefly outlined next.

Injury to the MCL and medial meniscus is frequently caused by a lateral force, either to the knee itself or to the body of the individual while the knee is extended, or excessive amounts of lateral twisting of the knee in a flexed position. During flexion the ACL is taut, so may be disrupted as well in instances where the MCL is torn (Moore et al., 2015a). Current epidemiological literature reports MCL injury occurring as the most frequent ligamentous injury in high school populations (Swenson, Collins, Best, et al., 2013), and up to 13% of all internal knee traumas, meaning injury occurring to the ligaments and structures within or associated with the joint capsule itself, such as menisci, collateral ligaments and cruciate ligaments (Majewski et al., 2006). Majewski et al. (2006) reported 44.8% of knee injuries in athletes across all ages involve internal knee trauma, including injuries to the ACL occurring in 45.4% of these internal knee traumas (20.3% occurrence overall). Nicolini et al. (2014) report the ACL to be injured in up to 54% of all sporting knee injuries. 46.9% of these ACL injuries were associated with at least one secondary injury, including injury to structures such as the MCL, meniscus, or PCL (Nicolini et al., 2014). PCL injuries are less common, accounting for as little as 1.4% of internal knee injuries (Majewski et al., 2006), but may occur when excessive force is applied to the tibial tuberosity, especially in a flexed knee position. With a PCL rupture, it is very common for the MCL and/or LCL to be injured as well (Moore et al., 2015a). Other knee injuries include knee distortion (sprains) (33.8%) and acute or chronic cartilage lesions (10.6%) (Majewski et al., 2006).

The most distal joint of the lower limb is the ankle joint. The ankle is a hinge-type joint that can be classified by two separate ‘joint’ articulations. The ankle joint proper, also referred to as the talocrural joint is formed between the distal ends of the tibia and fibula, and the superior part of the talus (Moore et al., 2015a). This articulation allows for dorsiflexion and plantarflexion of the foot to occur. The subtalar joint, which is formed between the inferior part of the talus and the superior part of the calcaneus, allows for inversion and eversion of the foot (Moore et al., 2015a). Although the ankle is classified as a hinge joint, it has much more bony stability than the knee. The lateral (fibular) and medial (tibial) malleoli surround the superior talus in the 'malleolar mortise', creating a tight grip-like fit. This fit is tightest in dorsiflexion due to the wider anterior part of the talus articulating with the malleoli versus the narrower posterior part of the talus articulating with the malleoli in plantarflexion (Moore et al., 2015a).

Due to this narrowing of the posterior talus, this makes the ankle joint relatively unstable in plantarflexion, so the ankle then relies more heavily on the surrounding ligamentous, muscular and tendinous structures for additional stability (Moore et al., 2015a). The ankle is supported both laterally and medially by ligamentous structures; however the medial aspect of the ankle has a much larger surface area covered by ligamentous protection. Laterally, the ankle is supported by the anterior and posterior talofibular ligaments, the calcaneofibular ligament, and the bifurcate ligaments, primarily. These ligaments are all independent of each other, and act like tethers holding the fibula to the associated foot structures. Medially the ankle is supported by a collection of ligaments, commonly referred to as the deltoid ligament, as well as the calcaneonavicular ligament. The deltoid ligament is comprised of the anterior and posterior tibiotalar ligaments, the tibionavicular ligament, and the tibiocalcaneal ligament. As the ligament names suggest, this structure spans from the medial malleolus to the talus, calcaneus and navicular, creating very strong medial reinforcement for the ankle. The calcaneonavicular ligament, also known as the spring ligament, further supports the medial aspect of the foot and ankle, and also helps with weight distribution and maintenance of the longitudinal arch of the foot (Moore et al., 2015a).

Further stabilizing the ankle from eversion is the fact that the lateral malleolus of the fibula extends further inferiorly than the medial malleolus of the tibia. This makes the ankle much easier to invert, because of the lesser ligamentous stability and less bony stability (Moore et al., 2015a). Sprains of the ankle ligaments are the most common ankle injury, and the anterior talofibular ligament, on the lateral side of the ankle joint, is the most commonly torn ligament, specifically (Moore et al., 2015a). In athletes, ankle sprains are reported as 52.6% of all ligament sprains, and up to 17% of all injuries overall in a high-school aged population (Swenson, Collins, Fields, et al., 2013). Up to 73% of those who sprain their ankle will do so again, which can lead to a condition of chronic instability for those individuals (Hoch, Farwell, Gaven, & Weinhandl, 2015). This instability can lead to self-reported loss of function, as well as reduced dorsiflexion range of motion (Hoch et al., 2015). Other common ankle and lower leg injuries include Achilles tendon injury (10.7% of all soft tissue injury across all ages), peroneal tendon rupture, and gastrocnemius and tibialis posterior tendon rupture (Clayton & Court-Brown, 2008).

The anatomy overview helps to understand the differences in the classification and function of each joint in the lower body and lower limbs. This overview outlines the immense strength through the pelvic girdle and hip joint, the relative bony instability and lack of muscular protection at the knee joint, and the strong bony, ligamentous, and tendinous integrity of the ankle joint. The knee, which is already the least stable joint of the three lower limb joints, is also unfortunately positioned between the body’s two largest lever arms, which increases the knee’s susceptibility to injury. This arrangement may then be made worse or exacerbated by difference in the female and male anatomy, as the alignment of the hip joint in the pelvis can change the angular displacement and forces transferred to the knee joint, and subsequently, to the ankle joint. Along with the passive bony and soft tissue control at these joints outlined, an individual's ability to control their muscular contractions and overall movement execution can help prevent injuries. Inadequate muscular control at the ankle joint during landing can generate aberrant movement at the knee and hip joints, which may not be properly guarded by the muscles surrounding these joints to prevent such movements, depending on the individual's responsiveness to sudden changes in alignment. Jumping and/or landing quality, kinematics and/or kinetics are usually the measures used to quantify this level of control and the individual's skill level. This task execution can then be used to display the individual's risk of injury, determined by their ability to control their limbs.

Unilateral versus Bilateral Tasks

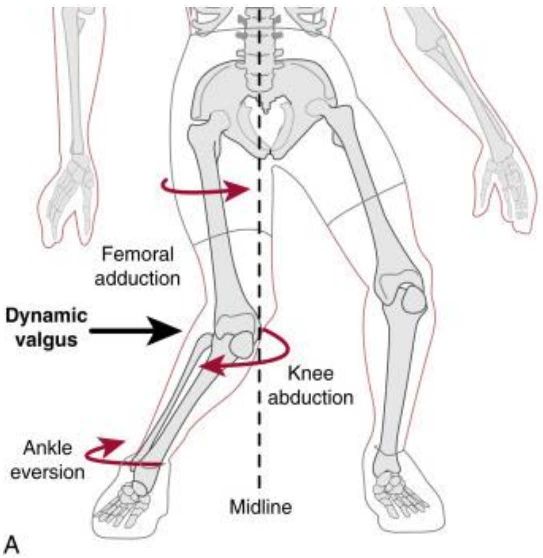
Tasks consisting of jumping and/or landing are commonly used to assess athletic performance, specifically of the trunk and lower limbs. This performance can be quantified with absolute outcomes such as power, strength, or distance covered, or the execution of the task can be quantified with movement outcomes such as kinematic and/or kinetic measurements. Bilateral counter movement jumps (CMJs), which are characterized by an individual who begins in an upright erect position, and then performs a jump by quickly flexing at the hip, knee and ankle into a squatting position and immediately jumping upwards (Enoka, 2008; Kockum & Heijne, 2015), have been used frequently to assess movement performance and risk for lower extremity injuries, but mostly from an absolute outcomes perspective (Andrews et al., 2016; Ebben et al., 2009; Gathercole et al., 2015; Heishman et al., 2018; Maulder & Cronin, 2005; Stroube et al., 2013; Trzaskoma et al., 2015), and less commonly including movement outcomes (García-Pinillos et al., 2016; Holden et al., 2015; Schmitz, Cone, Copple, Henson, & Shultz, 2014; van der Does, Brink, Benjaminse, Visscher, & Lemmink, 2015).

Other bilateral tasks that are commonly used to assess performance or task execution are drop jumps which are characterized by an individual standing on a raised box or platform at a height above ground level, and the individual steps off the height and once landing on the ground immediately jumps upward (Andrews et al., 2016; Bates et al., 2013; Earl et al., 2007; Galloway et al., 2018; Gathercole et al., 2015; Ishida et al., 2018; Kondo & Someya, 2016; Malloy, Morgan, Meinerz, Geiser, & Kipp, 2015; McCurdy et al., 2014; Nilstad et al., 2015; Pain, 2014; Pappas, Hagins, et al., 2007; Pappas, Sheikhzadeh, Hagins, & Nordin, 2007; Schmitz, Cone, Tritsch, et al., 2014; Shultz et al., 2015; Smith, Sizer, & James, 2009), drop landings, which are similar to drop jumps, but do not involve the immediate jump once the landing on the ground has occurred (Brown, Palmieri-Smith, & Mclean, 2009; Gehring et al., 2009; Heebner et al., 2017; Homan, Norcross, Goerger, Prentice, & Blackburn, 2013; Y. Kim, Youm, Son, Kim, & Lee, 2017; Norcross et al., 2013; Pappas, Hagins, et al., 2007; Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2013; Wu, Zhang, Liu, Zhang, & Xie, 2013; Zhang, Xia, Dai, Sun, & Fu, 2018), stop-jump tasks, which involve some sort of run up to a double foot stop and subsequent jump up or forward (B. Dai, Butler, Garrett, & Queen, 2014; Boyi Dai et al., 2019)and common bilateral squats (Macrum, Bell, Boling, Lewek, & Padua, 2012; McCurdy et al., 2014).

Interestingly, these bilateral tasks are more commonly reported with kinematic or kinetic measurements, compared to the CMJ. However, the studies listed previously that include other bilateral tasks still fail to show the whole picture when it comes to lower body movement execution and performance. This is especially true in instances when the researchers are trying to define risky mechanics and give recommendations for at risk populations, but do not investigate and include all parameters that contribute to lower body mechanics such as ground reaction forces, kinematic joint variables, and kinetic joint variables. Further, CMJs have been shown to be most reliable over multiple trials, and most sensitive to detecting neuromuscular fatigue versus drop jumps and squat jumps (Gathercole et al., 2015).

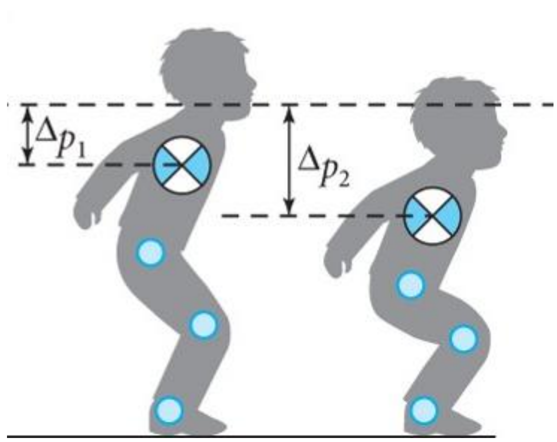
Mentioned earlier, the mechanism of lower body injury commonly occurs during landing or stance, and includes excessive knee (see Figure 1, (Giangarra, Mankse, & Brotzman, 2018)) (Cortes et al., 2013; Dalton et al., 2011; Shimokochi & Shultz, 2008) or hip abduction (Lawrence et al., 2008), stiff legged landings with low angles of knee flexion, hip flexion, and ankle dorsiflexion (see Figure 2, (Flanagan, 2014)) (Bates et al., 2013; Boyi Dai et al., 2019; Norcross et al., 2013; Shimokochi & Shultz, 2008), rapid deceleration requiring high eccentric forces (Schilaty et al., 2017; Shimokochi & Shultz, 2008) and creating higher ground reaction forces (Norcross et al., 2013). The mechanism of injury for a lower body joint obviously will not always demonstrate all of the above mechanisms, but at one time or another, have been associated to an increased risk of injury, all mechanisms should at least be kept in mind during analysis.

Figure 1: Knee abduction in landing



Reprinted from *Clinical Orthopaedic Rehabilitation: A Team Approach* (p. 309), by C. E. Giangarra, R. C. Mankse, & S. B. Brotzman, 2018, Philadelphia: Elsevier Inc.

Figure 2: Stiff legged landing



Reprinted from *Biomechanics: A Case-Based Approach* (p. 152), by S. Flanagan, 2014, Burlington, MA: Jones & Bartlett Learning.

Along these lines, the ground reaction forces and moments of force produced while an individual expresses the specific movement characteristics being studied also cannot be ignored. Ground reaction forces are the reaction forces reflected by the surface in which an object or individual is interacting with (Enoka, 2008). The surface must push back with the same amount of force that the object or individual is exerting on the surface, or else the object or individual would theoretically sink into or break through that surface. When measuring ground reaction forces, the equal but opposite force to that which the individual is exerting into the surface is being measured. From this, how the individual is interacting with the surface specifically, can be studied. Higher forces through the lower limbs can contribute to higher joint moments, which have been deemed possibly causative of lower extremity injury (Podraza & White, 2010). Due to this, it is imperative to study all joints of the lower body, along with trunk kinetics and kinematics, to study how the joints may compensate for one another.

For these bilateral tasks outlined previously, the movement of the trunk and the segments of the lower leg are usually the major focus of analysis, along with their associated joint angles. The trunk, hip, knee, and ankle joints all form a working unit that must counteract forces transferred to them. The forces created or absorbed by the lower limbs control and contribute to the whole body center of mass, as the ground reaction forces also represent the acceleration of the whole body center of mass (Enoka, 2008). The lower limbs subsequently provide propulsive and braking forces, which control the movement of the body above the lower limbs, namely the trunk. Interestingly, the studies that include movement outcomes usually only assess one or two of these joints, or report only one plane of movement.

The sagittal, frontal, and transverse planes are all very important in movement execution, as well as all of the joints involved as these joints can move in at least two planes during dynamic tasks. The common mechanisms of injury suggested earlier included movements in the frontal plane, specifically higher amounts of knee and hip adduction, and movements in the sagittal plane, specifically lower amounts of knee, hip and ankle flexion. Abnormal or excessive rotations about these joints, in the transverse plane, have also been attributed to injuries of the knee, specifically, which were outlined in the previous anatomy section (Boden, Sheehan, Torg, & Hewett, 2010; Ishida, Yamanaka, Takeda, & Aoki, 2014; Myer, Ford, & Hewett, 2008; Shimokochi & Shultz, 2008).

Another type of movement that should be assessed is unilateral movement execution. Many activities or tasks within an activity need to be performed while on one leg. Even very simple tasks such as walking require an individual to be able to balance and perform on one leg to have successful movement. Unilateral assessment has generally been done with single-leg squats (Hollman, Galardi, Lin, Voth, & Whitmarsh, 2014; McCurdy et al., 2014; Pasanen et al., 2015; Weeks et al., 2015), single-leg CMJs, either vertically or horizontally driven (Ceroni, Martin, Delhumeau, & Farpour-Lambert, 2012; Ebben et al., 2009; Heebner et al., 2017; Jayalath, DeNoronha, Weerakkody, & Bini, 2018; H. Kim, Son, Seeley, & Hopkins, 2015; Kockum & Heijne, 2015; McElveen, Riemann, & Davies, 2010; Meylan et al., 2009; Mudie, Gupta, Green, & Clothier, 2016; Shultz et al., 2015; Taylor et al., 2016; Trzaskoma et al., 2015; van der Does et al., 2015), single-leg drop landings (Brazen, Todd, Ambegaonkar, Wunderlich, & Peterson, 2010; Brown et al., 2009), and single-leg drop jumps (Ebben et al., 2009; Hansberger, Acocello, Slater, Hart, & Ambegaonkar, 2018; Jayalath et al., 2018; Lessi, Flávia dos Santos, Fylipe Batista, Clemente De Oliveira, & Serrão, 2017; Lessi & Serrão, 2017; McCurdy et al., 2014; Pain, 2014; Pappas, Hagins, et al., 2007; Pasanen et al., 2015).

Unilateral stance with limited knee flexion is another common posture associated with knee injury, or placing the knee under increased levels of stress (Nyland, Smith, Beickman, Armsey, & Caborn, 2002; Shimokochi & Shultz, 2008). During unilateral stance, the line of gravity associated with the body center of mass moves posterior to the knee and ankle joints, increasing the required contributions from muscles performing knee extension and ankle plantarflexion for the individual to remain standing (Nyland et al., 2002). Injury incidence literature also outlines that knee injuries can occur more frequently in a unilateral stance versus bilateral (Nyland et al., 2002). Due to the individual having to land on one leg, half of their body mass is on the opposite side of their center of mass compared to their support leg, and the base of support for the task is decreased drastically (Weinhandl et al., 2015). This can create higher frontal plane demands, leading to higher frontal plane movement at the knee, hip and trunk through the duration of the unilateral task (Brown et al., 2009; Pappas, Hagins, et al., 2007). The individual also has to rely solely on the strength of that singular leg, making movement execution or control more tasking on the muscular system, which can thus classify unilateral tasks as being relatively more dangerous than bilateral tasks. Similar to bilateral tasks, very few analyses of unilateral jumping and landing actually report kinematic or kinetic data (Brown et al., 2009; Hansberger et al., 2018; Kariyama, Hobara, & Zushi, 2017; Lessi et al., 2017; Lessi & Serrão, 2017; McCurdy et al., 2014), meaning these analyses cannot definitively report on quality of movement or injury risk due to improper or unsafe task execution.

Although unilateral and bilateral movements are both important, few researchers actually compare unilateral and bilateral jumps or landings in the same study, on the same individuals (Ebben et al., 2009; Heebner et al., 2017; Kockum & Heijne, 2015; McCurdy et al., 2014; Meylan et al., 2009; Pain, 2014; Pappas, Hagins, et al., 2007; Taylor et al., 2016; Trzaskoma et al., 2015). Bilateral tasks have the potential to hide asymmetries between limbs in an individual (Kockum & Heijne, 2015), and unilateral and bilateral movements have the potential to show different results, respectively. Heebner et al. (2017) studied the differences in landing mechanics in drop jumps and stop jumps, both unilaterally and bilaterally, and found that one task alone is not likely to represent an individual's performance adequately enough to predict injury risk, so more than one task should be included in analysis if more accurate conclusions are to be made. This notion is further supported by a study conducted by Donohue and colleagues in 2015 that outlined differences in hip and knee mechanics during unilateral and bilateral tasks. These authors concluded that unilateral tasks were superior to use for observing hip mechanics, where bilateral tasks are superior to use for observing knee mechanics (Donohue et al., 2015). Even though knee injuries are more common than hip injuries in the literature (Clayton & Court-Brown, 2008; Fernandez et al., 2007; Maffulli et al., 1996; Majewski et al., 2006; Roos et al., 2015; Sentsomedi & Puckree, 2016), hip mechanics may contribute to knee injury, so it is still of importance to study all joints of the lower body to assess possible injury mechanics.

