Effect of Cyclic and Sustained Squatting Exposures on Hemodynamics and Subsequent Changes in Lower Limb Jumping Mechanics

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Occupational exposure to high knee flexion postures such as squatting or kneeling is associated with an increased risk of developing knee osteoarthritis. The exact mechanisms behind the increased risk are currently unknown. The literature is inconclusive on whether the duration spent in knee bending postures or the act of cycling through these postures is more detrimental to the knee. The goal of the study was to investigate whether the type of squat (cyclic or sustained) leads to different changes in power, neuromuscular control and lower-limb muscular blood flow parameters. It was hypothesized that sustained squatting would cause more detrimental effects to biomechanical and hemodynamic measures that are related to injury than cyclic squatting. Knee joint power, knee extensor muscle activation patterns, and lower limb kinematics were recorded before and after exposures to cyclic and sustained squats, whereas vastus medialis muscle oxygenation was measured during squat exposures.

Thirty healthy young participants (15 Male/15 Female, age: 22.3 ± 2.2 years, height: 1.70 ± 0.09 m, weight: 66.88 ± 11.16 kg) were recruited for the study. Participants completed a cyclic and sustained squatting exposure. The total time spent in a squat posture was equivalent between exposures. The cyclic squat consisted of a 40-second squat followed by 20 seconds of rest, repeated for six cycles. The sustained squat was a static squat hold of four minutes. Two countermovement jumps were performed pre and post each squatting exposure, for a total of eight countermovement jumps. Between squat exposures, a four minute standing recovery occurred. Vastus medialis muscle oxygenation was measured using near-infrared spectroscopy. Lower limb kinematics were collected using 3D-motion capture, kinetics were measured using two embedded force plates, and vastus medialis and vastus lateralis muscle activity was collected with surface electromyography.

The sustained squatting exposure was found to cause a significantly greater decrease to peak knee power from baseline compared to the cyclic squat (−0.71 W/kg and −0.33 W/kg respectively, $p = .016$). A sex difference was also found, with males experiencing greater decreases in knee power than females (−0.73 W/kg vs. −0.32 W/kg, $p = .013$). A significant interaction occurred for integrated EMG (iEMG) between muscle and phase ($p = .037$). During the deceleration phase on average iEMG values decreased from baseline values, and increased during the preparatory phase (−2.48 mV·s vs. 0.62 mV·s), with vastus medialis activity being reduced by a larger degree than vastus lateralis. Changes to tissue saturation index % during the squat exposure also displayed a sex main effect ($p = .012$), with on average males experiencing decreases and females increases (−1.97% vs. 2.60%). Regardless of squat type, the squatting exposure did not cause significant changes to frontal plane motion, delays in muscle onset or changes in percent normalized muscle oxygenation.

Historically, occupational squatting and its relationship to knee osteoarthritis has been studied from an epidemiological framework, therefore, the current study was novel in that it provided a more systematic and quantitative assessment of squatting exposures. The study demonstrated that acute exposures to high knee flexion postures cause detrimental changes to power generation, neuromuscular control and hemodynamics. The results suggested that sustained exposures were more detrimental than cyclic exposures. Sex effects indicated that males were more affected by the squatting exposures than females. Our work highlights the importance for workplace guidelines in occupations with frequent squatting to limit the duration of static high knee flexion activities, and provide ample rest between exposures.

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Chapter 1: Introduction

Osteoarthritis (OA) is a chronic disorder that affects over 10% of the Canadian population (Arthritis Alliance of Canada, 2011) with 60% of those suffering from OA reporting pain in the knee or in both the knee and hip joint (Macdonald, Sanmartin, Langlois, & Marshall, 2014). In addition to aging and obesity, occupational exposure to high knee flexion activities, such as squatting or kneeling, is a risk factor for developing knee OA (Amin et al., 2008; P. Baker, Reading, Cooper, & Coggon, 2003; Coggon et al., 2000; Cooper, McAlindon, Coggon, Egger, & Dieppe, 1994; Sandmark, Hogstedt, & Vingård, 2000; Seidler, Bolm-Audorff, Abolmaali, Elsner, & knee osteoarthritis study-group, 2008; Virayavanich et al., 2013). These high knee flexion activities (> 120º of knee flexion) are regularly performed in the workplace by carpet and tile layers (Ditchen, Ellegast, Hartmann, & Rieger, 2013; Kivimaki, Riihimäki, & Hanninen, 1992), farmers (Nonnenmann, Anton, Gerr, & Yack, 2010; Sandmark et al., 2000), aircraft luggage handlers (Stålhammar, Leskinen, Kuorinka, Gautreau, & Troup, 1986), childcare workers (P. Baker et al., 2002), and housekeepers (Dahaghin, Tehrani-Banihashemi, Faezi, Jamshidi, & Davatchi, 2009). Deep knee bending is also performed in the home during activities of daily living. Despite the extensive epidemiological research linking high knee flexion activities and knee OA, there is no consensus on the exact mechanism for the relationship. It also remains to be determined whether it is the cumulative time spent in these positions that is most important, or the number of transitions in and out of these postures. Confounding the issue is the fact that multiple characteristics of these movements could potentially be detrimental to the knee joint.