Unilateral and bilateral jumps have also been shown to require or induce disparate ranges of joint angles and overall range of motion, which is noted in studies conducted by McCurdy et al. (2014), Pappas et al. (2007), Taylor et al. (2016), and Earl et al. (2007), with bilateral tasks having 10 to 50% more flexion through the hip and knee compared to unilateral tasks. Unilateral tasks also tend to elicit higher hip adduction values, while bilateral tasks tend to elicit higher knee adduction values (Earl et al., 2007; McCurdy et al., 2014; Pappas, Hagins, et al., 2007; Taylor et al., 2016). These variances may be due to important differences in the neuromuscular pathways being used in bilateral and unilateral tasks, muscle weaknesses being exacerbated by unilateral protocols, or differences in alignment and size of the base of support mentioned previously. A few of these authors have also compared male and female values, and while there are some slight differences in knee mechanics in the frontal and sagittal planes, and in both unilateral and bilateral tasks, these are not always statistically different, and it is unclear whether these different values would be significant with respect to injury risk (Herrington & Munro, 2010; Holden et al., 2015). Also, researchers have looked at female landing mechanics specifically (Fox, Bonacci, McLean, Spittle, & Saunders, 2014), suggesting different mechanics from males, but when compared to a population of both males and females, the results for the solely female group do not differ from the group of both males and females (Pappas, Hagins, et al., 2007)

Vertical versus Horizontal Movement

Paucity in current literature also exists for comparing jumping or landing tasks moving vertically as well as horizontally. Propelling the body forward as the jump occurs is more similar to tasks that would occur more frequently during sport or physical activity, such as performing a lay-up or jump shot in basketball, performing a stem shot in handball, going up for a strike or block in volleyball, or coming out of a cartwheel or backflip in gymnastics. Both horizontal and vertical jumps are used in sport and activities, and they both produce different demands that need to be recognized and overcome by the individual to ensure a safe and successful landing. Vertical jumps, especially employed as a CMJ, require changing the speed and direction of the individual's center of mass as it accelerates first downward, then upward, and finally downward again (Enoka, 2008).

The ability to propel the center of mass upward is what determines how high an individual will jump. The maximum height that can be achieved depends primarily on the timing of the muscle activity in the legs, as well as the absolute magnitude of force that is created by those muscles (Enoka, 2008). Also, as the individual lands from the CMJ, slowing the velocity of the center of mass as it is affected by gravity requires eccentric action from the lower limbs (Enoka, 2008). Horizontal movements also require changing the direction of the individual's center of mass, but in a translational manner as well as against or with gravity. This requires ameliorating shear forces as well, which have more potential to contribute to lower body injury than purely axial forces. Due to the different forces required by the body to control horizontal and vertical jumping or landing tasks, it is imperative to include both in movement execution analyses, to study how an individual controls their movement during different tasks involved in physical activity.

Augustsson and Thomee (2006) also suggest that performing jumps that move horizontally will automatically change the kinematics that result, regardless of whether it is unilateral or bilateral. These authors posit that vertical jumps will create higher amounts of joint flexion, because the individuals allow for force absorption over a longer period of time (more range of motion), and horizontal jumps will have lower joint flexion (Augustsson et al., 2006). These authors also highlight the fact that, in their study, there was only one repetition performed at a time, and with the higher levels of flexion on the vertical jumps, the participants probably would not be able to perform another jump from this position if they were required to (Augustsson et al., 2006).

Single Repetitions versus Multiple, Consecutive Repetitions

The notion outlined previously that higher levels of flexion in vertical jumps or landings might hinder the ability to perform a second jump can be extended to propose that these individuals would not be in the most efficient position to stay upright, or perform a second task, as would be required in a sport or activity situation. This is an important reason indicative of why multiple repetitions should be used in an analysis protocol, so the participant is required to perform more than one task consecutively and perform these tasks as if they did need to respond to produce subsequent movements successfully.

Along with work done by the muscles to create energy to actively move and control the body, there is also passive work through mechanical energy transfer between body segments. Each body segment exerts a force on its adjacent segment by force displacements through the joint center that joins the two segments (Winter, 2009). Since this transfer of energy happens passively, it does not require muscle action to occur. Because of this, it can be very important to conserve this energy and utilize it to reduce the amount of muscle force required for a movement (Winter, 2009). Four common causes of inefficient movement are co-contractions, isometric contractions against gravity, generation of energy at one joint and energy absorption at another, and jerky movement patterns (Winter, 2009). Using a task that is performed in a consecutive manner may help to show these causes of inefficient movement, and may uncover what needs to be done to ameliorate them. It may not be possible to target all four issues with one study, but at least keeping these factors in mind is an important starting point.

There are many other reasons why using a consecutive jumping task instead of a single jump or landing would be beneficial. When an individual is asked to perform only one singular jump, they can focus entirely on that one movement, and may be more aware of how they are moving than they would be in a real competition-like scenario. Theories of attention suggest that there are different ways that attention can be used or split between separate tasks. If attention is considered to be a limited resource, then it can be measured by the amount of interference created between two or more tasks being performed simultaneously (Schmidt & Lee, 2011a). Overall, theories on how attention is divided suggest that if tasks are fairly simple and do not require a lot of attention, more than one task can be performed simultaneously.

However, as a task's difficulty increases, the task takes a larger portion of the available attention, or pushes the attention required for all tasks over some theoretical capacity, and execution of one or both tasks decreases (Schmidt & Lee, 2011a). Executing a task in an open environment compared to a closed environment, as mentioned earlier, can also draw on this pool of attention. If the individual has more to attend to in the environment such as would be the case in an open environment, it can increase the level of attention required from the individual (Schmidt & Lee, 2011a, 2011b).

Almonroeder et al. (2017) conducted a divided attention study on female basketball players, in which the athletes were required to perform a stop or a cut in reaction to a basketball on a projected image. The athletes had to do so in one of three different levels of complexity, including a simple movement, a movement while holding a basketball, and a movement holding a basketball followed by a subsequent chest pass. The authors found that during the trials holding the ball compared to the simple movement, athletes executed the task with less hip flexion. Further, during the trials that required a subsequent pass the athletes executed the task with less hip flexion, knee flexion, and greater knee abduction compared to trials holding the ball during the task (Almonroeder et al., 2017). Brown et al. (2009) also included a reaction component in their unilateral drop landing task study, and found decreased hip flexion at initial contact, and increased peak hip adduction and hip and knee internal rotation during the unanticipated trials. These results propose that as the athletes needed to allocate more attention away from their movement, they moved with what is suggested to be less desirable mechanics.

In competition, an athlete would be required to perform many tasks in sequence, such as landing from a jump and moving elsewhere immediately after, as in a basketball shot, for example. Or perhaps, as happens in soccer, the individual would have to run up to head the ball, and decide exactly where they were going to step before jumping up, and also land safely and move quickly into dealing with their opponent and the ball play. An example in gymnastics would be performing one jump or flip and needing to immediately move into the next part of their floor routine. By having the participant perform multiple bilateral jumps in a row, and alternating feet in unilateral jumps, this more closely emulates the task demands found in sport and activity, and may cause the individual to elicit different mechanics than they would have in a single task.

A 2018 study that only included single repetitions of a movement stated having the ability to understand effects of a subsequent jump on landing biomechanics may be informative to evaluate movement control (Ishida et al., 2018). More authors support this viewpoint and suggest that plyometric or repeated activities may be better suited to assess sport performance as these repeated movements are more sport specific (Myer et al., 2008; van der Does et al., 2015). Van der Does et al., 2015 used 3 consecutive countermovement jumps in their protocol, which, while being more sport specific, may be limited to only 1 or 2 jumps able to be analyzed in to correct context. The first jump does not have a preceding jump, and the last does not have a subsequent jump, but does have a preceding jump. Using more than 3 jumps may be more beneficial to have a few jump trials that do indeed have a preceding and subsequent jump, creating a more activity- specific scenario. Maulder & Cronin (2005) also included repeated vertical and horizontally driven jumps, but only assessed reliability in jump height or distance, and coached the depth of the jumps. Myer et al. (2008) also used a repetitive tuck jump task, but strictly to subjectively assess movement.

Furthermore, performing multiple tasks in a row may require the individual to very quickly transition from an eccentric task such as absorbing a landing into a concentric task such as pushing off into a side step or into a second jump. This could increase the forces on the bones, or the velocities and joint moments occurring for that individual. These high stress scenarios may also contribute to risk of injury, not just the movements themselves.

Putting it All Together

Looking at all the parameters that can be added to a jumping or landing task, such as unilateral and bilateral, multiple repetition and single-repetition, and horizontally and vertically driven, there are some studies that do attempt to incorporate these different parameters together. Two studies examined both vertical and horizontal jumps in a unilateral protocol, however, only absolute outcomes including force production, distance travelled, and flight time were analyzed (Maulder & Cronin, 2005; Meylan et al., 2009). Maulder & Cronin (2005) did include multiple consecutive repetitions, and found that horizontally moving jumps were less variable than vertically moving jumps, and that consecutive jumping had the most variability. However, as mentioned, this research only assessed jump height or distance. Meylan et al. (2009) also found the most variability in vertically moving jumps. Taylor et al. (2016) and Kariyama et al. (2017) also considered horizontal and vertical movement in their jumping protocols, with both unilateral and bilateral protocols. Taylor et al. (2016) only included single repetitions, while Kariyama et al. (2017) utilized consecutive jumps in unilateral tasks. Van der Does et al. (2015) also used consecutive jumps, but in a bilateral CMJ task, in injured and uninjured populations.

All three groups also included joint moments and angles during the movements in their reports (Kariyama et al., 2017; Taylor et al., 2016; van der Does et al., 2015). Taylor et al. (2016) found significant differences in sagittal and frontal plane movements between unilateral and bilateral landings, with bilateral landings exhibiting lower ground reaction forces, higher hip and knee flexion, and lower rotational moments for most hip and knee movements in the sagittal and frontal planes. Kariyama et al. (2017) reported higher ground reaction forces, increased pelvic movement, and increased frontal plane trunk movement in horizontally moving jumps compared to vertically moving jumps. In these two studies however, they did not analyze ankle movements during the jumping and landing tasks. Van der Does et al. (2015) did analyze the hip, knee, and ankle, and were able to show less landing stability, and increases in ankle dorsiflexion and knee flexion moment, and decreases in ankle dorsiflexion, knee flexion and hip flexion angle in injured compared to uninjured populations.

A sixth study utilized stop jumps and drop jumps, in both a unilateral and bilateral arrangement (Heebner et al., 2017). These authors did look at all three lower limb joints, but again, only used one repetition at a time (Heebner et al., 2017). Heebner et al. (2017) reported very few similarities between the tasks they analyzed, which included unilateral and bilateral stop jumps and drop landings. Drop landings created higher ground reaction forces, and peak tibial shear forces, and stop jump tasks exhibited higher hip and knee flexion compared to drop jump tasks (Heebner et al., 2017). Further, individuals had higher ground reaction forces, and lower hip and knee flexion in unilateral tasks compared to bilateral tasks (Heebner et al., 2017). The above outlined studies give a comprehensive overview of how horizontal and vertical movement, as well as unilateral and bilateral stance can create very different kinematic and kinetic profiles. However, none of these studies included a fatiguing protocol to see how fatiguing mechanics may translate into actual competition and sport activity.

From this overview, it is apparent that there are many different ways to assess jumping and landing mechanics, all with their own advantages and disadvantages. The current literature includes studies that have investigated joint kinematics and kinetics, but perhaps not all joints that should be considered. A study that contains kinematic and kinetic information about all lower limb joints, including the hip, knee and ankle, as well as the trunk, could possibly shed light on the relationship that all these joints share, and how each joint can contribute to risky movement. Also, very few studies have included more than one repetition of a movement consecutively, which the author believes may also help to elucidate where mechanics start to break down during activity. Additionally, including a fatiguing protocol has the potential to further outline how mechanics change during competition or sport activity, and over time lead to an increased risk of injury.

Fatigue Effect in Movement Execution Research

As mentioned previously, a higher prevalence of lower extremity injuries usually occur in competition compared to practice. This may suggest that the degree of fatigue incurred by an individual may be a factor involved in injury. Most commonly, cycle sprint protocols are used to assess fatigue and fatigue index scores (Billaut et al., 2006; Bishop, 2012; Glaister, Howatson, Pattison, & McInnes, 2008; Keir et al., 2012; La Monica et al., 2016; Monks, Compton, Yetman, Power, & Button, 2017; Zarrouk et al., 2012), but are rarely used as a fatiguing mode for studies assessing kinematics and kinetics. A number of studies in this review included a dynamic fatiguing protocol, such as sprinting, jumping, or multiple running and jumping tasks combined in one protocol (Baghbani et al., 2016; Behrens et al., 2015; Brazen et al., 2010; Chappell et al., 2005; Cortes et al., 2013; Coventry, Ball, Parrington, Aughey, & McKenna, 2015; H. Kim et al., 2015; Lessi et al., 2017; Lessi & Serrão, 2017; Mudie et al., 2016; Pappas, Sheikhzadeh, et al., 2007; Schmitz, Cone, Tritsch, et al., 2014; Shultz et al., 2015; Smith et al., 2009). These protocols could cause the participants to elicit similar movement patterns to those that would occur in competition-like scenarios, but may not reach the levels of fatigue experienced in such scenarios.

Some researchers opted to use more concentrated fatigue protocols, focusing on quadriceps and hamstrings exhaustion specifically, utilizing squats (Andrews et al., 2016; Madigan & Pidcoe, 2003), lunges (Weeks et al., 2015), leg press to exhaustion (Gehring et al., 2009) and isokinetic or isometric dynamometry (Augustsson et al., 2006; Y. Kim et al., 2017; Rozzi et al., 1999). The majority of studies included kinematic data, with less including kinetic data. However, very few studies included all three lower body joints (ankle, hip and knee) (Augustsson et al., 2006; Brazen et al., 2010; H. Kim et al., 2015; Y. Kim et al., 2017; Madigan & Pidcoe, 2003; Schmitz, Cone, Tritsch, et al., 2014), and only three studies also included trunk or pelvis kinematics (Lessi et al., 2017; Lessi & Serrão, 2017; Weeks et al., 2015). Again, the nature of the fatigue elicited would most likely not be representative of the fatigue incurred in a competition-like scenario.

Y. Kim et al. (2017) studied sagittal plane hip, knee and ankle kinematics and kinetics during a jump landing followed by a cutting manoeuvre. The authors induced fatigue through an isokinetic knee extension and flexion protocol, and found less ankle and knee sagittal plane range of motion after the fatiguing protocol, but no change in hip kinematics. Y. Kim et al (2017) also found increased work at the ankle and hip, and decreased work at the knee post-fatigue (Y. Kim et al., 2017). These results seem sensible since the fatiguing protocol targeted the thigh musculature, specifically. H. Kim et al. (2015) used a task based fatigue protocol consisting of running, and lateral and vertical CMJs, and studied sagittal plane kinematic and kinetic changes in a side cutting task. The authors used a reduction in CMJ jump height as their indication of fatigue, but only found reduced flexion at the ankle, knee and hip at initial contact in the side cutting task post-fatigue (H. Kim et al., 2015). This may suggest that a reduction in CMJ height may not be an acceptable measurement or cut-off for fatigue attainment, or that changes occurred in the frontal plane, if any did occur.

Two studies conducted by Lessi and colleagues in 2017 reported values for the knee, hip, pelvis and trunk at initial contact and peak flexion, for both males and females during a unilateral jump landing task, as well as before and after fatigue. The population tested in these studies were healthy and injured recreational athletes, but only healthy values were reported in the current study. The pre-fatigue values reported in these two studies aligned well with other reported values in jump landing literature (Fox et al., 2014; Herrington & Munro, 2010; Holden et al., 2015). The only significant differences these authors found between males and females were in knee adduction and trunk forward flexion post-fatigue at initial contact and trunk forward flexion at peak flexion. Differences overall from pre- to post-fatigue that were found include pelvic drop in the frontal plane increased, knee flexion decreased, and trunk flexion increased in post-fatigue conditions (Lessi et al., 2017; Lessi & Serrão, 2017). The fatigue protocols again were task based, and included bilateral squats, vertical jumps, and step ups (Lessi et al., 2017; Lessi & Serrão, 2017). These tasks are more likely to fatigue mainly the thigh musculature, so also may not be representative of a competition-like fatigue. So, although some of these studies did find differences pre- to post-fatigue, we cannot be certain these results would be the same in competition, because the type of fatigue or the methods to induce fatigue are not comparable to activity performance.

Types of Fatigue

In investigations using a fatiguing protocol as part of the study, it is important to state what type of fatigue is being targeted and analyzed. Fatigue can be classified as localized to a specific muscle group, or widespread to a larger muscular region of the body. Physiologically, fatigue can be classified as peripheral or central, with peripheral fatigue said to refer to a decline in muscle function because of changes that are occurring at the neuromuscular junction (NMJ) itself or distal to it. Central fatigue on the other hand is seen as a reduction in the voluntary action of the muscle due to exercised-induced changes occurring in the motor units proximal to the NMJ (Patrek, Kernozek, Willson, Wright, & Doberstein, 2011). The mechanism for fatigue occurring at the NMJ itself, when the action potential delivered to the muscle from the central nervous system (CNS) fails to cross the junction into the muscle, however, is not yet understood (McArdle, Katch, & Katch, 2015).

Fatigue occurs due to disruption in the chain of events that occur from the CNS to the muscle fiber, but the type of fatigue classifies where along this chain of events the breakdown occurs (McArdle et al., 2015). Cortes et al. (2014) state neuromuscular changes such as altered EMG activity, increased isometric force variability, tremors in standing, and altered limb motion are inevitable consequences of fatigue. It is also stated that fatigue creates a decrease in joint flexion and progressive loss of movement variability, which can negatively impact other physiological processes, and ultimately lead to a decline in overall function, and possibly an increased chance of injury (Cortes et al., 2014).

In prolonged submaximal effort, a decline in muscle function is thought to be due to a lack of additional motor-unit recruitment as the motor-units primarily or initially activated become unresponsive. However, during short-term maximal exertion the cause of declined function is presumed to be due to lack of oxygen delivery to the muscle and increased blood and muscle lactate (McArdle et al., 2015). As a result of this high level of uncertainty on the exact mechanism or type of fatigue occurring, it is difficult to target one specific type of fatigue when implementing fatigue protocols. Some researchers, such as Weeks et al. (2015) have tried defining fatigue as general fatigue, rather than central or peripheral, specifically. Weeks et al. (2015) define general fatigue as fusion of effects on the muscular system, as well as the cardiovascular and respiratory systems. Millet & Lepers (2004) report that in prolonged exercise it is difficult to discern whether fatigue is peripheral or central in nature, specifically, without measuring electrical activity such as twitch impulses or EMG. These authors suggest that after prolonged exercise peripheral fatigue may be present as alterations in signal propagation, excitation-contraction coupling failure, and modification to the contractile apparatus itself, but central fatigue may still be present as well (Millet & Lepers, 2004).

On the other hand, Augustsson et al. (2006) report that changes in fatigued conditions are probably the result of changes in the contractile apparatus, and not necessarily reduced muscle activation from the CNS. Beurskens et al. (2016) used a cognitive task during postural control research to discern whether fatigue occurring due to prolonged exercise occurs peripherally or centrally. This created a dual-task scenario, where the participant would have to concentrate on their task as well as their balance, compared to a single-task of simply standing in a balanced manner. A decrement in postural control was seen in the dual-task tests compared to the single task tests prior to the fatiguing protocol, and this relationship did not become further stressed after fatigue (Beurskens, Haeger, Kliegl, Roecker, & Granacher, 2016). Their result helps further conclude that fatigue due to physically exhaustive exercise is occurring peripherally, as a cognitive task does not further change the postural response after fatigue (Beurskens et al., 2016).

Millet & Lepers (2004) build on this theory and believe that fatigue is most likely task dependent, as they observed different responses in limb extensor strength loss when comparing cycling, running and skiing as fatiguing exercises, even when paired for duration and intensity.

Zhang et al. (2018) also used two different fatiguing protocols with one consisting of only running and the other consisting of running and jumping. They found different responses on movement execution depending on the type of fatigue used (Zhang et al., 2018). Millet & Lepers (2004) also state that within the same task, training type, training level, and fitness level will also impact the influence of fatigue. This suggests that the protocol used should be participant specific, not the same exact protocol for each individual. This means having each participant perform the same protocol, but the cessation of that protocol should be dependent on the participant wanting or needing to terminate, not having the protocol end after a specified distance or time. This is important as individuals will possess different fitness levels and thus have different responses to exercise. The following sections will outline different types of fatiguing protocols that have been used in previous literature.

Exhaustive Running Protocols

Three studies included in this review utilized an exhaustive running protocol to elicit fatigue in assessing jumping and landing mechanics (Dalton et al., 2011; García-Pinillos et al., 2016; Quammen et al., 2012), however, each of these studies was missing an important piece of information in one way or another. Dalton et al. (2011) studied balance and vertical jump and used a treadmill-based fatiguing protocol, but their outcome measures were strength and jump height, and they did not analyze kinematic or kinetic data. Interestingly, the treadmill protocol used did not elicit differences in jump height, which is usually used as a marker of fatigue, although jump height was not used in that manner for this study (Dalton et al., 2011). Garcia-Pinillos et al. (2016) tested CMJ and used a type of shuttle run as their fatiguing protocol, and while they did quantify kinematic data of the hip, knee, and ankle, they did not allow the participants to use their arms in their CMJ trials. Other authors have limited participants in the same manner (Pappas, Sheikhzadeh, et al., 2007), however this limitation would ultimately change the individual's movement execution from what would normally occur. This would ultimately make it somewhat difficult to properly assess injury risk or quality of movement. Thirdly, Quammen et al. (2012) studied stop jumps and side cuts, and used a slow oxidative VO_{2max} protocol, and also quantified kinematics and kinetics of the hip and knee, but only analyzed the dominant leg of participants, not both. These studies provide a good starting point for introducing fatigue into movement analysis, but also outline the limitations that were created, such as augmenting natural movement execution, not studying kinematic or kinetic data, or only including one leg in analyses.

Another group of researchers also elicited fatigue with an incremental treadmill test, but their study goal was to assess postural control in unilateral and bilateral standing balance, not during a jumping or jump-landing task (Beurskens et al., 2016). Beurskens et al. (2016) revealed that as the participant reached higher levels of fatigue, they also increased their ventilation rate. This increasing ventilation actually increased the participant's postural sway as measured by their center of pressure displacement and velocity. Beurskens et al. (2016) were able to show that at as early as 20% decrement of maximum performance, postural control was significantly reduced, creating an increase in postural sway. This increase in postural sway (or lack of postural control) has the potential to further contribute to poorer mechanics in a more dynamic task such as jumping tasks. From this, it could be speculated that as long as the ventilation rate was high, it would not matter how long the protocol used to create the fatigue to increase the ventilation was, just that increasing the ventilation rate would increase postural sway and decrease postural control.

Cortes, Onate & Morrison (2014) specifically studied the effects of fatigue on movement variability. A VO_{2peak} and subsequent interval running for 30 minutes was used as their fatiguing protocol. The authors only measured the dominant leg, but found significant decreases in many lower limb kinetic and kinematic measurements in a side-step cutting action. Cortes et al. (2014) found that fatigue also caused increased amount of variability in the regularity of the force signal produced in a side step cutting task, but a decrease in the variability of the actual amplitude of the signal. This observed increase in variability in the regularity of the force signal, or increased complexity of the signal is proposed to illustrate that fatigue can cause a general decline in or loss of coordination during a dynamic movement (Cortes et al., 2014). Cowley & Colleagues (2014) also investigated movement variability but in upper limb movements, with localized or widespread fatiguing protocols. Muscle fatigue of the shoulder flexors (localized) was compared to muscle fatigue of the arm and trunk (widespread). The authors found that localized fatigue affected range of movement, with shorter and slower movements occurring after fatigue. However, the localized fatigue allowed for correction in timing errors to occur faster than in the widespread muscular fatigue condition (Cowley, Dingwell, & Gates, 2014).

Millet & Lepers (2004) compared the effects of prolonged running, cycling and skiing on limb extensor muscle strength. The results showed that there was a larger difference in strength losses and activation deficits in running versus skiing. The study also reported that since cycling is mainly a concentric exercise, that it induces lower muscular damage compared to running (Millet & Lepers, 2004). Cortes et al. (2014) also used a treadmill running protocol to create fatigue, but these researchers looked at the effect on side step cutting, not a jumping or landing task (Cortes et al., 2014). Similar to the results found by Augustsson and colleagues (2006), Cortes et al. (2014) found differences in knee kinematics and GRFs, specifically as decreased knee flexion angle and moment, and decreased anteroposterior, mediolateral, and vertical GRFs.

These researchers also found a loss of smoothness for force production and knee motion, which they suggest may be reflective of an overall decline in coordination, which could mean central fatigue has occurred (Cortes et al., 2014). These results along with the postural control results presented earlier (Beurskens et al. 2016) show that fatigue has the potential to change the resultant movement performance of the affected individual. Although the outlined protocols are all prolonged or longer in nature, duration does not necessarily matter as much as the response that is created.

Short Fatigue Protocols

Although a prolonged running protocol is more representative of the duration of field and court sport activities, it is unrealistic to say a prolonged running protocol is similar to how the athlete would be performing throughout the full duration of these activities. Court and field sports usually consist of jogging or lower intensity performance interspersed with sprints or bursts of higher speed or power required. Gymnastics, similarly, consists of short sprints into a set of movements, followed by a stop or pause before continuing into the next phase of movement. With this in mind, a repeat sprint running protocol may be more representative of the experiences of these types of athletes.

When a sprint is included as part of a ‘mixed’ fatigue protocol it is hard to determine which task is causing more fatigue, or if it has to be that combination of tasks to elicit fatigue. Further, short protocols such as leg press or lunging to exhaustion, and isokinetic flexion-extension protocols have been shown to elicit fatigue (Andrews et al., 2016; Augustsson et al., 2006; Gehring et al., 2009; Y. Kim et al., 2017; Madigan & Pidcoe, 2003; Rozzi et al., 1999; Weeks et al., 2015), so, even though the type of fatigue is different, it helps support the fact that the protocol does not necessarily have to be long to create fatigue.

Weeks et al. (2015) investigated the effects of a lunging fatigue protocol on single-leg squat mechanics. They found that post-fatigue changes were more apparent at the trunk and pelvis, and less so at the knee and hip. This is suggesting that movements were made more proximal to preserve upright stability, which may have been done to reduce the moments and demands at the knee. This would possibly reduce the force contribution required from the fatigued quadriceps group (Weeks et al., 2015). Augustsson et al. (2006) also locally fatigued the quadriceps, using weighted unilateral knee extensions as their fatiguing protocol, and studied the effect of fatigue on unilateral hop execution. The resulting changes in kinematics and kinetics included decreased hip and knee flexion angles, decreased knee and ankle joint power, and decreased GRFs during the take-off for the fatigued jumps (Augustsson et al., 2006). However, Augustsson et al. (2006) reported that these values recovered to pre-fatigue levels as early as three minutes post-exercise. This suggests that the fatigue incurred was peripheral in nature, and did not have the capacity to affect the CNS completely. It can also suggest that because the two protocols outlined here were muscle group specific and did not affect the whole system, this likely was not representative of fatigue in sport or activity.

Sprinting Fatigue Protocols

Sprinting on even ground can be classified as an anaerobic task, with a small amount of muscular fatigue. If an incline were introduced, the sprint would then induce more muscular fatigue than in the level ground scenario. If the sprint is repeated, it could then create aerobic fatigue instead of purely anaerobic fatigue (Girard et al., 2011; Keir et al., 2012; Little & Williams, 2007), and increase the effect of the muscular fatigue. Keir et al. (2012) also determined that running, no matter the length of time, requires muscles from the upper extremities, trunk and lower extremities to all contribute to movement execution and performance, and can therefore create higher cardiac output demands as more muscles working require more oxygen delivery and substrate evacuation. This can further contribute to higher VO2max or peak results and maximal HRs during exercise compared to cycling (Keir et al., 2012). Again, this would be more specific to the amount of fatigue incurred during sport and competition performance.

Repeat sprint literature shows similar HR and heart rate recovery (HRR) responses as prolonged running protocols (Abrantes et al., 2012; Danieli et al., 2014; Taskin et al., 2014) and also produce similar rating of perceived exertion (RPE) values as the prolonged running protocols (Girard et al., 2011; Keir et al., 2012; Selmi et al., 2016). Girard et al. (2011) even show that as a participant progressed to a second and third repeated sprint, they were utilizing more of their aerobic pathways versus remaining in an anaerobic work range, which may be expected from a sprint protocol.

Sprints have been used as part of a fatiguing protocol along with other tasks, as mentioned previously (Baghbani et al., 2016; Behrens et al., 2015; Chappell et al., 2005; Schmitz, Cone, Tritsch, et al., 2014; Shultz et al., 2015), but not as frequently used as the sole fatiguing task. Most studies only look at sprint time decrement as an outcome variable (Bishop, 2012; Gantois et al., 2017; Girard et al., 2011; Glaister et al., 2008; Keir et al., 2012; Ruscello et al., 2013; Sanders et al., 2017; Selmi et al., 2016; Tolusso, Laurent, Fullenkamp, & Tobar, 2015) after a repeat sprint fatiguing protocol, with few studies actually looking at other outcomes, such as neuromuscular performance (Goodall, Charlton, Howatson, & Thomas, 2014; Monks et al., 2017), balance (Pau, Ibba, & Attene, 2014), lower body kinematics (Coventry et al., 2015) and effect of a sloped running surface (Padulo et al., 2016).

Determining Fatigue

When investigating level of fatigue, some researchers have used a percent drop in vertical or horizontal jump distance to gauge the level of fatigue of individuals in their study. The amount of reduction in jump distance included in studies ranges from 50% (Behrens et al., 2015), 30% (Horita, Komi, Hämäläinen, & Avela, 2003), 20% (H. Kim et al., 2015; Lessi et al., 2017; Lessi & Serrão, 2017; Quammen et al., 2012; Weeks et al., 2015), and as little as 10% reduction (Cortes et al., 2013). All studies listed above did elicit significant differences due to their fatiguing protocols. However, not all the researchers were looking at jump mechanics, but those researchers who did look at jump mechanics did see significant differences in mechanics with as little as 20% deficit in jump height (Cortes et al., 2013; H. Kim et al., 2015; Lessi & Serrão, 2017; Quammen et al., 2012; Weeks et al., 2015). It should be reiterated, however, that not all studies that used a fatigue protocol saw significant decrease in jump height (Dalton et al., 2011). Dalton et al. (2011) were not using jump height as a measure of fatigue, rather jump height was a separate outcome variable, but it is still important to see that some protocols, according to this measure, did not show decrement in jump height.

The issue with using percent drop in jump height or distance is that it does not take the actual kinematics or kinetics into consideration, and some studies have shown that there is higher knee and hip flexion post fatigue in a bilateral task (Coventry et al., 2015) and some show a more stiff landing after fatigue for bilateral (Quammen et al., 2012) and unilateral tasks (Cortes et al., 2013; H. Kim et al., 2015; Lessi & Serrão, 2017). Since there is not a general consensus, and repeated or consecutive tasks have not been used in a study together, to the author’s knowledge, it is hard to say what will occur post-fatigue for both bilateral and unilateral jumping tasks.

Another common measure of fatigue is the RPE scale that has been mentioned previously. Whole-body RPE is quantified by the participant assessing sensation arising from their muscles, joints, skin, and cardiorespiratory system, such as pounding heart, labored breathing, and other circulating factors (Knicker, Renshaw, Oldham, & Cairns, 2011). When using the Borg RPE scale, the participant rates these sensations on a scale ranging from 6 to 20 (Heyward & Gibson, 2014). Although RPE is a subjective, qualitative measure, it is usually well-correlated with quantitative heart rate measures, and gives a more relevant scaling of the individual's fatigue compared to jump height, which just measures the muscular fatigue predominantly in the quadriceps group.

Purpose and Aims

The purpose of the current study was to investigate the effect of fatigue and sex on knee joint mechanics during two jumping tasks. The goal of this study was to determine if one of the two jumps included was more effective in showing post-fatigue differences and outline possible recommendations on which movement may be 'higher risk'. The two jumping tasks were analyzed prior to and after a full-body treadmill-based sprint fatiguing protocol, in order to assess how repeating a movement can affect movement execution before and after fatiguing exercise. Due to the inconsistencies in sex-based injury rates in the literature review of this document, a sex-based analysis was performed in the research study. The majority of epidemiological studies state females are at a higher risk of lower extremity injury, specifically to the knee joint, so it is necessary to examine both sexes separately to see how fatigue potentially affects this relationship between sex and injury risk.

The first aim of the study was to assess kinematics and kinetics of bilateral consecutive CMJs (vertical) pre- and post-fatigue. The second aim of the study was to assess unilateral forward-moving single-foot jumps (FMSFJs) (horizontal) pre- and post-fatigue. The third aim of the study was to compare the bilateral and unilateral kinematic and kinetic outcomes, to assess which of these may be more sensitive to change post-fatigue. The fourth aim of the study was to compare male and female values in the CMJ and FMSFJ protocol to investigate any sex differences in jump landing mechanics pre- and post-fatigue.

The primary outcome variables were knee flexion and abduction (angle and moment) values. These were chosen because the knee is the middle joint of the lower limb and is thereby affected by both the hip and ankle. This is due to the fact that with the knee and hip located at either ends of the femur, and subsequently the knee and ankle located at either ends of the tibia and fibula, the joint pairs are physically connected. The hip is also affected by both the knee and trunk, but injuries to this joint are much lower since it is much stronger and better protected. Since primary outcome variables are related to the knee joint, this study has the potential to demonstrate the effects of change at the knee itself, as well as change at the hip and ankle subsequently affecting the knee.

Secondary outcome variables included trunk lateral and forward flexion angle, hip flexion and adduction (angle and moment) and ankle dorsiflexion and eversion (angle and moment). These variables were chosen and included initially as movements at the trunk, hip and ankle could contribute to further abduction of the knee and have also been identified as contributing to common mechanisms of lower body injury. These joints and movements also have the potential to be affected by fatigue. Despite selection of primary outcome measures, secondary outcome measures pertaining to joints and segments proximal and distal to the knee were included to account for potential compensatory movements between joints of the lower limb, as a function of fatigue.

Outcome variables that were analyzed include joint angles at initial contact and peak values during landing. The associated peak joint moment values were also analyzed. Large joint moments have been shown to contribute to stress or injury at the lower extremity joints (Podraza & White, 2010) so these data are being considered along with the angle values.

As outlined in the review section of this document, common mechanisms of lower body injury include any or a combination of the following during landing or stance: excessive knee adduction or abduction; excessive hip adduction; stiff legged landings with low angles of knee flexion, hip flexion and ankle dorsiflexion; rapid deceleration, requiring high eccentric forces during landing; and landings that create higher ground reaction forces. The outcome variables being analyzed will enable us to determine if the participants were moving into any of these decidedly riskier or potentially unsafe statures. In the current study eccentric forces and accelerations will not be analyzed. However, by investigating the joint moments, the impact of the external forces will be exhibited and measured at specific joint locations, rather than looking at whole body accelerations or reaction forces, which may be more beneficial to injury risk and prediction literature.

Hypotheses

The primary hypothesis was that all participants would demonstrate less knee and hip flexion during the post-fatigue conditions compared to the pre-fatigue conditions in both the FMSFJ and CMJ protocols. The secondary hypothesis was that participants would demonstrate more knee abduction and trunk lateral flexion during the post-fatigue FMSFJs (as compared to any other condition). The third hypothesis was that all participants would demonstrate more flexion at the trunk, hip, knee, and ankle, and less ankle eversion during the CMJs compared to the FMSFJs. The fourth hypothesis was that differences during the FMSFJ protocols would be larger or more pronounced post-fatigue than in the CMJs. The fifth hypothesis was that there would be increased joint moments during landing in the FMSFJ protocols compared to the CMJ (per leg) at peak values. The sixth hypothesis was that during both jump protocols and in pre- and post-fatigue conditions, males would utilize more knee flexion and less knee abduction compared to females. Again, this suggests that females would adopt mechanics that increase injury risk compared to males.

Overall, these hypotheses predict that post-fatigue mechanics would be similar to those that have been proposed to increase injury risk, including lower sagittal plane joint excursions and higher frontal plane joint excursions. Also, these hypotheses predict that the FMSFJ specifically would produce movements post-fatigue that have been suggested to increase injury risk, including further decreased sagittal plane joint excursions, increased frontal plane joint excursions, and increased joint moments. Further, it is predicted that fatigued unilateral tasks performed by female participants would result in mechanics associated with a high suggested risk of injury mentioned earlier, with pre-fatigue bilateral tasks performed by males showing well-controlled mechanics, with the lowest suggested risk for injury.

Chapter II: Study Design

Methods

Participants

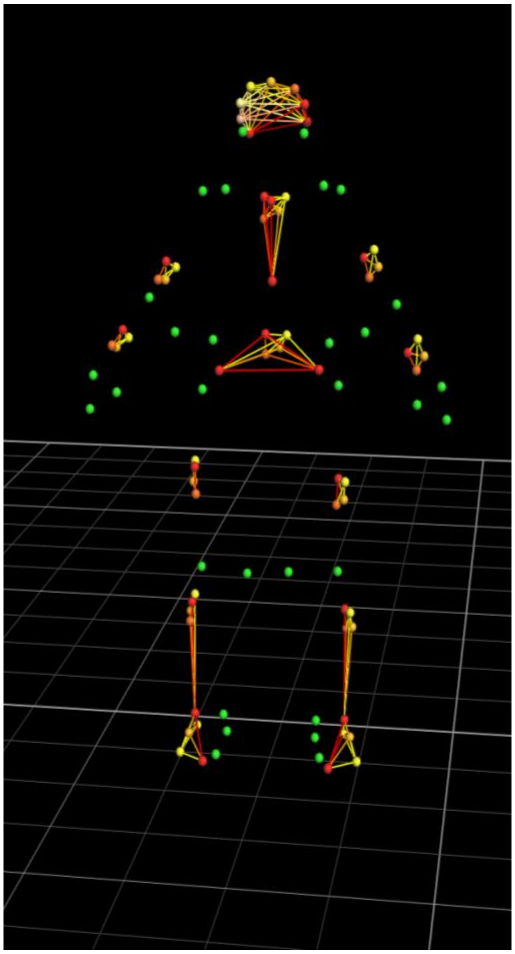
All study methods received ethical approval from the Education/Nursing Research Ethics Board at the University of Manitoba (E2018:102 (HS22449)). In order to complete the proposed research, forty participants were recruited. Sample size estimates were obtained using $\alpha = 0.05$ and $\beta = 0.2$, statistical differences found in knee abduction in a similar study conducted by McLean et al. (2007) investigating fatigue effects on drop landing technique (McLean et al., 2007). Knee abduction was chosen as it is one of the primary outcome variables of the current study. Sample size estimates also included consideration of sex-based analyses. This calculation suggested 16 participants per group, so the decision to conservatively have 20 participants per group to cover at least a 10% drop out rate was made.

The participants were between the ages of 18 and 35 years old who have medical clearance based on a Physical Activity Readiness Questionnaire (PAR-Q+) (Warbuton, Jamnik, Bredin, & Gledhill, 2018). Current level of physical activity was established via self-report, requiring participants to be actively participating in an average of at least 200 minutes of moderate-to-vigorous physical activity per week. This cut off of 200 minutes per week ensured participants exceeded the recommended levels of physical activity, and therefore are not inactive or undertrained. Exclusion criteria included neurological conditions, any history of serious lower limb injury, including torn ligaments or tendons, or fractures, and acute injuries within the last year that did not require surgery, but resulted in a recovery time of more than four weeks. Participants were counter balanced to account for sex and testing order.