The proposed mechanism for the development of knee OA due to exposure to high knee flexion postures is multifaceted, and incorporates both biomechanical and physiological components (Figure 1.1). Exposure to high knee flexion postures, specifically squatting, causes disturbances to the blood flow of the lower limb through kinking of major arteries and veins (Brotmacher, 1957). This further causes metabolic processes of the articular cartilage to be compromised (Findlay, 2007), thus increasing the risk of cartilage degeneration and/or damage. Simultaneously, reduced muscular blood flow may lead to decreases in quadriceps strength. Quadriceps dysfunction increases the risk of knee OA and patellofemoral pain syndrome (Øiestad, Juhl, Eitzen, & Thorlund, 2015). Deficits in strength and/or power could manifest as impairments of neuromuscular control, demonstrated by delayed onset of muscle activity between the medial and lateral sides of the muscle pairs of the lower limb, and leading to reduced dynamic control of the knee joint centre (Cavazzuti, Merlo, Orlandi, & Campanini, 2010; Cowan, Bennell, & Hodges, 2000; Myer et al., 2015). This sequence of events could cause abnormal loading patterns at the knee, which would increase the risk for cartilage degradation, ultimately increasing the risk of developing knee OA or other knee disorders. In the case of cyclic exposure to high flexion postures, upon return to standing, lower limb blood flow may be elevated following intermittent compression. This could allow for partial recovery from the exposure and potentially improved function on the subsequent task (Zuj, Prince, Hughson, & Peterson, 2018).