Instrumentation and Set Up

Eight Vicon Vero cameras (model 2.2, Vicon Motion Systems, Los Angeles, CA, USA) were used to record kinematic data (100Hz). Four force platforms (two of model 9260AA6 and two of model 9286BA, Kistler, Amherst, NY, USA) that are arranged in a T-shaped array, and embedded in the laboratory floor, shown in Figure 1, were used to measure reaction forces and moments (2000Hz). All motion capture data and analogue-to-digital converted signals were synchronously recorded by Vicon Nexus software (version 2.7.0, Vicon Motion Systems, Los Angeles, CA, USA).

Figure 3: Retroreflective marker set up



Participants were outfitted with retroreflective markers, 1cm in diameter, placed bilaterally at anatomically relevant locations, consisting of calibration markers and tracking markers (see Figure 3) (Singer, Prentice, & McIlroy, 2012) . The calibration markers define segment endpoints for the pelvis, trunk, head and upper and lower limbs, which in turn help determine the inertial properties, center of mass locations, and local coordinate system positions and orientations of each segment. The calibration markers were only on the participant for the standing reference trial, and then were removed for the subsequent jumping and running trials. The tracking markers were on the participant through the standing reference trial and all subsequent jumping and running trials. The calibration markers were placed bilaterally, on the acromion process, greater tubercle of the humerus, anterior to the external auditory meatus of the ear, medial and lateral humeral epicondyles, radial and ulnar styloid processes of the wrist, head of the third metacarpal, iliac crest, greater trochanter of the femur, medial and lateral femoral condyles, medial malleolus of the tibia, medial aspect of the calcaneus and base of the first metatarsal.

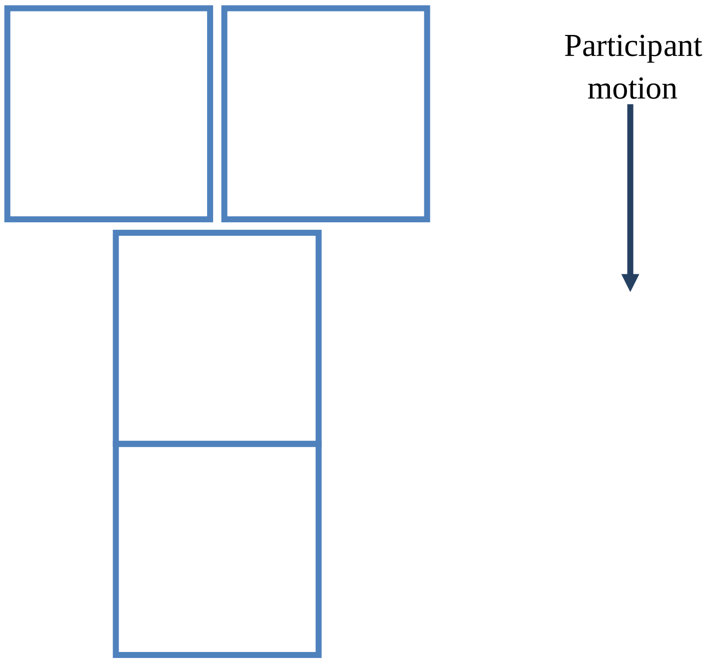
The tracking markers were placed bilaterally, on the anterior superior iliac spine (ASIS), lateral malleolus of the fibula, distal phalanx of the great toe, head of the 5^{th} metatarsal, lateral aspect of the body of the calcaneus, a point on the superolateral forefoot, in between but superior to the 5^{th} metatarsal marker and the lateral calcaneus marker, and single markers on the sternal notch and xyphoid process. The tracking marker set also included rigid retroreflective clusters consisting of four markers each, and an 8-marker head strap that were used to determine 3D kinematics of body segments. These clusters were placed bilaterally on the lateral aspect of the thigh, shank, upper arm and lower arm, and one cluster was placed on the sacrum and on the upper back between the scapulae, and one marked head strap.

Individual retroreflective markers were affixed to the participant's skin or clothing with the use of double-sided tape. All marker clusters, except the upper back cluster, were affixed to the participant with the use of nonslip bands secured with Velcro tabs. The upper back cluster was affixed to the participant with Velcro straps, and the 8-marker head cluster was affixed on a padded Velcro strap. All marker clusters affixed via the nonslip bands were additionally secured with two-inch elastic adhesive tape (Lightplast Pro, BSN Medical, Laval, QC, Canada) to protect against movement of the bands during the jumping and sprinting protocols.

Following Cardan angle sequence (x-y-z) and Right Hand Rule assumptions, positive x-, y-, and z-axes for the laboratory coordinate system were oriented to the right of the participant, forward, and upward, respectively.

A Precor treadmill (model TRM 835, Woodinville, WA, USA) was used to conduct both submaximal fatigue protocols, one for the orientation session and one for the testing session. The participant's heart rate was measured via a Polar heart rate monitor (model RS800CX, Lachine, QC, Canada) only during treadmill protocols. These data were used as part of the fatigue rating assessment.

Figure 4: Force plate arrangement



Participation Outline

The participant was required to attend two sessions in the lab. The two sessions were conducted four to seven days apart, to avoid fatigue or muscle soreness from affecting the second session. The first session was approximately 45 minutes long, and the second session was approximately 60 minutes long. The first session was an orientation session in which the participant was pre-screened for submaximal physical activity, and collection of required general information occurred, including activity level, sport participation, and anthropometrics, which will be outlined later. The orientation session was also used to assess participant comfort on the incline sprint fatigue protocol, and to ensure they could perform the two jumping tasks required. The second session consisted of the jumping and fatiguing protocols that were used in the 3D motion capture analysis. The two jumping protocols included a countermovement jump (CMJ) protocol, and a forward-moving single-foot jump (FMSFJ) protocol.

To reiterate, the countermovement jump protocol was chosen as CMJs have been shown to be reliable as a repeated measure, and are comparable to previous literature (Gathercole et al., 2015). As a CMJ may not be specifically sport-related, the FMSFJ protocol was also included to be more relevant to sport tasks, and to also include unilateral task execution. Using these two protocols also allows for analysis of a vertically driven and horizontally driven task (CMJ and FMSFJ, respectively), which again, are both aspects of a sporting or competition-like context.

The CMJ protocol consisted of at least five consecutive CMJs performed with a goal of maximum height in the jump. In general, a CMJ was performed with an arm swing occurring as the participant loads into a squat position, and then immediately jumps upward. In this protocol, the CMJs were consecutive, so the participant was to immediately jump again as they finished landing in the preceding jump. The FMSFJ protocol consisted of at least six consecutive jumps, which allowed at least three jumps on each leg during each trial. The goal for the FMSFJs was also maximum height, but the participant was stepping forward with each jump. In general, the FMSFJ was performed as a single leg jump with the contralateral leg driven upward. The participant could use their arms as they deemed appropriate for the jump (swinging arms in phase with their legs, opposite, or not using them at all), as long as they were still trying to attain maximum jump height. The participants were not instructed on specifically how they should perform the jumps, but a general explanation was given to each participant, and they were asked to practice both jump protocols when ensuring the participant was able to perform the tasks in the orientation session.

Orientation Session

The participant was presented with a consent form and was cleared to participate through use of the inclusion and exclusion criteria outlined earlier, as well as completion of a PAR-Q+ form and associated blood pressure and heart rate testing (Warbuton et al., 2018). Blood pressure and heart rate was taken while the participant was calm in a seated position prior to activity, to ensure participants were within acceptable physiological parameters to safely participate in a submaximal treadmill protocol. To be cleared for activity, the participant's resting blood pressure must have been below 144/94 mmHg and resting heart rate must have been below 99bpm (Heyward & Gibson, 2014).

General information was also collected at this time, including characteristics and anthropometrics. General characteristics that were collected from the participants included their age, sex, sport history, injury history, and their average time commitment per week for physical activity. Anthropometric measurements that were collected from the participants included height, weight, hip circumference, and waist circumference.

Sex-based differences were analyzed as it remains unclear whether injury risk is related to sex, (Finch et al., 2015; Maffulli et al., 1996; Majewski et al., 2006; Nicolini et al., 2014; Swenson, Collins, Best, et al., 2013; Swenson, Collins, Fields, et al., 2013) or more specifically, landing mechanics. The participants were grouped into males and females before being counter balanced for jump order performed during testing. This was done to ensure there was equal representation of both sexes for both options of which jump protocol was performed first.

The participant was asked to perform the two jumping tasks included in the jumping protocol to ensure the participant understood the movements required for them to complete, and to ensure they were physically capable and coordinated enough to perform the task. The participant performed the jumping tasks until they felt comfortable with the protocol. During their 5-minute self-selected treadmill warm up, the participant was also shown the incline sprint that was used in the second session fatigue protocol, and was asked to begin one sprint, to make certain they are comfortable straddling, then mounting and running on the treadmill at a high speed and incline. If these practice trials went well, the participant was cleared to return for the second session of testing.

In the orientation session the participant was also made aware of the activity and dietary restrictions they were to follow the day prior to the second session, including limiting caffeine consumption 4 hours prior to the testing session, limiting alcohol consumption 12 hours prior to the testing session, limiting food intake 2 hours prior to the testing session, especially if they thought they would get nauseous during the protocol, and limiting heavy or strenuous exercise for at least 24 hours prior to the testing session.

Once the participant had completed the pre-screening for the second session, the first session continued, and the participant performed their submaximal heart rate peak testing. This was assessed using a graded treadmill submaximal aerobic test. The Bruce treadmill protocol was used as it has been shown to be a reliable test for reproducing maximal and submaximal work rates (Dabney & Butler, 2006; Esco et al., 2015; Nordrehaug, Danielsen, Stangeland, Rosland, & Vik-Mo, 1991; Roy & McCrory, 2015). A graphical representation of the progression of the test is outlined in Figure 2. The purpose of the Bruce submaximal treadmill test was to determine each participant’s peak heart rate in a submaximal test, which was then used as a gauge of their effort given in the sprint fatigue test they performed in the second session.

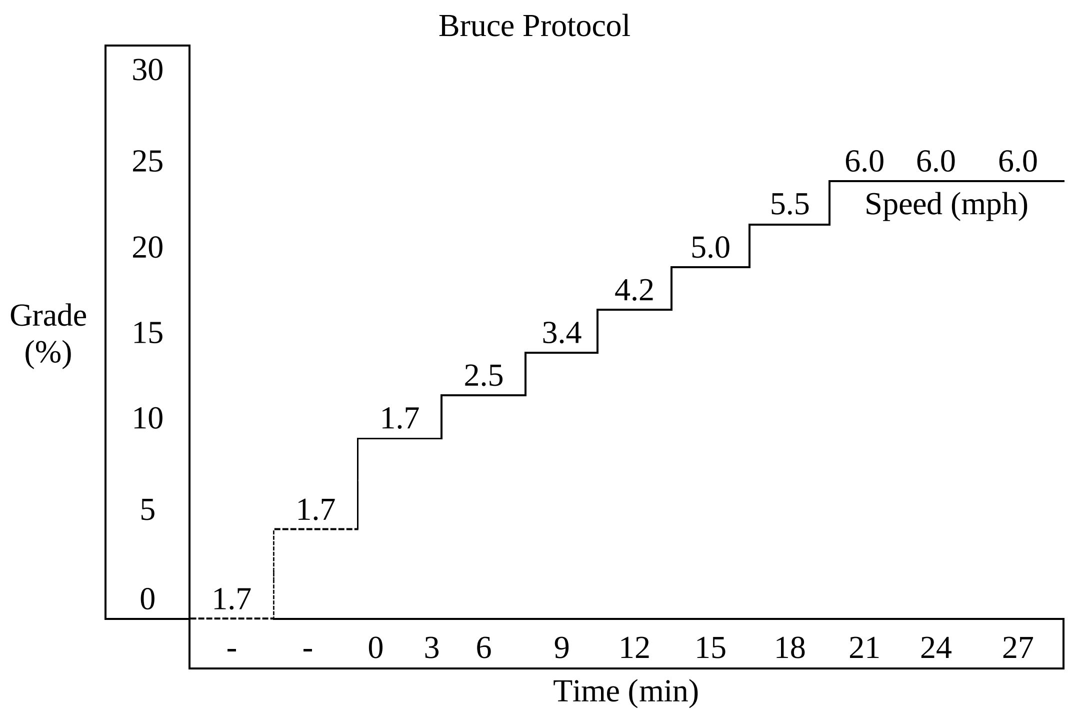
We determined peak HR directly via the Bruce Protocol because literature describing HR peak prediction is not clear, and the equations proposed are only appropriate for the specific cohort that was used to create the equation, including specific activity and age ranges. HR prediction equations also tend to overestimate the HR value for individuals (Camarda et al., 2008; Esco et al., 2015; Roy & McCrory, 2015). Shargal et al. (2015) attempted to create HR peak prediction equations for both sexes across age groups, and found that only 49% of variance in HR was dependent on age. This resulted in only moderate regression results, ranging from 0.69 to 0.73 (Shargal et al., 2015).

The participant's heart rate was measured via a Polar heart rate monitor (model RS800CX) throughout testing. The Bruce submaximal treadmill test increases the workload for the participant by changing both the treadmill speed and percent incline. Since the target population for this study is healthy, the first two test stages can be omitted. Thus, the first test stage (minutes 1–3) starts at a 1.7 mph walking pace at 10% grade. At the start of the second stage (minutes 4–6) the grade is increased by 2% and the speed is increased to a 2.5 mph pace. In each subsequent stage of the test, the grade is increased by 2% and the speed was increased by either 0.8 or 0.9 mph until the participant is exhausted (Heyward & Gibson, 2014).

The two physiological criteria that were used to indicate attainment of submaximal fatigue and a VO_{2peak} are:

- HR fails to increase with the next increase in exercise intensity
- Rating of perceived exertion (RPE) is greater than 17 using the Borg scale (6 to 20) (Heyward & Gibson, 2014)

Figure 5: Bruce Protocol



Once the participant decided to volitionally end the test, the incline and speed of the treadmill was reduced to a comfortable walking pace, and the participant commenced a cool down period, at their own self-selected pace, for at least 5 minutes. The participant was given the option to walk on the treadmill for a cool down or to pace around the room. They could choose whichever option they preferred.

The Second Data Collection Session

The second session began with ensuring the participant followed the activity and dietary restrictions required for testing. After ensuring they had, the participant was again physiologically cleared for submaximal activity by measuring heart rate and blood pressure. If this process was successful, the participant progressed into the pre-fatigue jumping protocol, followed by the sprint fatigue protocol, and finally the post-fatigue jumping protocol. This is explained in further detail in the following sections.

Session Two Jumping Protocol

The participant was marked with the retroreflective marker set and outfitted with the HR monitor outlined previously and stayed marked through the remainder of the testing protocols. Once the participant was set up for data collection, a standing reference trial was collected prior to collection of the experimental trials. The participant was asked to stand in anatomical position, oriented roughly with the laboratory coordinate system (forward and in line with the walkway). This data was used to determine the segment endpoints, segment embedded local coordinate systems, and the transformation matrices between the local and global coordinate systems for each segment. Following collection of the standing reference trial, calibration markers were removed.

After the calibration trial had been completed successfully, the participant was asked to perform the pre-fatigue jump protocol, consisting of three sets of five consecutive bilateral CMJs and three sets of six consecutive unilateral FMSFJs, alternating jumping leg, allowing three jumps on each leg. The participant was instructed to jump as high and fast as they could for both the CMJ and the FMSFJ protocols. Trunk and lower limb kinematics and kinetics during all trials of the jump protocols were recorded and collected using Vicon 3D motion capture and analyzed using Visual 3D analysis software. As mentioned previously, the order of jumps was counter balanced to control for order effects. The test followed a repeated measures design, meaning the two types of jumps stayed blocked together, but the order in which the two were performed was counter balanced.

During the CMJ trials the participants were asked to stand on the two posterior force plates (horizontal of the T-shape orientation, model 9260AA6) and to try to stay on the force plates throughout the jump trials. However, if the participant did drift forward, they were not corrected. During the FMSFJ trials, the participant was told to try and stay in the middle of the walkway and try to hit the force plates as they progressed forward, without specifically targeting the force plates. A few practice trials were done with the participant only using partial effort, in an attempt to find a good starting point so that they make contact with the force plates more regularly throughout their trials, and so that they did not jump too far forward between each jump. If they did happen to land on the force plates, the available data was analyzed. However, consistent data in these trials was not necessarily available for all participants, if the participant did not happen to hit the force plate completely.

The distance covered horizontally or vertically by either jump was not recorded. The participant's movements were in no way being coached or limited, as this may have affected their natural execution of the task. The jump tests were performed on a 20-foot walkway, which allowed an abundance of room to complete the required number of jumps consecutively. If the participant was not completing at least 6 jumps forward on the walkway, they were told to try and take smaller steps in between the jumps, but this was the only modification made or told to the participant in regard to their movement. The jumping protocol was performed both before and after the submaximal treadmill sprint fatigue protocol. The order assigned for the jump tests prior to the sprint fatigue protocol was the order that was used with the post-fatigue jump tests as well.

Sprint Fatigue Protocol

Immediately after completion of the last jump trial the participant moved over to the treadmill area. Distal foot retroreflective markers were removed and set aside during the treadmill protocol and were placed back onto the participant immediately after their last sprint finished, which was immediately before the participant performed their post fatigue jump protocols. This was decided to be included in the procedure after many foot markers dislodged during pilot test sprinting. Since the marker placement is over bony landmarks, it is almost certain that the markers were put back in the same position after the treadmill protocol, ensuring the calibration trial orientations were still valid. Next, the participant continued on to the treadmill and performed a 3-minute walking warm up, while the submaximal treadmill sprint protocol was explained to them. During this time the participant practiced executing a straddle stop, to ensure they were able to dismount the treadmill belt when they wanted to end their sprint trials.

The treadmill fatiguing protocol was designed to induce fatigue in multiple muscle groups, and aimed to more appropriately reproduce fatigued physiology and mechanics that are similar to those occurring during competition (Dalton et al., 2011). The treadmill sprint protocol was first introduced by Cunningham & Faulkner in 1969. The treadmill was set at an incline of 20%, and speed of 7.0 mph for women and 8.0 mph for men. In the original article speed was set at 8.5mph, but this was for a single repetition of the test, and used in a strictly male population (Cunningham & Faulkner, 1969). More recent literature uses 8.0 mph for males and females (Clarke et al., 2012; C. Thomas, Plowman, & Looney, 2002; D. Q. Thomas, Larson, Rahija, & McCaw, 2001), however, in pilot testing it was found that 8.0 mph was too fast for some females to maintain for a full sprint. Female participants began terminating their test because of reaching the end of the treadmill belt, and not necessarily because they were completely exhausted. Due to this, 7.0mph was chosen as the speed for females, and 8.0 mph was chosen as the speed for males.

When completed once, this sprint protocol elicits anaerobic fatigue in the participant. In this study, the treadmill sprint was repeated three times, with two-minute rests in between, to create a longer duration fatigue, targeting both the aerobic and muscular systems. This treadmill protocol was submaximal in nature, meaning the participants continued to volitional fatigue, but absolute fatigue was not measured via expired gas analysis. The two physiological criteria that were used to indicate attainment of submaximal fatigue were:

- HR reached or approached predicted max, as determined by the submaximal graded protocol from the orientation session
- Rating of perceived exertion (RPE) was greater than 17 using the Borg scale (6 to 20) (Heyward & Gibson, 2014)

During pilot testing, two minutes of rest seemed to allow the participant to recover enough, but not fully, before commencing the next sprinting trial. This was determined based on subjective feedback from the participants, as well as heart rate. Also, in repeat-sprint ability literature, a ratio of 1:3 to 1:6 is most commonly used in over ground sprints (Gantois et al., 2017; Girard et al., 2011; Goodall et al., 2014; Keir et al., 2012; Little & Williams, 2007; Ruscello et al., 2013; Selmi et al., 2016) as well as cycle sprints (Billaut et al., 2006; La Monica et al., 2016; Monks et al., 2017; Zarrouk et al., 2012), and since the goal time in the proposed protocol is 30-50 seconds, two minutes would be approximately a 1:4 work:rest ratio. After the third sprint, the participant was immediately brought back to the walkway, the retroreflective markers were placed back onto the distal foot. The entire retroreflective marker set was reassessed to make sure that none of the markers moved or fell off, and then the participant performed the post-fatigue jumping trials.

As mentioned previously, the post-fatigue jumping protocol was exactly the same as the pre-fatigue protocol, in order and in content, with five CMJs and six FMSFJs being performed with the same counter balanced order as the pre-fatigue jumping protocol. This was performed immediately after the treadmill sprint protocol to avoid decay in fatigue response and effect.

Data Processing

All motion files were observed visually in Vicon to ensure marker trajectories were correctly labelled through the full trial. Following this all motion files were processed with Visual 3D software before statistical analyses occurred. The location of the force platforms was expressed relative to the origin of the lab space, to ensure force platform data were accurate with respect to the participant's motion. Interpolation of any missing marker trajectory data was also performed. The interpolation fills data gaps of up to 30 frames (0.300 s) in length, with a 3rd order polynomial function, with a numerical fit of three frames previous to and after the gap.

A Lowpass, zero-lag, 4th order, Butterworth filter was used on force plate data, with a frequency cut off of 15 Hz used. A 20th order, critically damped filter was used on individual marker data, with a frequency cut off of 6 Hz. These filters attenuated high-frequency noise caused by error in the automatic processing of marker centroid locations, and error caused by vibrations recorded by the force platforms. At this time unlabelled marker trajectories were also removed from the data set. Motion files were again inspected visually to ensure the interpolation did not cause error in 3D reconstruction. Technically the interpolation process was correct, but sometimes errors can arise in reconstruction, due to the trajectory in each plane being interpolated independently. If any jumps in a given trial contained improper reconstruction, expressed as an unnatural segment movement, those jump repetitions were excluded from analysis.

Segment masses and moments of inertia were derived using Dempster's table (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014) for the biomechanical model. Newton-Euler equations were used to calculate joint moments of force. All joint angles, angular velocities and moments of force were resolved into the proximal segment coordinate system. As mentioned earlier, the calibration markers determine proximal and distal segment endpoints, which in turn determine the segment geometries, inertial properties, center of mass locations, and local coordinate systems of each segment. Joint moment values were normalized to the participant's body mass before exporting.

Motion files were processed with coding pipelines that identified the specific windows of information that were to be analyzed, namely, the ground contact and landing phase through to toe off for each jump. For the CMJs, the window of analysis was specified as starting with the specified limb's initial contact, indicated by the first frame after the minimum velocity of the great toe marker was reached, or the first frame where a force reading on the force plates was detected. The minimum velocity of the great toe marker was individually analyzed for each participant, not set by a cut-off criterion. If these two events did not coincide to the same frame, then the frame in which a force plate reading was first detected was used. The window of analysis ended with the specified limb's toe off, indicated by the first frame after the rapid rise in velocity of the great toe marker, indicative of flight, or where a force reading is no longer detected on the force plate. If these two events did not coincide to the same frame, then the frame in which a force plate reading was no longer detected was used.

For the FMSFJs the analysis had to be slightly different as the participant was not on the force plate for every jump that occurred. Also, because the individual was only using one limb in the jump and landing that was to be analyzed, the cycle in which the toe off corresponded to the limb jumping and landing had to be identified separately from when the limb was in swing while the target limb was performing the jump. Thus, initial contact and toe off of the target limb were identified through strictly marker trajectory data rather than with corresponding force plate data. Temporal pattern recognition was used to identify initial contact and toe off, and subsequent pipelines were run to identify contralateral and ipsilateral initial contact and toe off labels. A contralateral initial contact and toe off described the motion of the limb when it was the swing leg helping with the drive up off the ground in the jump, while the other limb, labelled as the ipsilateral leg was performing the jump. The points of ipsilateral initial contact and toe off describe the motion of the limb when it is performing the jump. Initial contact for the window of analysis was defined as the frame corresponding with the ipsilateral initial contact label. The end of the window of analysis was defined as the frame corresponding with the contralateral initial contact label. Since it is unilateral landing that we were interested in analyzing, the window of analysis must then correspond to this, which was why this window spans from initial contact to subsequent initial contact, instead of to the toe off.

As mentioned earlier, angles and moments followed a Cardan angle sequence (x-y-z) and Right Hand Rule assumptions, so that positive values in the x-, y-, and z-directions were to the right of the participant, and forward and upward, respectively. This allowed ankle dorsiflexion, knee extension, and hip flexion angles and moments to be positive in the sagittal plane, and knee adduction, hip adduction, and ankle inversion angles and moments to be positive for the right limb, and negative for the left limb, in the frontal plane.

Data Analysis

The dependent kinematic variables that were specifically analyzed include knee flexion and abduction, trunk forward and lateral flexion, hip flexion and abduction, and ankle dorsiflexion and eversion. These variables were analyzed separately at initial contact and peak excursion. Dependent kinetic variables that were analyzed include peak knee adductor, hip adductor and ankle invertor moments that occurred during stance.

The data collected from the force platforms was analyzed for the jumps that resulted in a successful force recording. This meant that the participant had to land fully and completely on the force plate for the trial to be viable.

Statistical Analyses

A 3-factor repeated measures ANOVA (Jump (2 levels: CMJ and FMSFJ), Fatigue (2 levels: Pre and Post) and Sex (2 Levels: Male and Female) was run for each variable of interest to understand the influence of fatigue on unilateral and bilateral jump protocols while also taking sex into consideration. Jump and fatigue were within-subject factors; sex was a between-subject factor. Marginal means were utilized to express main effects. Two-way interactions involving only within subject factors were analyzed with paired samples t-tests. Two-way interactions with the between subject factor were analyzed with independent samples t-tests and paired samples t-tests. Effect size for the initial ANOVA was reported using partial eta squared (η^2). A significance level of $p<0.05$ was used. A Bonferroni correction was applied to follow up t-tests where the p-value was corrected to $p<0.0125$ to account for 4 family-wise comparisons. Descriptive statistics were included for demographic measurements such as height, weight, age, sex, activity level, and type of activity engaged in.

Chapter III: Results

Testing was completed with forty participants. The sample included twenty females (age 24.00±3.68 years, BMI 23.54±2.97kg/m2, hip:waist ratio 0.74±0.04) and twenty males (age 25.35±4.22 years, BMI 24.86±2.81kg/m2, hip:waist ratio 0.82±0.03). All participants were well over the minimum cut off for activity participation of 200 minutes per week (457.75±193.41 min), and participated in a range of sports including running, triathlon, cycling, figure skating, aerial hoop, jiu jitsu, dodgeball, basketball, volleyball, ultimate frisbee, softball, squash, soccer, rugby, ringette, and hockey. It should be noted that not all of these sports qualify for inclusion into the study, but all activity was recorded for each participant.

The following tables (Table 1, 3, 5, and 7) include the average angle values of variables of interest at initial contact (IC) and at peak excursion of the knee, trunk, hip, and ankle in the frontal and sagittal plane across all subject trials for main effects of jump type and fatigue type (CMJ, FMSFJ, Pre-fatigue and Post-fatigue). Tables 2, 4, 6 and 8 include the average angle values of variables of interest at initial contact (IC) and at peak excursion, for the four study categories (PRE_CMJ, POST_CMJ, PRE_FMSFJ, and POST_FMSFJ). All participants' data were included from all three trials for each of the four study categories. FMSFJ trials that resulted in a complete force plate landing in a jump repetition were noted, and the corresponding repetition and limb of the participant's CMJ trial was taken. This was done so that an equal amount of FMSFJ and CMJ data were analyzed. No difference between left and right limb execution was noted, so the limbs were pooled for each variable. Due to Right Hand Rule assumptions y-axis variable values for the left limb were inverse of values given for the right limb. To account for this, all left limb values were inverted to correspond and pool with right limb values for analysis.

Heart rate attained during the sprint fatigue protocol was lower than the heart rate attained during the submaximal treadmill fatigue protocol. Heart rate values from the sprint fatigue protocol were 90.77±2.95% of the submaximal treadmill fatigue protocol values. During the sprint fatigue protocol in the second session all but one of the participants met or exceeded the minimum RPE of 17 (average 18.38±1.25) to indicate exhaustion. Sprint duration for the first sprint ranged from 22 to 60 seconds, and 6 to 40 seconds on the last sprint. Fatigue indexes ranged from -12.9% to 82.9% (average 36.2%).

Angle and moment results will be outlined by joint, starting with the primary outcome variables at the knee, and then the trunk, hip, and ankle.

Knee Variables

Table 1: Knee angle results at initial contact and peak values, separated by jump and fatigue

Angle variables (degrees)	CMJ	FMSFJ	Pre-Fatigue	Post-Fatigue
IC Knee Flexion a,b	-20.96±5.62	-10.48±3.61	-16.29±3.80	-15.15±4.64
IC Knee ABD/ADD b	0.59±2.49	-0.44±2.79	1.15±2.73	0.79±2.77
Peak Knee Flexion a,b	-91.58±12.18	-42.35±8.63	-69.47±7.47	-64.46±8.42
Peak Knee ABD b	-4.90±4.42	-1.58±3.35	-3.03±3.91	-3.45±4.89

Statistical differences:
a denotes main effect of fatigue
b denotes main effect of jump type

Polarity of values:
knee flexion (-)/extension(+)
knee abduction(-)/adduction(+)

Table 2: Knee angle results at initial contact and peak values, across the four jump and fatigue conditions

Angle variables (degrees)	PRE_CMJ	POST_CMJ	PRE_FMSFJ	POST_FMSFJ
IC Knee Flexion $_{d,e}$	-22.26±5.50	-19.66±7.16	-10.32±4.11	-10.64±3.77
IC Knee ABD/ADD $_{c}$	1.69±2.61	1.17±2.85	0.61±2.78	0.39±2.67
Peak Knee Flexion	-94.87±11.29	-88.28±13.99	-44.06±9.23	-40.64±9.35
Peak Knee ABD $_{d,e}$	-4.43±4.04	-5.37±5.13	-1.63±3.26	-1.53±3.81

Statistical differences:
$_{c}$ denotes sex effect or interaction
$_{d}$ denotes jump interaction
$_{e}$ denotes fatigue interaction

Polarity of values:
knee flexion (-)/extension(+)
knee abduction(-)/adduction(+)

There was a main effect of jump type and fatigue for knee flexion angle at initial contact with higher flexion in CMJ trials compared to FMSFJ trials [$F(1,38) = 170.247$, $p<0.001$, $\eta_{p2}=0.818$], and higher values pre-fatigue compared to post-fatigue trials [$F(1,38) = 5.195$, $p=0.028$, $\eta_{p2}=0.120$]. There was also a jump*fatigue interaction for knee flexion angle at initial contact. Paired samples t-tests were run and showed higher flexion values in CMJ trials when comparing pre-fatigue values to post-fatigue values ($p=0.010$). Knee flexion angles at initial contact were also higher in CMJ landings in the pre-fatigue ($p<0.000$) and post-fatigue ($p<0.000$) conditions compared to FMSFJ landings.

There was a main effect of jump and fatigue for peak knee flexion angle with more knee flexion in CMJ trials compared to FMSFJ trials [$F(1,38) = 434.271$, $p<0.001$, $\eta_{p2}=0.920$], and more flexion in pre-fatigue conditions compared to post-fatigue conditions [$F(1,38) = 41.584$, $p<0.001$, $\eta_{p2}=0.523$].

There was a main effect of jump type and sex for knee adduction angle at initial contact with more knee adduction in CMJ trials compared to FMSFJ trials [$F(1,38) = 9.959$, $p=0.003$,

η_{p}^{2}=0.208], and more knee adduction in male landings compared to female landings (1.86±2.38 vs 0.07±2.76) [F(1,38) =6.398, p=0.016, η_{p}^{2}=0.144]. There was a main effect of jump type for peak knee abduction angle with high knee abduction angle values in CMJ trials compared to FMSFJ trials [F(1,38) =59.404, p<0.001, η_{p}^{2}=0.610]. There was also a jump by fatigue interaction for peak knee abduction angle. Paired samples t-tests showed higher knee abduction angle values in the post-fatigue CMJ trials [t(1,39) = -0.277, p=0.033)] compared to the pre-fatigue CMJ trials, while there was not a difference pre-fatigue compared to post-fatigue in the FMSFJ trials. Moreover, there were higher peak knee abduction angle values in CMJ pre-fatigue conditions [t(1,39) = 6.855, p<0.000] and post-fatigue conditions [t(1,39) = -7.324, p<0.000] compared to respective FMSFJ trials. Peak knee adduction moment showed no significant results. Sagittal plane knee moments were not investigated in the current study.

Trunk Variables

Table 3: Trunk angle results at initial contact and peak values, separated by jump and fatigue

Angle variables (degrees)	CMJ	FMSFJ	Pre-Fatigue	Post-Fatigue
IC Trunk Flexion [b]	-16.53±12.15	-11.42±8.61	-13.44±10.93	-14.51±12.67
IC Trunk Lateral Lean	0.00±2.85	-0.21±2.76	-0.08±3.06	-0.12±2.52

Statistical differences:
[a] denotes main effect of fatigue
[b] denotes main effect of jump type

Polarity of values:
trunk flexion (-)/extension(+)
trunk lateral lean FMSFJ contra(+)/ipsi(-)
trunk lateral lean CMJ left(+)/right(-)

Table 4: Trunk angle results at initial contact and peak values, across the four jump and fatigue conditions

Angle variables (degrees)	PRE_CMJ	POST_CMJ	PRE_FMSFJ	POST_FMSFJ
IC Trunk Flexion	-15.36±13.06	-17.70±14.29	-11.52±8.00	-11.32±10.01
IC Trunk Lateral Lean d	0.27±2.99	-0.26±2.71	-0.42±3.13	0.013±2.35

Statistical differences: c denotes sex effect or interaction d denotes jump interaction e denotes fatigue interaction	*Polarity of values:* trunk flexion (-)/extension(+) trunk lateral lean FMSFJ contra(+)/ipsi(-) trunk lateral lean CMJ left(+)/right(-)

The analysis revealed a main effect of jump type for trunk flexion angle at initial contact with more flexion through the trunk in the CMJ trials compared to the FMSFJ trials [$F(1,38) = 10.045$, $p=0.003$, $\eta_{p2}=0.209$].

There was a jump by sex interaction for trunk lean angle at initial contact [$F(1,38) = 4.871$, $p=0.033$, $\eta_{p2}=0.114$]. Paired samples t-tests showed a difference in male values for CMJ values compared to FMSFJ values (0.65±2.20 vs. -0.45±2.21) [$t[1,39] = 2.335$, $p=0.031$], but no difference in female values for CMJ compared to FMSFJ. Unfortunately, due to the way in which trunk lean was calculated for the FMSFJ trials, we cannot determine if there is a true difference between jump types. CMJ trials were calculated as left or right ward lean, while FMSFJ trials were calculated as ipsilateral or contralateral lean, dependent on which limb was landing in the unilateral jump. Consequently, we cannot compare the means of the CMJ to the FMSFJ because positive and negative values may or may not indicate the same direction of lean.

Hip Variables

Table 5: Hip angle results at initial contact and peak values, separated by jump and fatigue

Angle variables (degrees)	CMJ	FMSFJ	Pre-Fatigue	Post-Fatigue
IC Hip Flexion b	20.19±13.08	3.23±10.91	11.30±16.19	12.11±14.73
IC Hip ABD/ADD b	-8.53±2.52	-6.76±3.39	-7.95±3.41	-7.34±3.50
Peak Hip Flexion a,b	94.58±19.73	5.62±12.34	52.37±12.92	47.83±16.63
Peak Hip ABD a,b	-14.62±4.22	-7.52±3.53	-11.52±3.33	-10.62±3.25
<u>Statistical differences:</u> a denotes main effect of fatigue b denotes main effect of jump type			<u>Polarity of values:</u> hip flexion(+)/extension(-) hip abduction(-)/adduction(+)	

Table 6: Hip angle results at initial contact and peak values, across the four jump and fatigue conditions

Angle variables (degrees)	PRE_CMJ	POST_CMJ	PRE_FMSFJ	POST_FMSFJ
IC Hip Flexion	19.71±16.30	20.67±12.71	2.90±10.97	3.56±11.32
IC Hip ABD/ADD	-8.76±2.96	-8.30±2.86	-7.15±3.67	-6.38±3.84
Peak Hip Flexion c,d,e	98.41±18.90	90.75±21.79	8.23±10.27	4.92±12.62
Peak Hip ABD d	-15.07±4.47	-14.18±4.62	-7.98±4.11	-7.06±3.87
<u>Statistical differences:</u> c denotes sex effect or interaction d denotes jump interaction e denotes fatigue interaction			<u>Polarity of values:</u> hip flexion(+)/extension(-) hip abduction(-)/adduction(+)	

There was a main effect of jump type for hip flexion angle at initial contact with more flexion in CMJ trials compared to FMSFJ trials [$F(1,38) = 131.701$, $p<0.001$, $\eta_{p2}=0.776$]. There was a main effect of jump type for hip abduction angle at initial contact with more abduction in CMJ trials compared to FMSFJ trials [$F(1,38) = 8.429$, $p=0.006$, $\eta_{p2}=0.182$].

There were main effects of jump type and fatigue for peak hip flexion angle with more hip flexion in the CMJ trials compared to the FMSFJ trials [F(1,38) =870.019, p<0.001, η_{p2}=0.958] and more hip flexion pre-fatigue compared to post-fatigue [F(1,38) =24.607, p<0.001, η_{p2}=0.393]. There was also a jump by fatigue interaction for peak hip flexion angle [F(1,38) =14.302, p=0.001, η_{p2}=0.273]. Paired samples t-tests showed more hip flexion in CMJ pre-fatigue compared to post-fatigue values [t(1,39) = 4.673, p<0.000)], there was no differences in pre-fatigue peak hip flexion angle compared to post-fatigue peak hip flexion angle values for FMSFJ trials. Moreover, there was more hip flexion for CMJ trials compared to FMSFJ trials in both pre-fatigue [t(1,39) = -30.684, p<0.000] and post-fatigue conditions [t(1,39) = -26.736, p<0.000]. There was a 3-way jump by fatigue by sex interaction for peak hip flexion angle [F(1,38) =4.306, p=0.045, η_{p2}=0.102]. This interaction was split into two 2-way jump by fatigue ANOVAs, one for male values and one for female values. The male 2-way ANOVA had a main effect of jump and fatigue with higher hip flexion angles in the CMJ trials compared to the FMSFJ trials (11.08± 11.38 vs. 1.40± 4.25) [F(1,19)=559.415, p<0.001, η_{p2}=0.967] and higher hip flexion angles in the pre-fatigue conditions compared to post-fatigue conditions (-95.22± 17.00 vs. -85.53± 8.94) [F(1,19)=18.587, p<0.001, η_{p2}=0.495]. There was a jump by fatigue interaction in the male 2-way ANOVA [F(1,19) = 14.729, p=0.001, η_{p2}=0.437], so paired samples t-tests were run to find specific differences. In male CMJ trials hip flexion angles were higher pre-fatigue compared to post-fatigue (99.64±15.09 vs. 88.55±21.15) [t(1,19) = 4.356, p<0.001]. CMJ trial hip flexion values were also higher than FMSFJ trial values in both the pre-fatigue (99.64±15.09 vs. 4.42±14.43) [t(1,19) = -25.046, p<0.001] and post-fatigue conditions (88.55±21.15 vs. 3.02± 13.55)[t(1,19) = -20.198, p<0.001]. In the female 2-way ANOVA there were main effects of jump and fatigue, which revealed higher hip flexion angle values in the

CMJ trials compared to the FMSFJ trials (95.06±2.99 vs. 7.53±1.00) [$F(1,19)=351.793$, $p<0.001$, $\eta_{p2}=0.949$], as well as higher hip flexion angle values in the pre-fatigue conditions compared to post-fatigue conditions (52.70± 48.21 vs. 49.88± 47.11) [$F(1,19)=6.409$, $p=0.020$, $\eta_{p2}=0.252$], respectively. Sagittal plane hip moments were not investigated in the current study.