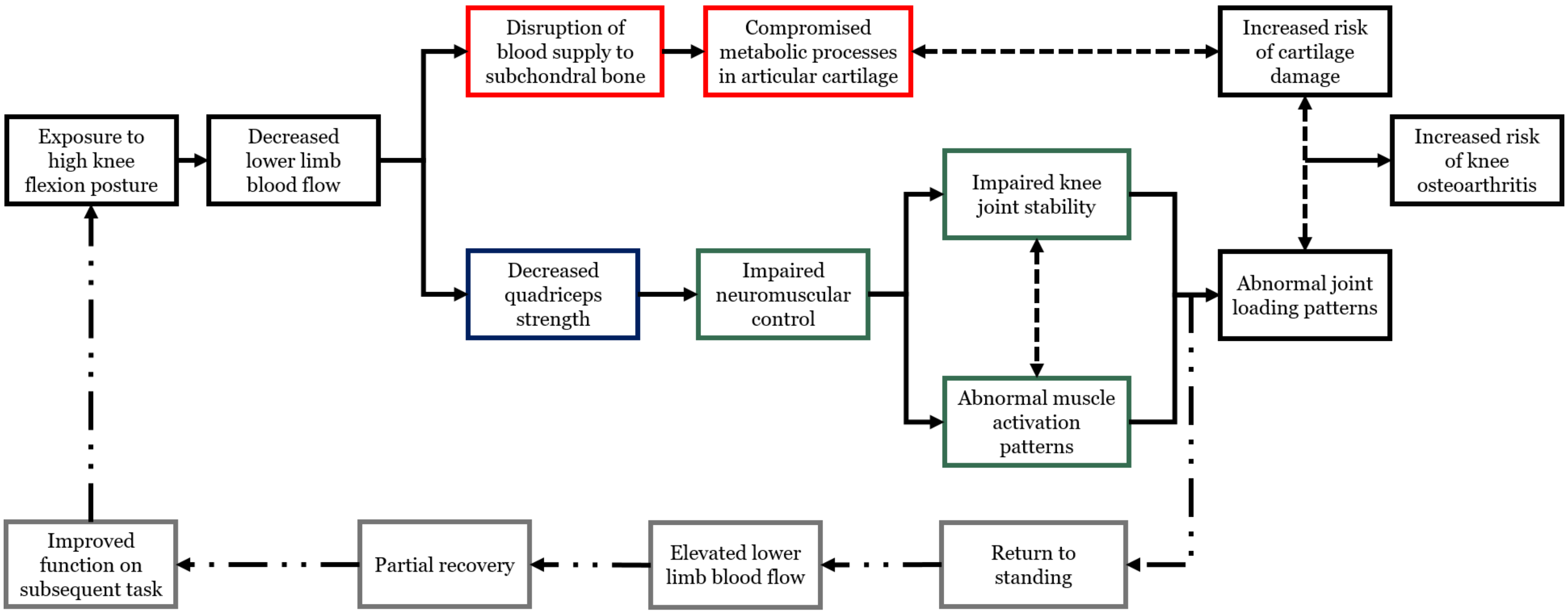


Figure 1.1 Proposed mechanism for development of knee OA. Red boxes indicate hemodynamics mechanisms. Blue box indicates muscular changes. Green boxes indicate neuromuscular control mechanisms. Grey boxes indicate cyclic squat exposure outcomes. Solid lines indicate typical squat exposure pathway. Dashed arrows with two arrow heads indicate two-way or cyclic processes. Dot-dashed lines indicate cyclic squat exposure pathway.

Chapter 2: Purpose and Hypotheses

2.1 Purpose

The primary purpose of the proposed study was to investigate the hemodynamic and biomechanical differences between cyclic and sustained squatting. Research on the differences between these two types of squatting is scarce, often considering these movements to be equivalent or, at a minimum, not specifying the temporal characteristics of the squatting exposure. The study was novel, in that it directly compared biomechanical and hemodynamic measures between sustained and cyclic squatting, potentially challenging a view of equivalent exposures. Additionally, past research investigating the influence of squatting on OA tended to be epidemiological and retrospective in nature. The study allowed for a more systematic collection on the impact of exposure to the two types of squatting from a biomechanical and physiological standpoint. A secondary purpose was to determine if one type of squat results in more detrimental biomechanical or physiological changes that could be associated with the development or progression of OA. When investigating the potential risk of developing knee osteoarthritis, blood flow of the lower limb has rarely been examined as a possible mechanism of injury. The study attempted to provide insight into what is occurring at a hemodynamic level in the local muscle blood flow.

The global objective of the study was to relate high knee flexion movements to mechanisms involved in the progression and development of knee osteoarthritis, patellofemoral pain syndrome (PFPS) and/or detrimental knee joint health, however, it was not a longitudinal study and thus cannot lead to causal evidence for disease progression. Nevertheless, if significant differences were found after acute exposures to sustained and cyclic squatting exposures in a healthy young population, it would provide insight into whether a specific type of squatting predisposes an individual to potentially harmful mechanics that could increase the risk of knee joint disease.

2.2 Hypotheses

Table 2.1 Questions and hypotheses

<table>
<tr><td>Power question</td><td colspan="2">1. Does knee joint power (measured during the takeoff phase a countermovement jump) decrease more as a result of sustained squatting, compared to cyclic squatting?</td></tr>
<tr><td>Power hypothesis</td><td colspan="2">1. The sustained squat will cause greater reductions in power than the cyclic squat exposure.</td></tr>
<tr><td>Neuromuscular control questions</td><td>2a. Does sustained squatting result in greater deficits in neuromuscular control during countermovement jumps (measured as greater deviations from joint center from plane)?</td><td>2b. Do sustained and cyclic squats create different muscle activation patterns (measured as muscle onset of medial and lateral vastii, integrated EMG during preparatory and deceleration phases)?</td></tr>
<tr><td>Neuromuscular control hypotheses</td><td>2a. Sustained squatting will result in greater deficits in neuromuscular control during countermovement jumps.</td><td>2b. Sustained squatting will cause delayed onset between lateral and medial vastii, and greater increases and decreases in integrated EMG for vastus lateralis and vastus medialis respectively in the preparatory and deceleration phase.</td></tr>
<tr><td>Blood flow question</td><td colspan="2">3. Does cyclic or sustained squatting create greater reductions in hemodynamic variables (ΔTSI%, % of Max Occlusion)?</td></tr>
<tr><td>Blood flow hypothesis</td><td colspan="2">3. The sustained squatting protocol will cause greater reductions in hemodynamic variables than the cyclic squatting protocol.</td></tr>
</table>

Chapter 3: Literature Review

3.1 Overview of Knee Osteoarthritis

Knee osteoarthritis is a degenerative joint disease. As the disease progresses, it can cause mobility issues and an inability to perform activities of daily living. The disease is defined by radiographic evidence, knee pain symptoms or a combination of the two. Radiographic definitions are the most commonly used, and are often classified according to the Kellgren-Lawrence (K-L) grade. The K-L grade for OA is based on five criteria; osteophyte formation; presence of periarticular ossicles; narrowing of joint cartilage; pseudocystic areas in the subchondral bone; changes in shape of the bone ends (Kellgren & Lawrence, 1957). K-L grades are scored from 0-4, with 0 being no indication of osteoarthritis and 4 being an indication of severe osteoarthritis (Arden & Nevitt, 2006; Kellgren & Lawrence, 1957).