There was a main effect of jump type and fatigue for peak hip abduction angle with more hip abduction in CMJ trials compared to FMSFJ trials [$F(1,38) =101.493$, $p<0.001$, $\eta_{p2}=0.728$] and more abduction in pre-fatigue trials compared to post-fatigue trials [$F(1,38) =6.261$, $p=0.017$, $\eta_{p2}=0.141$]. There was a jump by sex interaction for peak hip abduction angle [$F(1,38) = 5.850$, $p=0.020$, $\eta_{p2}=0.133$]. Paired samples t-tests showed higher values of hip abduction in CMJ for both males (-15.88±3.85 vs. -7.07±3.44) [t(1,19 = 8.185, $p<0.000$] and females (-13.36± 4.29 vs. -7.96±3.65) [$t(1,19) = 5.924$, $p<0.000$] compared to FMSFJ trials. There was a main effect of jump and fatigue for peak hip adduction moment values, with higher hip adduction moment values in CMJ trials compared to FMSFJ trials [$F(1,38) =19.947$, $p<0.001$, $\eta_{p2}=0.344$] and higher hip adduction moment values pre-fatigue compared to post-fatigue [$F(1,38) =4.148$, $p=0.049$, $\eta_{p2}=0.098$].

Ankle Variables

Table 7: Ankle angle results at initial contact and peak values, separated by jump and fatigue

Angle variables (degrees)	CMJ	FMSFJ	Pre-Fatigue	Post-Fatigue
IC Ankle DF/PF a,b	-50.03±5.55	-46.76±8.58	-49.28±7.05	-47.51±7.66
Peak Ankle DF/PF	1.67±4.37	2.34±5.93	2.36±5.56	1.64±5.10
Peak Ankle EV/INV a,b	3.21±4.80	0.07±3.80	2.39±3.56	0.89±3.90
Statistical differences: a denotes main effect of fatigue b denotes main effect of jump type		*Polarity of values:* ankle plantarflexion(+)/dorsiflexion(-) ankle eversion(-)/inversion(+)		

Table 8: Ankle angle results at initial contact and peak values, across the four jump and fatigue conditions

Angle variables (degrees)	PRE_CMJ	POST_CMJ	PRE_FMSFJ	POST_FMSFJ
IC Ankle DF/PF	-50.70±5.45	-49.37±5.64	-47.87±8.18	-45.65±8.93
Peak Ankle DF/PF c	2.12±4.73	1.21±4.63	2.60±6.34	2.07±5.56
Peak Ankle EV/INV c	3.93±4.63	2.49±4.91	0.85±3.57	-0.72±3.90
Statistical differences: c denotes sex effect or interaction d denotes jump interaction e denotes fatigue interaction		*Polarity of values:* ankle plantarflexion(+)/dorsiflexion(-) ankle eversion(-)/inversion(+)		

There was a main effect of jump and fatigue for ankle angle at initial contact, with more dorsiflexion in CMJ trials compared to FMSFJ trials [$F(1,38) = 8.653$, $p=0.006$, $\eta_{p2}=0.185$], and more dorsiflexion in pre-fatigue conditions compared to post-fatigue conditions at initial contact [$F(1,38) = 12.727$, $p=0.001$, $\eta_{p2}=0,251$].

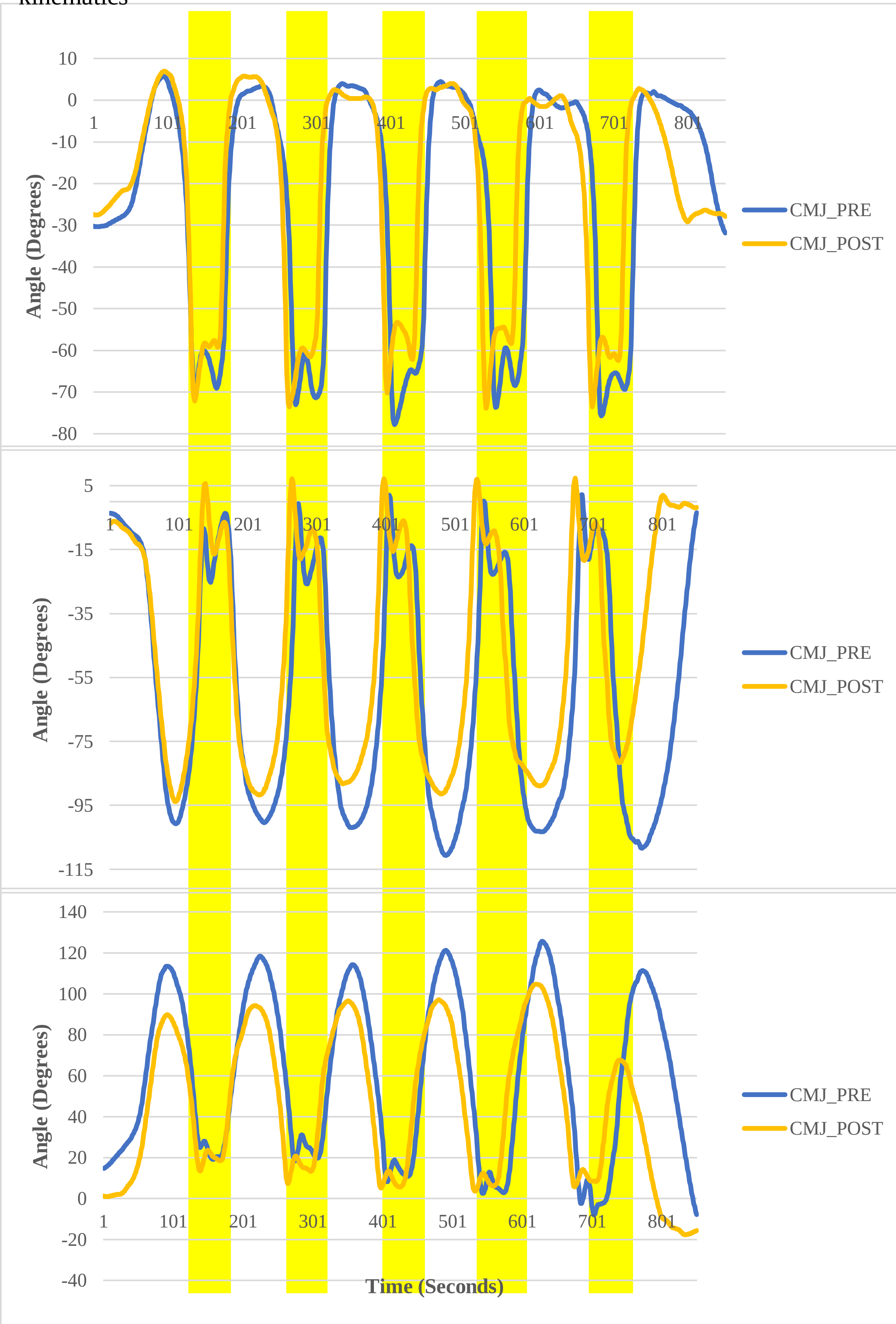
There was a main effect of sex for peak dorsiflexion angle with females exhibiting more dorsiflexion compared to males (3.43± 5.38 vs. -0.58± 3.06) [$F(1,38) = 4.245$, $p = 0.046$, $\eta_{p}^{2} = 0.100$].

There was a main effect of jump and fatigue for peak ankle eversion angle with a higher ankle eversion angle in the CMJ trials compared to the FMSFJ trials [$F(1,38) = 26.722$, $p < 0.001$, $\eta_{p}^{2} = 0.413$] and higher ankle eversion angle in the pre-fatigue conditions compared to post-fatigue [$F(1,38) = 35.597$, $p < 0.001$, $\eta_{p}^{2} = 0.484$]. There was a jump by sex interaction for peak ankle eversion angle [$F(1,38) = 4.517$, $p = 0.040$, $\eta_{p}^{2} = 0.106$]. Paired samples t-tests showed a higher angle value in CMJ trials compared to FMSFJ trials for the female group only (4.06±1.03 vs. -0.37±0.98) [$t(1,19) = 6.171$, $p < 0.000$).

There was a main effect of jump type for peak inversion moment with a higher moment value in FMSFJ trials compared to CMJ trials [$F(1,38) = 140.636$, $p < 0.001$, $\eta_{p}^{2} = 0.787$].

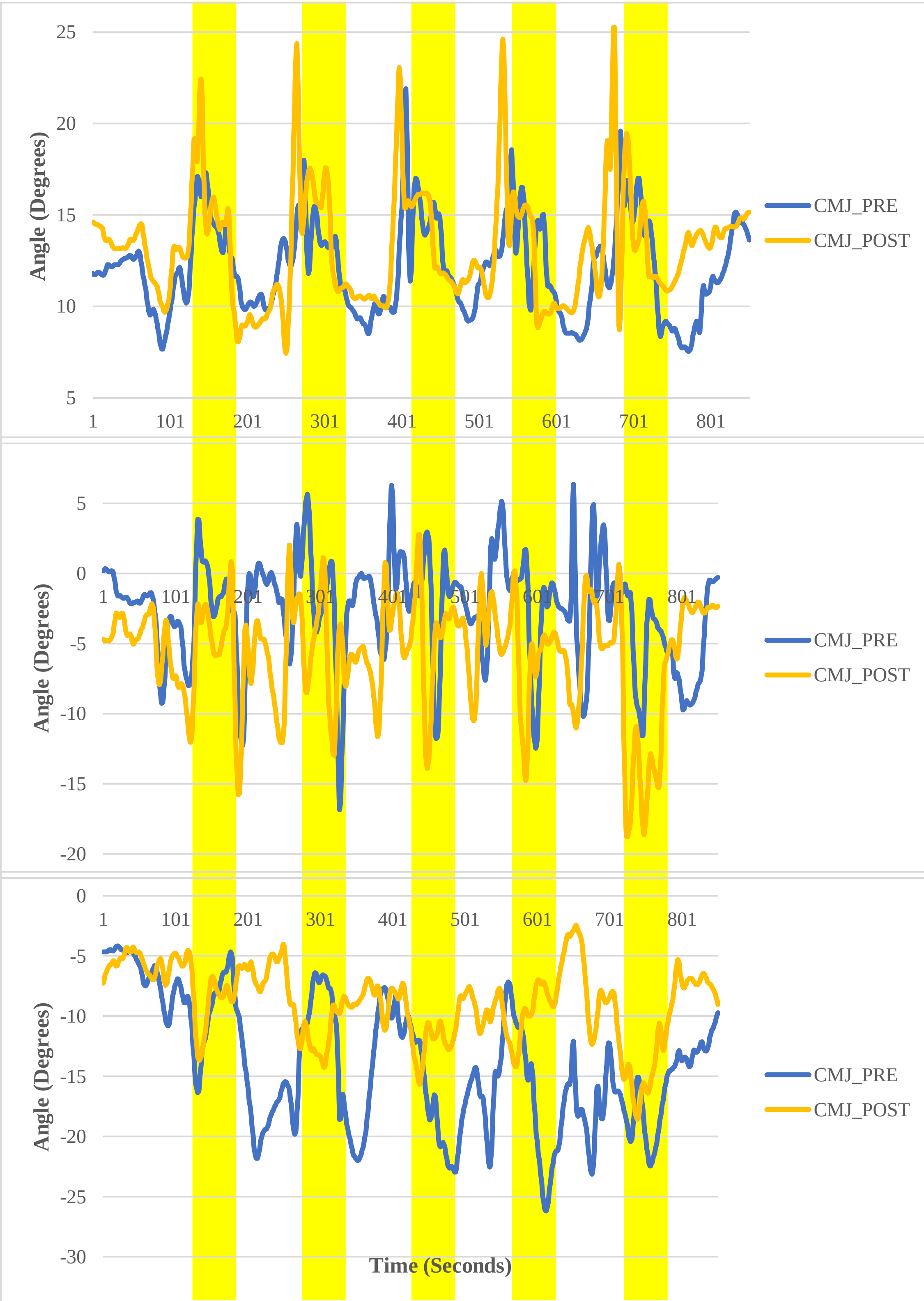
Below are graphical representations of one representative female participant's angle data throughout the CMJ and FMSFJ protocols. These graphs illustrate an example of the movement patterns created to complete the task execution involved in this study. In all graphs, PRE- values are orange, and POST- values are blue For the FMSFJ graphs the areas within the highlighted areas indicate the landing phase on the target leg, which is the right leg in this example.

Figure 6: Female participant flexion/extension and dorsiflexion/plantarflexion CMJ kinematics



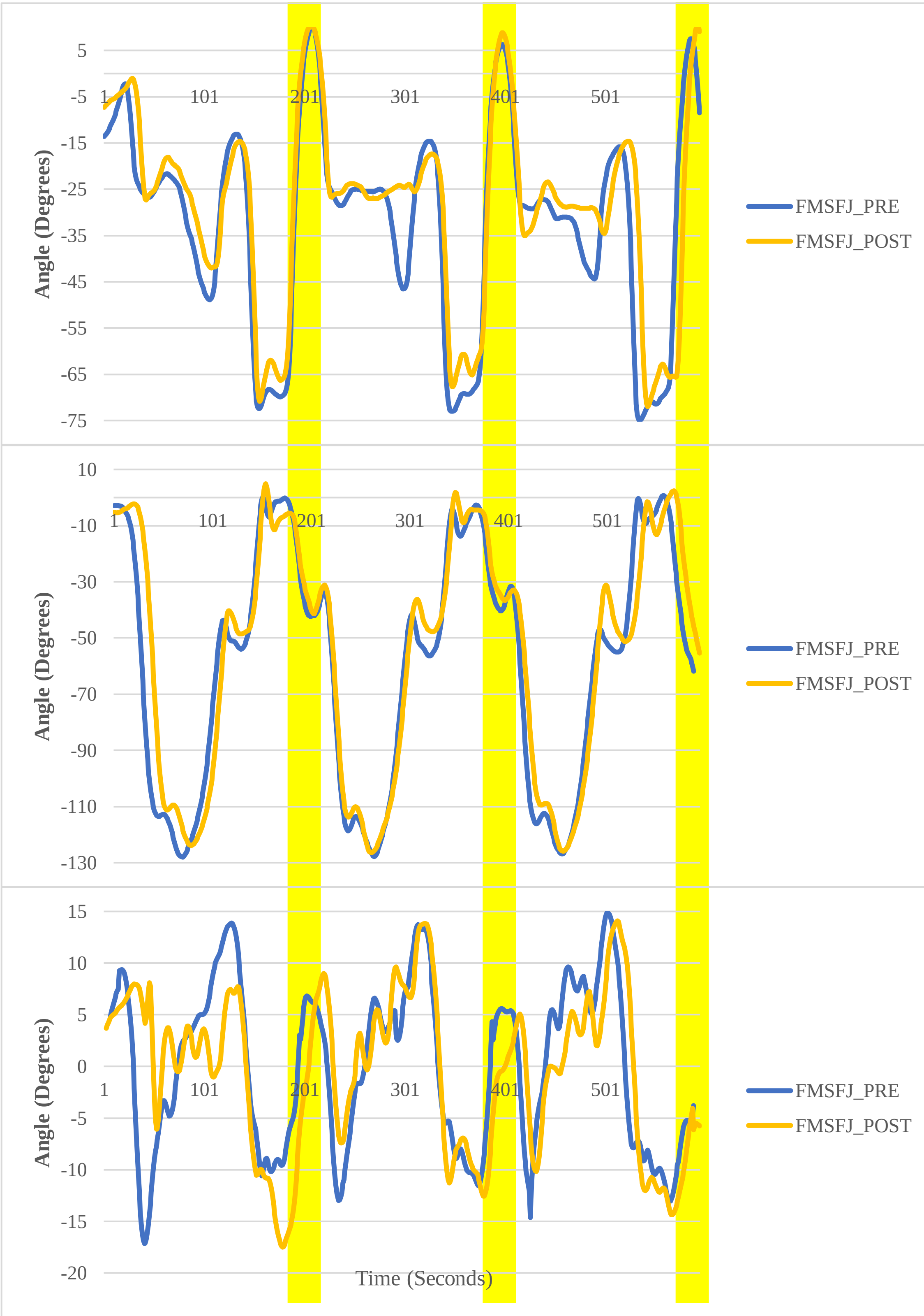
Top graph: Ankle dorsiflexion(+)/plantarflexion(-); Middle graph: Knee flexion(-) /extension(+); Bottom graph: Hip flexion(+)/extension(-). The highlighted area indicates the landing phase on the target leg.

Figure 7: Female participant adduction/abduction and inversion/eversion CMJ kinematics



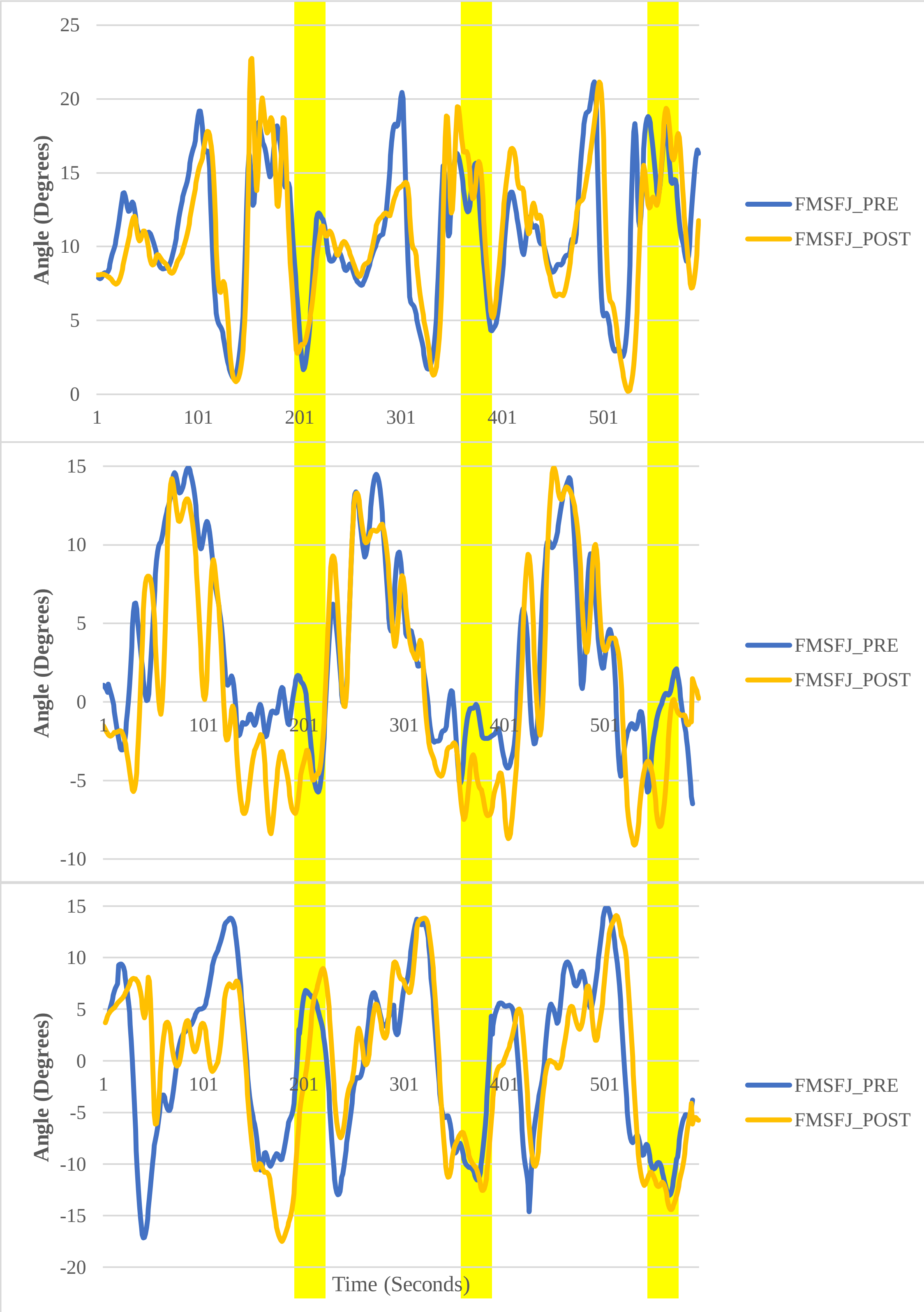
Top graph: Ankle inversion(+)/eversion(-); Middle graph: Knee adduction(-)/abduction(+); Bottom graph: Hip adduction(-)/abduction(+). The highlighted area indicates the landing phase on the target leg.

Figure 8: Female participant flexion/extension and dorsiflexion/plantarflexion FMSFJ kinematics



Top graph: Ankle dorsiflexion(+)/plantarflexion(-); Middle graph: Knee flexion(-)/extension(+); Bottom graph: Hip flexion(+)/extension(-). The highlighted area indicates the landing phase on the target leg.

Figure 9: Female participant adduction/abduction and inversion/eversion FMSFJ kinematics



Top graph: Ankle inversion(+)/eversion(-); Middle graph: Knee adduction(-)/abduction(+); Bottom graph: Hip adduction(-)/abduction(+). The highlighted area indicates the landing phase on the target leg.

Chapter IV: Discussion

The purpose of our study was to investigate the effect of fatigue and sex on knee joint mechanics during two jumping tasks. The goal of this study was to determine if one of the two jumps included was superior in showing post-fatigue differences and outline possible recommendations on which movement may be ‘higher risk’ for injury. The two jumping tasks were analyzed prior to and after a full-body treadmill-based sprint fatiguing protocol, in order to assess how fatigue influences movement execution. It was expected that sagittal plane movements including flexion at the trunk, hip, knee and ankle would be larger in the CMJ protocol, but decrease post-fatigue in both the FMSFJ and CMJ protocols. It was also expected that frontal plane excursions such as knee abduction would increase post-fatigue in both the FMSFJ and CMJ protocols. These differences between pre- and post-fatigue, if found, were expected to be larger in the FMSFJ protocol compared to the CMJ protocol. Lastly, we expected males and females to differ in knee flexion and abduction values, with females landing stiffer with less knee flexion and with more knee abduction.

Thirteen of the sixteen variables of interest showed a main effect of jump, indicating that the CMJ and FMSFJ angles and moments were different from each other regardless of sex and fatigue condition. There was more flexion through the trunk, hip, knee and ankle (dorsiflexion) at initial contact in the CMJ protocol compared to the FMSFJ protocol, and more flexion through the hip and knee at peak angle values in the CMJ protocol compared to the FMSFJ protocol. There was also more hip abduction, knee abduction and ankle eversion in the CMJ protocol compared to the FMSFJ protocol at initial contact and peak values. Peak hip adduction moment was higher in the CMJ protocol while peak inversion moment was higher in the FMSFJ protocol. This is not a surprise, as the two jumping tasks used in these study protocols are quite different, and differences in execution of a unilateral task compared to a bilateral task are reported in the literature (Earl et al., 2007; McCurdy et al., 2014; Pappas, Hagins, et al., 2007; Taylor et al., 2016). The CMJ task is bilateral and vertically driven, whereas the FMSFJ task is unilateral and somewhat horizontally driven. However, there was more effect on the hip in the frontal and sagittal planes pre-fatigue to post-fatigue compared to the knee. All angle values for pre-fatigue and post-fatigue CMJ and FMSFJ protocols can be found in Table 1 on page 70.

The primary hypothesis predicted that participants would demonstrate less knee and hip flexion during the post-fatigue conditions CMJs compared to the pre-fatigue conditions in both the FMSFJ and CMJ protocols. The results were consistent with this hypothesis, as there was a main effect of fatigue for peak hip and knee flexion, and ankle dorsiflexion and knee flexion at initial contact, which showed angle values decreasing from pre- to post-fatigue conditions. There was also a jump by fatigue interaction for both hip and knee flexion which outlined specifically in the CMJ that there was less peak hip flexion and knee flexion at initial contact in the post-fatigue compared to pre-fatigue CMJ protocol. There was only one 3-way interaction found in this study, involving peak hip flexion angle. The analysis revealed that both males and females had higher peak hip flexion angle values in the CMJ protocol compared to the FMSFJ protocol, as well as higher peak hip flexion angle values pre-fatigue compared to post-fatigue in the CMJ protocol, but not in the FMSFJ protocol. These results echo the main effects found for the whole study population, and again are consistent with the primary hypothesis, and third hypothesis, that predicted lower hip flexion values in the FMSFJ protocol compared to the CMJ protocol. It has been shown previously that flexion values decrease post-fatigue in unilateral jump landings (Smith et al., 2009) and bilateral jump landings (Y. Kim et al., 2017; Schmitz, Cone, Copple, et al., 2014; van der Does et al., 2015).

The secondary hypothesis predicted that participants would demonstrate more knee abduction and trunk lateral flexion during the post-fatigue FMSFJ protocol compared to any other jump or fatigue condition. Peak abduction angles were actually higher in the CMJ trials compared to the FMSFJ trials at the hip and knee. There was a jump by fatigue interaction for peak knee abduction angle, which showed values were higher in the CMJ protocol compared to the FMSFJ protocol in both the pre-fatigue and post-fatigue conditions. There was also no difference in trunk lateral bend between jump types, which similarly was expected to have differences. It was expected that frontal plane movements would be greater in the FMSFJ protocol due to the unilateral nature, and the fact that the center of mass would be closer to the edge of the base of support (Enoka, 2008; Weinhandl et al., 2015). However, participants' landing posture in the FMSFJ protocol was much more erect and stiffer than was expected. This may be due to the fact that participants were told to aim for maximum height and to make the jumps as consecutive as possible, which may have led to participants jumping shallower to allow for quicker progression into the next jump. This could also be because the FMSFJ protocol did not include drop jumps, or forward bounds, which have been previously used in literature, and were the comparison values for this study (Augustsson et al., 2006; Ebben et al., 2009; Lessi & Serrão, 2017; Pasanen et al., 2015; Taylor et al., 2016).

These results are also not consistent with previous literature that has shown unilateral jump tasks exhibiting higher angle excursions in the frontal plane (Kariyama et al., 2017). This discrepancy between the current study and previous literature may be due to the fact that athletes used in the current study were specifically involved in jumping and landing sports. This in turn may have allowed the participants to have finer control over their landing strategy. Alternatively, this discrepancy may be due to the fatiguing protocol possibly not affecting the muscles involved in abduction such as the hip adductors (Moore et al., 2015a) as much as the muscles involved in flexion of the hip and knee. This again could have been a strategy in the CMJ protocol in which participants were trying to get into a lower position to create a higher jump. Alternatively, it could have been caused by the participants not being truly fatigued. However, previous literature supports the notion that a fatigue index of 7 to 10% decay of sprint time is an appropriate indicator of performance decrement (Morin, Dupuy, & Samozino, 2011; Ruscello et al., 2013). In any case, the majority of participants in this study were exceeding the minimum 10% fatigue index shown in previous literature to indicate a fatigued execution.

The third hypothesis predicted that overall participants would demonstrate more flexion at the trunk, hip, knee, and ankle, and less ankle eversion in the CMJ protocols compared to the FMSFJ protocols. The results were mostly consistent with this hypothesis, and revealed higher angles of flexion through the trunk, hips, and knees at initial contact in the CMJ trials compared to the FMSFJ trials. Peak flexion values were also further into flexion at the hip and knee in the CMJ protocols compared to the FMSFJ protocols. There was a jump by fatigue interaction for peak hip flexion angle, and knee flexion at initial contact. These interactions showed more hip flexion at peak, and knee flexion at initial contact in the CMJ protocol pre- versus post-fatigue, as well as more hip and knee flexion in CMJ compared to FMSFJ in both the pre-fatigue and post-fatigue conditions. These results also agree with previous studies that have shown that jump moving horizontally, much like the FMSFJ protocol in this study, usually produce lower values of joint flexion compared to vertically driven jumps like the CMJ protocol used in this study (Augustsson et al., 2006) whereas these vertically driven jumps are more likely to produce higher values of hip and knee flexion (Taylor et al., 2016). However, the effect of fatigue overall can lower the amount of flexion produced by an individual, so a reduction in flexion angle values in both jump protocols was still expected.

The exception to the third hypothesis is the ankle plantarflexion at initial contact and peak ankle eversion data where there was more plantaflexion and eversion in the CMJ protocol compared to the FMSFJ protocol. Higher plantaflexion angle values may have been occurring in the CMJ protocol compared to the FMSFJ protocol due to the participants jumping higher off the ground in the CMJs, potentially creating more plantarflexion at push off, and then staying near that level of plantarflexion until meeting the ground again in landing. Eversion may have been higher because individuals performing the CMJ task may have been trying to get into a lower stance to create more push off, and greater knee and hip flexion may force the ankle into more eversion, to get the body further down into the squat position. There was less eversion in the FMSFJ task than we were expecting perhaps due to unexpected motion in the trunk, or stiffer landings than were expected. If the participant was leaning toward the limb they were landing on in the FMSFJ task, this would most likely lead to less eversion, while if they were leaning toward the swing leg or contralateral leg during landing, this may lead to more eversion. The results in table 4 show that at landing, participants were near zero degrees of trunk lateral flexion, meaning they were in an almost vertical position at the trunk, not leaning in either direction. Participants were also leaning slightly backward at initial contact during the FMSFJ task, while it was expected for participants to have a forward lean. This change in trunk posture may have influenced the entire execution of the FMSFJ landings, and created intercompensations at the joints all the way down the limb, creating the lower flexion, abduction, and eversion values than were expected.

The fourth hypothesis predicted there would be larger differences pre-fatigue compared to post-fatigue in the FMSFJ protocol compared to the CMJ protocol, but this does not seem to be the case. All jump by fatigue interactions showed changes in the CMJ pre- to post-fatigue, but not in the FMSFJ protocol. Nevertheless, the FMSFJ protocol overall demonstrated much lower joint flexion values. A study by Shimokochi & Shultz (2008) stated that knee flexion values at or lower than 30 degrees at maximum flexion would classify a jump landing as putting the individual at risk for injury. Both the CMJ and FMSFJ protocols show below 30 degrees knee flexion at initial contact, but the CMJ protocol greatly surpasses this at peak flexion, whereas the FMSFJ protocol is just into the 40 degree range of flexion at peak values, so is still quite rigid at peak flexion.

The fifth hypothesis predicted that joint moments would be higher in the FMSFJ protocol compared to the CMJ protocol, but these results are not fully consistent with that hypothesis. The only variable that was higher in the FMSFJ compared to CMJ trials was peak inversion moment (0.804 Nm/kg and 0.285 Nm/kg, respectively), however there was a higher hip adduction moment in the CMJ trials compared to the FMSFJ trials (0.621 Nm/kg and 0.289 Nm/kg, respectively) as well as higher values pre-fatigue compared to post-fatigue (0.496 Nm/kg and 0.414 Nm/kg, respectively). There may have been higher hip adduction values in the CMJ trials compared to the FMSFJ trials as the participants moved through a larger range of motion in the CMJ trials, and perhaps pushed off the ground harder in these prolonged landings compared to the FMSFJ jumps. The inversion moment result was expected as previous literature has shown that unilateral jump tasks exhibit higher moments at landing as well as higher angle excursions in the frontal plane (Kariyama et al., 2017). This relationship may be due to the individual needing to absorb their full body landing through one leg instead of two, as well as landing with the majority of their body weight to the medial side of their base of support, potentially causing more frontal plane moment in landing execution (Nyland et al., 2002; Weinhandl et al., 2015). It has also been reported than moment values increase with a decrease in joint flexion (Schmitz, Cone, Tritsch, et al., 2014; van der Does et al., 2015), and since we expected lower flexion values in the FMSFJ protocol compared to the CMJ protocol, this relationship in moment was also expected to be seen across the three lower limb joints. In task execution, the magnitude of joint moments most certainly need to be considered, as the force going through a joint during movement is what ultimately causes injuries. If a joint is positioned in a 'risky' manner, but no force is going through the joint, there is a low probability for injury. However, if this joint also had a high force associated with the movement, then there may be a higher probability for injury. All factors need to be considered, including joint motion, moment, and the relationships between the joints involved with the movement, to be able to understand the resultant effect of the individuals performance or execution on their body.

The sixth hypothesis predicted that during both tasks and in pre-and post-fatigue conditions, males would utilize more knee flexion and less knee abduction compared to females. A main effect of sex was found for peak dorsiflexion angle and knee adduction or abduction angle at initial contact. No sex differences were seen for all other angles and moments. Female participants exhibited higher angle values of peak ankle dorsiflexion, and lower knee adduction angles at initial contact compared to male participants. This is somewhat consistent with the sixth hypothesis. Females were in a more abducted position compared to males, but it was still in adduction, and close to a neutral position rather than an abducted position. This is also only at initial contact, while peak values were not different between the sexes, but were into abduction values at that point. A difference in peak ankle dorsiflexion between sexes was not expected, however higher dorsiflexion angles in females compared to males would suggest the female participants were in a more stable position at the ankle compared to males. Previous literature investigating differences between male and female kinetic and kinematic measures in CMJ and drop landing tasks have seen little to no difference in measures, except for males utilizing more knee flexion (Herrington & Munro, 2010; Holden et al., 2015), so the fact that there were little sex differences found in this study is somewhat consistent with previous studies.

Other results that were not included in a hypothesis that were found include main effects of fatigue for peak hip abduction and peak hip adduction moment. The analysis has shown lower angle post-fatigue compared to pre-fatigue for peak hip abduction angle and lower moment values for peak hip adduction moment. These moment values would be expected to increase as the frontal plane movement decreased, but that was not the case. This may have again been due to intercompensations at the joints through the lower limb, and although there was an increased motion at the hip, the effect of this may have been transferred down the leg to the knee and ankle, as seen by increases in ankle eversion moment. There were also jump by sex interactions for peak eversion angle, peak hip abduction angle, and trunk lean angle at initial contact. For peak eversion angle females exhibited inversion through landing in the CMJ protocol but eversion through the FMSFJ protocol. For peak hip abduction, males and females separately had higher values in the CMJ protocol compared to the FMSFJ protocol. For trunk lean angle at initial contact males had differences in their values in the CMJ protocol compared to the FMSFJ protocol. However, as was mentioned in the results section, this interaction cannot be properly interpreted due to the differences in reporting lean values in the FMSFJ and CMJ protocols. These sex differences found were not expected, but may be due to training differences or differences in muscle recruitment strategies in males compared to females.

There were no differences between males and females (sex interactions) for peak eversion, peak hip abduction angle or for trunk lean angle at initial contact. We expected to see differences in male and female movement strategies at the knee, with more flexion and less abduction in males compared to females. We did find a difference in knee abduction values but not to the extent we were expecting. These effects of jump separated by sex found for ankle eversion and hip abduction were unexpected. Earlier it was noted that females had more ankle dorsiflexion than males, and along with this increased eversion in the FMSFJ, this actually suggests that females were not in a safer position at the ankle, as they may be overloading the medial structures of the ankle in this flexed and everted position (Moore et al., 2015a).

Overall, the results of this study show higher flexion in the sagittal plane, higher medial displacement (adduction and eversion) in the frontal plane and higher excursion from initial contact to the peak angle occurring in the CMJ protocol compared to the FMSFJ protocol. Effects of fatigue were only seen in the CMJ protocol, which may indicate that this protocol is more sensitive to fatigue levels of participants or athletes being assessed. The FMSFJ protocol elicited much stiffer landings with lower flexion values and higher moments at the ankle level compared to the CMJ protocol, which, according to previous literature, is more indicative of increased risk of injury to the lower limb (Bates et al., 2013; Boyi Dai et al., 2019; Norcross et al., 2013; Shimokochi & Shultz, 2008). The CMJ protocol elicited higher moment values in hip adduction, which again, may have influenced not just the hip movement, but task execution at the knee and ankle as well. Many authors suggest using one task is likely inadequate to represent an individual’s performance or predicted risk of injury (Donohue et al., 2015; Heebner et al., 2017), and that seems to keep true with the results of the current study.

Assumptions

There are some assumptions that were made in this study. First, it had to be assumed that the participants selected are average representatives of the population being targeted. Although the participants fit the inclusion criteria, they may still have atypical movement patterns. There is no way for us to control for these atypical movement patterns, but a solution to somewhat screening them out is the use of the orientation session in which it can be assessed that the participant understands the movements required for them to complete, and that they are physically capable and coordinated enough to perform the two jumping tasks required. The participants had a chance to practice the tasks in the orientation session, as well as before their data collection if they wanted a reminder of how they are to perform the tasks. This also should have negated any learning effects that may have occurred in the study. This all may not be of importance in the current study, however, as this is a within subject design. Nevertheless, it was assumed that the population is an average representation so that the results of this study can be compared to similar studies conducted in the past.

Another assumption was that those involved are comfortable running on a treadmill, and also running on a treadmill at a high incline. Some participants voiced concern over the speed of the treadmill, and took some time to get comfortable with the speed of the run that they were asked to perform. This was alleviated in the orientation session when the participants were able to practice the incline sprint on the treadmill before needing to do it maximally in the second session protocol. No participants needed to be excluded due to fear of sprinting on the treadmill.

A third assumption was that all individuals participating are trained in jumping and landing. This was assumed by their participation in a team court or field sport, or an individual sport that includes jumping and landing or cutting movements. However, this does not outline their skill in jumping and landing, but simply their comfort or ability to perform the tasks asked of them.

Along these same lines, it was assumed that all participants were normally aligned, with normal amounts of strength and flexibility. If this was not the case, there may have been subtle differences in movement execution that could have been magnified with fatigue.

Limitations & Delimitations

A limitation to this study is an inability of ensuring absolutely maximal effort given in all fatiguing protocols. This is somewhat controlled for by the population being active, with more of a competitive nature showing in participants, asking what the longest time is and what the best manner to execute the test is. This shows that the participants were going to try and perform well, but may not perform to their absolute max if they feel they were performing at least above average. A few participants had a negative fatigue index on their sprint fatigue protocol, which suggests that they were not trying their absolute hardest on the first or second sprint, or did not fully understand that they were to go for as long as they possibly can on each sprint. This could also mean that they simply recovered quickly, and were able to perform well on all three sprints. This is possible as the participants did have longer times on their Bruce protocol, but it is unclear what this truly shows. However, subjective feedback from the participants ensured that they were indeed quite tired, and their RPE values given did indeed meet cutoff criteria for perceived maximal fatigue. Also, the 10% decrement in sprint time noted in literature to indicate fatigue was not necessarily indicating maximal fatigue, but fatigue nonetheless (Morin et al., 2011; Ruscello et al., 2013). In the current study, the average fatigue index was 36.2%, however, which is well above this 10% cut off.

A second limitation involved the comfort level of the participants. Some participants did voice concerns that if they were to continue longer in their fatigue protocol they felt they may not be able to recover their stride if they were to make a mis-step or go too close to the bottom end of the treadmill belt. This could have also contributed to lower than absolute maximum effort from the participants that voiced this concern. There was no harness set up available to negate the worry of the participants of falling off the treadmill, which may have helped get more maximal performance on the fatigue protocols. In any case, significant results did still occur, so this limitation may not have had as much of an impact as it could have.

Also, the orientation of the force plates in the lab made it difficult to get the participants to fully and completely hit the force plates in their landings without coaching them to hit or aim for the plates specifically. Many times the participant was very close to hitting the force plate accurately, but it was not a full step so could not be analyzed. This greatly reduced the number of jump repetitions that could be analyzed out of the full data set, which may have affected the variability of results.

A fourth limitation, which is tied to the third assumption, is that we did not control for sport performance level of the participants. It was only required that the participants were involved in the sports or activities outlined in the inclusion criteria, but they could have been recreationally involved or competitively involved. This may have affected the jump execution data in this study.

Another limitation was that the analysis performed for this study was joint by joint, which did not allow for direct analysis of the interrelationships between joints. However, these relationships can be discussed and we can speculate how the joints are playing a role with each other by directly looking at the results joint by joint and observing how they change with each other through fatigue conditions and in the different jump protocols.

A delimitation of this study is the use of primarily sagittal plane tasks in the jump protocols. Due to the short width of the walkway available for testing, any large laterally driven movements were not the safest option for the participants to perform. We are fully aware that this will limit the applicability of the results of this study.

Along with this, due to lack of space, the forward-moving jumps could not be leaps or bounds, which may have changed the participants natural habit of forward moving jumps. The participants may have been jumping more ‘delicately’ or carefully if they were focusing on not jumping too far forward to fit enough repetitions in on the 20 foot walkway. We also did not measure jump distance or height in this study, which may have allowed for further investigation into performance of these jump protocols.

Conclusion

Results from this study indicate that the CMJ and FMSFJ protocols are different tasks, as evidenced by the many main effects for jump type. It can also be stated that the CMJ protocol elicited more differences in movement execution between fatigue conditions. Comparing the CMJ and FMSFJ protocols, it seems that the landings produced in the CMJ protocol are less risky, as they are performed with a larger range of joint motion and larger peak joint angles in the sagittal plane. However, with the FMSFJ protocol being performed in a possibly riskier manner, this protocol may be better for assessing future injury risk in an athletic population, while the CMJ protocol may be better for assessing participant sensitivity to fatigue.

Implications of Research

This research study will contribute to the base of literature by providing normative data for a moderately active average population and how they move in a unilateral and bilateral manner, and how fatigue affects those movements.

The information learned from this study can be valuable to researchers and sport coaches or trainers alike as there is now some insight into how injuries may occur in competition, as well as later on in competition duration or season progression, as joint motions decreased post-fatigue. These injuries have the potential to be due to fatigue, which can still only be assumed. However, this research shows the relationship of fatigue and bilateral and unilateral task execution in an athletic population.

Significance

This research study focused on trunk and lower extremity kinematic and kinetic measurements of active, healthy individuals and how these mechanics may change when influenced by fatigue. The information addressed and studied in this research study can be highly relevant for coaches, physicians, therapists, and trainers to teach body awareness. The results of the research study may also therefore contribute to injury prevention and risk screening assessment in competitive athletes.

Future Directions

The current study outlined some novel aspects of jump execution, however there are always questions left unanswered. In future studies it would be beneficial to investigate individual variability for each participant, to see if there are any ‘red flags’ in the movement of a specific individual, as would be done with a clinician or team trainer. The execution of these tasks would be looked at pre-fatigue compared to post-fatigue, and if there was a large enough difference (what that is, we may not know yet) present between values for a specific variable then this may be a component of the individual’s movement that should be investigated further. Differences may be normal, or potentially may be due to muscular or neuromuscular deficits.

It would also be beneficial to look at jump performance metrics as well, such as jump distance or height, and time during contact for the two jump protocols. This information may help tell the story of how fatigue is affecting potential sport or competition performance, not just movement execution.

The data could also be stratified by performance in the Bruce protocol or sprint protocol, to see if movement execution was affected by predicted fitness levels, sprint time, or fatigue index. This may allow for insight into if fitness plays a positive, negative, or neutral role on movement execution prior to and after fatigue.

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Appendix

Appendix I: Borg RPE Scale

Rating	Perceived Exertion Descriptor
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (Heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Appendix II: Par-Q+

2018 PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	**YES**	**NO**
1) Has your doctor ever said that you have a heart condition ☐ OR high blood pressure ☐?	☐	☐
2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** ______	☐	☐
5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** ______	☐	☐
6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it ***does not limit your current ability*** to be physically active. **PLEASE LIST CONDITION(S) HERE:** ______	☐	☐
7) Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.
Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow International Physical Activity Guidelines for your age (www.who.int/dietphysicalactivity/en/).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

PARTICIPANT DECLARATION

If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness centre may retain a copy of this form for records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME ______________________ DATE ______________

SIGNATURE ______________________ WITNESS ______________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ______________________

If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at **www.eparmedx.com** before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity program.

2018 PAR-Q+

FOLLOW-UP QUESTIONS ABOUT YOUR MEDICAL CONDITION(S)

1. Do you have Arthritis, Osteoporosis, or Back Problems?
If the above condition(s) is/are present, answer questions 1a-1c — If **NO** ☐ go to question 2

1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	YES ☐ NO ☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	YES ☐ NO ☐

2. Do you currently have Cancer of any kind?
If the above condition(s) is/are present, answer questions 2a-2b — If **NO** ☐ go to question 3

2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and/or neck?	YES ☐ NO ☐
2b.	Are you currently receiving cancer therapy (such as chemotheraphy or radiotherapy)?	YES ☐ NO ☐

3. Do you have a Heart or Cardiovascular Condition? *This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm*
If the above condition(s) is/are present, answer questions 3a-3d — If **NO** ☐ go to question 4

3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
3b.	Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction)	YES ☐ NO ☐
3c.	Do you have chronic heart failure?	YES ☐ NO ☐
3d.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	YES ☐ NO ☐

4. Do you have High Blood Pressure?
If the above condition(s) is/are present, answer questions 4a-4b — If **NO** ☐ go to question 5

4a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
4b.	Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer **YES** if you do not know your resting blood pressure)	YES ☐ NO ☐

5. Do you have any Metabolic Conditions? *This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes*
If the above condition(s) is/are present, answer questions 5a-5e — If **NO** ☐ go to question 6

5a.	Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies?	YES ☐ NO ☐
5b.	Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness.	YES ☐ NO ☐
5c.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, **OR** the sensation in your toes and feet?	YES ☐ NO ☐
5d.	Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)?	YES ☐ NO ☐
5e.	Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future?	YES ☐ NO ☐

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6.	**Do you have any Mental Health Problems or Learning Difficulties?** *This includes Alzheimer's, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome*	
	If the above condition(s) is/are present, answer questions 6a-6b — If **NO** ☐ go to question 7	
6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
6b.	Do you have Down Syndrome **AND** back problems affecting nerves or muscles?	YES ☐ NO ☐
7.	**Do you have a Respiratory Disease?** *This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure*	
	If the above condition(s) is/are present, answer questions 7a-7d — If **NO** ☐ go to question 8	
7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
7b.	Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	YES ☐ NO ☐
7c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	YES ☐ NO ☐
7d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	YES ☐ NO ☐
8.	**Do you have a Spinal Cord Injury?** *This includes Tetraplegia and Paraplegia*	
	If the above condition(s) is/are present, answer questions 8a-8c — If **NO** ☐ go to question 9	
8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
8b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	YES ☐ NO ☐
8c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	YES ☐ NO ☐
9.	**Have you had a Stroke?** *This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event*	
	If the above condition(s) is/are present, answer questions 9a-9c — If **NO** ☐ go to question 10	
9a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
9b.	Do you have any impairment in walking or mobility?	YES ☐ NO ☐
9c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	YES ☐ NO ☐
10.	**Do you have any other medical condition not listed above or do you have two or more medical conditions?**	
	If you have other medical conditions, answer questions 10a-10c — If **NO** ☐ read the Page 4 recommendations	
10a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months **OR** have you had a diagnosed concussion within the last 12 months?	YES ☐ NO ☐
10b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	YES ☐ NO ☐
10c.	Do you currently live with two or more medical conditions?	YES ☐ NO ☐

PLEASE LIST YOUR MEDICAL CONDITION(S) AND ANY RELATED MEDICATIONS HERE: ____________________

GO to Page 4 for recommendations about your current medical condition(s) and sign the PARTICIPANT DECLARATION.

2018 PAR-Q+

If you answered NO to all of the FOLLOW-UP questions (pgs. 2-3) about your medical condition, you are ready to become more physically active - sign the PARTICIPANT DECLARATION below:

- It is advised that you consult a qualified exercise professional to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually - 20 to 60 minutes of low to moderate intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate intensity physical activity per week.
- If you are over the age of 45 yr and **NOT** accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.

If you answered **YES** to **one or more of the follow-up questions** about your medical condition:

You should seek further information before becoming more physically active or engaging in a fitness appraisal. You should complete the specially designed online screening and exercise recommendations program - the **ePARmed-X+ at www.eparmedx.com** and/or visit a qualified exercise professional to work through the ePARmed-X+ and for further information.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ **at www.eparmedx.com** before becoming more physically active.
- Your health changes - talk to your doctor or qualified exercise professional before continuing with any physical activity program.

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The authors, the PAR-Q+ Collaboration, partner organizations, and their agents assume no liability for persons who undertake physical activity and/or make use of the PAR-Q+ or ePARmed-X+. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.

PARTICIPANT DECLARATION

- All persons who have completed the PAR-Q+ please read and sign the declaration below.
- If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME ______________________________ DATE ______________________________

SIGNATURE ______________________________ WITNESS ______________________________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ______________________________

For more information, please contact
www.eparmedx.com
Email: eparmedx@gmail.com

Citation for PAR-Q+
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The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+ Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gledhill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or the BC Ministry of Health Services.

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Appendix III: Consent Form

panam CLINIC | Foundation

UNIVERSITY OF MANITOBA

RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM

Title of Study: An investigation of the effects of fatigue on repetitive unilateral and bilateral jump task execution

Principal Investigator: Alixandra Bellemare, BKin, Pan Am Clinic Foundation, 75 Poseidon Bay, Winnipeg, (204) 925-1558

Co-Investigators: Jonathan Singer, PhD, University of Manitoba, 179 Extended Education, Winnipeg, (204) 474-8469
Jeff Leiter, PhD, Pan Am Clinic Foundation, 75 Poseidon Bay, Winnipeg, (204) 927-2665

You are being asked to participate in a research study. Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this study and you may discuss it with your friends, family or (if applicable) your doctor before you make your decision. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand.

Purpose of Study

The incidence of lower limb injuries in physical activity and sport is high compared to incidence of upper limb injuries. The incidence of lower limb injuries in physical activity is also increasing compared to just a few years ago. It is thought that this increase in injury incidence may be due to the fact that more individuals are choosing to be active through sport, both through a wider range of age and at higher levels of intensity.

In these physical activity and sporting contexts, injuries are concentrated to the latter end of the activity, which may indicate that fatigue plays a role in injury causation. This research focuses on understanding the effect of fatigue on single leg and double leg jumping tasks in a moderately active population, to hopefully be able to determine the impact of fatigue on movement.

Study Procedures
If you participate in this study, you will be required to be at the University of Manitoba Biomechanics Lab for two testing sessions. Each session will be roughly 90 minutes in duration, making the total time requirement roughly three hours.

The first session will be an orientation session. At this orientation, your first task will be to complete a Physical Activity Readiness Questionnaire (PAR-Q Plus) and have your resting heart rate and blood pressure measured, which will indicate if it is safe for you to partake in physical activity. If you are cleared for exercise participation you will be introduced to the treadmill test that will be used, and the incline and speed of the sprint test that will be performed in the second session. You will also be asked to practice the two jumping protocols that are required in the second session, to ensure you are physically able to perform the tasks asked of you.

Prior to each session, it is requested that you limit caffeine consumption 4 hours prior to the testing session, limit alcohol consumption 12 hours prior to the testing session, limit food intake 2 hours prior to the testing session, and limit heavy or strenuous exercise at least 24 hours prior to the testing session.

Once you have been cleared to participate in the study and cleared to return for the second session of testing (comfortable with the jump and sprint protocols) you will perform a submaximal heart rate peak test. This will be performed as a maximal treadmill-based aerobic test (Bruce protocol). You will be required to wear a heart rate monitor. This test will be used to determine your specific peak heart rate, which will be used as a gauge of effort in the second testing session.

The second data collection session will include two jumping protocols and a treadmill sprint fatigue protocol. Anthropometric measurements (height, body weight, and waist circumference) will be recorded at this time for use in the biomechanical model. The biomechanical model is a mathematical model of your skeleton that is used to determine the position of your limbs in space while you are performing the tasks of the experiment.

You will be marked with reflective markers, and will wear a hear rate monitor throughout all testing. You will be asked to perform two blocks of single-leg and double-leg jumps, once before and once after a treadmill sprint fatigue protocol. During each jumping trial your movement will be measured via eight cameras set up around the perimeter of the lab that will record the reflective marker data, and force plates in the ground that will measure how you make contact with the ground.

The treadmill sprint fatigue protocol will include three maximal sprints on a treadmill raised to be inclined, with two-minute breaks between each test. You will be asked to rate your level of exertion, and your heart rate will be recorded throughout the test.

Participation in the study will be for 5 to 8 days, depending on the scheduling of your second session. The two sessions will be separated by 4 to 7 days, to ensure you are fully recovered from the first session before completing the second session.

The researcher may decide to take you off this study if unforeseen circumstances arise, such as loss of funding.

You can stop participating at any time. However, if you decide to stop participating in the study, we encourage you talk to the study staff first.

Eligibility Requirements

To be *eligible* for the study, participants must meet the following criteria:

- 18 to 35 years old
- Physically active ≥ 200 min/week
- Participates in a court or field sport, or an individual sport that involves jumping tasks at least 1x/week
- Ability to understand spoken and written English

You are *ineligible* to participate in this study if you possess any of the following:

- Serious lower limb injury, including torn ligaments or tendons, or fractures
- Acute lower extremity or back injury within the last year
- Chronic lower extremity or back injury that would impact lower limb strength or movement
- Neurological conditions
- Allergic to adhesives used in the study

Recording Devices

During all trials, a motion analysis system will record the position of each reflective spherical marker you have placed on your body. The cameras that record the position of these reflective markers only respond to infrared light and are not capable of recording images of anything other than the reflective markers (i.e. it is not possible to see images of your person, as you would see with a typical video camera). The information gathered from the position of these reflective markers is fed into the biomechanical model and used to compute the position of the participant's limbs in space while they perform the tasks of the experiment.

We will also record the forces that are exerted on the ground, using force platforms. A force platform is similar to a typical bathroom scale, except that a force platform also responds to forces applied in the front-to-back and side-to-side directions, in addition to forces in a downward direction.

Risks and Discomforts

The risks to participating in this study are very minimal. The fatiguing protocols require maximal exertion or 'best effort' in performing the submaximal peak heart rate test and treadmill sprint trials in an attempt to mimic what is possible during sport participation. This may result in some people feeling uncomfortable and/or exhausted. The jump protocols will be performed on a level walkway with no tripping hazards. Nevertheless, the risk of falling does always exist when you are moving. These tests may cause soreness in your legs immediately after testing or in the following days. This soreness typically goes away 48 hours after the exercise.

In some individuals, the adhesive tape used to affix the reflective markers to the skin has caused some redness and discomfort. If you have an allergy to adhesive tape or bandages, please make one of the investigators in the room aware of this and testing will not proceed. If, during testing, you notice that you are experiencing redness or discomfort at the sites of the reflective markers, please make one of the investigators in the room aware of this and testing will stop immediately.

Benefits

The expected benefits of this research are contributions to injury risk assessment and screening for those participating in athletic activity and competition. Apart from the opportunity to learn about how humans control their movement during jumping trials, there may or may not be direct benefit to the participants participating in the research.

Costs

All the procedures, which will be performed as part of this study, are provided at no cost to you.

Payment for Participation

You will receive no payment or reimbursement for any expenses related to taking part in this study.

Upon arriving to the university we will have provided a parking pass to cover the cost of your parking (Lot X). If you took public transportation to the university, we will have provided bus tickets to reimburse the cost of travelling to the university and to cover the cost of your return trip home.

Anonymity and Confidentiality of Data

Information gathered in this research study may be published or presented in public forums; however your name and other identifying information will not be used or revealed. Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law. All study documents related to you will bear only your assigned patient number and/or initials.

As the motion analysis cameras only record the position of the reflective markers located on your body, this data is completely anonymous. There is also no way to identify you from the forces you apply to the force platforms. You will be identified only by a participant identification code, which contains no personally identifiable information. These codes are alphanumeric cannot be linked back to any specific person.

This consent form and the bottom portion of the participant feedback form, which will contain your name and signature, will be kept in a locked filing cabinet in the principal investigator's office for five years after the completion of the study (the principal investigator's office is located behind two locked doors). Only the principal investigator will have access to the consent and feedback forms. After this time, the consent and feedback forms will be destroyed via a file shredder.

The University of Manitoba Education/Nursing Research Ethics Board may review records related to the study for quality assurance purposes.

If any of your research records need to be copied to any of the above, your name and all identifying information will be removed. No information revealing any personal information such as your name, address or telephone number will leave the University of Manitoba.

Voluntary Participation/Withdrawal from the Study

Your decision to take part in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time. If the study staff feel that it is in your best interest to withdraw you from the study, they will remove you without your consent. If you are an employee or student within the University of Manitoba or Pan Am Clinic facility, your participation and/or withdrawal from the study will not affect your performance evaluation in your job or studies.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study.

Questions

You are free to ask any questions that you may have about your participation and your rights as a research participant. If any questions come up during or after the study or if you have a research-related injury, contact the Principal Investigator, Alix Bellemare at (204) 925-1558

For questions about your rights as a research participant, you may contact The University of Manitoba, Fort Garry Campus Research Ethics Board Office at (204) 474-7122.

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

Results of the Study

All individuals who participate in this study are eligible to receive information on the outcomes of the study, via a 1-page synopsis of the key findings of the research. If you would like to receive information on the results of this study please state either your physical or electronic mailing address below:

Address: ____

City: ____

Postal code: ____

OR

Email: ____

Statement of Consent

I have read this consent form. I have had the opportunity to discuss this research study with Alix Bellemare and/or the study staff. I have had my questions answered by them in a language I understand. The risks and benefits have been explained to me. I believe that I have not been unduly influenced by any study team member to participate in the research study by any statements or implied statements. Any relationship (such as employer, supervisor or family member) I may have with the study team has not affected my decision to participate. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this study is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed. I authorize the inspection of any of my records that relate to this study by The University of Manitoba Research Ethics Board**.**

This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122 or by email at humanethics@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

Participant signature_________________________ **Date** ___________________
(DD/MM/YY)

Participant printed name: ____________________________

Relationship (if any) to study team members: _____________________________

****FOR STUDY TEAM MEMBER USE ONLY:**

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Printed Name: _______________________________ **Date** ___________________
(DD/MM /YY)

Signature: ______________________________

Role in the study: ________________________