Based on a longitudinal study in the US, the lifetime risk of symptomatic knee OA may be approximately 45%, with increased risk for those with knee a previous knee injury, and obesity (Murphy et al., 2008). Risk factors for the development of knee osteoarthritis can be non-modifiable or modifiable in nature. Non-modifiable risk factors include gender, age and ethnicity, modifiable factors include weight, muscular strength, activity level, occupational exposure to high knee flexion activities, and previous lower-limb injury (Arden & Nevitt, 2006; Blagojevic, Jinks, Jeffery, & Jordan, 2010; Coggon et al., 2000; Cooper et al., 1994; Murphy et al., 2008; Y. Zhang et al., 2001). Sustaining a knee injury in adolescence or young adulthood may place individuals at increased risk to develop knee OA (Gelber et al., 2000). Particularly for those who have a history of an ACL (Lohmander, Östenberg, Englund, & Roos, 2004) or meniscus injury (Ding et al., 2007; Englund et al., 2009; Takeda, Nakagawa, Nakamura, & Engebretsen, 2011). However, there is debate as to whether the risk factors for tibiofemoral and patellofemoral osteoarthritis differ (K. R. Baker et al., 2004; Thorlund et al., 2016). Gaining a better understanding of the risk factors for the development and progression of the disease could vastly decrease the burden of knee osteoarthritis on society, through increased mobility of individuals, reduction in medical costs, and continued employment.

3.2 Biomechanical Mechanisms

3.2.1 Knee Extensor Strength

Musculature of the lower-limb plays an important role for ambulation, and activities of daily movement, as well as force attenuation at the knee joint (Øiestad et al., 2015). Muscular imbalance or dysfunction could create irregular gait patterns; limit functional capacity or impair neuromuscular control. Subsequently, a reduction in knee extensor power output impairs the ability of the muscles to counteract forces at the knee joint, leading to poor neuromuscular control and abnormal loading patterns. Decreased knee extensor strength specifically has been associated with increased risk of knee OA and PFPS (Lankhorst, Bierma-Zeinstra, & van Middelkoop, 2012). Although, there is conflicting evidence on the role that muscular dysfunction plays on the development and progression of knee osteoarthritis. Further confounding the matter is research from several studies showing that a reduction in knee extensor strength may be a greater risk factor for the development or progression of knee OA for females, than it is for males (Glass et al., 2013; Slemenda et al., 1998).

Research indicates that the influence of decreased quadriceps strength on risk for development and progression of knee OA is influenced by many methodological factors. First, there appears to be differences due to study design, with longitudinal studies tending to find increased risk or progression of knee pain compared to cross-sectional studies (Accettura, Brenneman, Stratford, & Maly, 2015; Glass et al., 2013; Takagi et al., 2017). The operational definition of OA used for the study can also influence the findings. From epidemiological research, prevalence rates of knee OA tend to be greatest when using a radiographic operational definition (Pereira et al., 2011).

Females are at greater risk of developing knee OA than their male counterparts (Felson et al., 1995). There is also a sex difference in the rate of power and strength decline with age. Males lose leg extensor power at a greater rate than females (Skelton, Greig, Davies, & Young, 1994). However when normalized to weight, females had lower baseline knee extensor strength and power (Bassey et al., 1992; Skelton et al., 1994). Perhaps prevalence rates of OA are higher in females despite a more gradual decline in muscular power compared to men, because females have less power and strength at baselines, causing any decreases in these measures to be more detrimental.

Several studies using *in vivo* and *in vitro* methods have found decreased knee extensor strength to be a risk factor for the development of radiographic knee OA (Culvenor, Ruhdorfer, Juhl, Eckstein, & Øiestad, 2017; Øiestad et al., 2015; Rehan Youssef, Longino, Seerattan, Leonard, & Herzog, 2009; Slemenda et al., 1998; Takagi et al., 2017; Thorlund et al., 2016). In a large cross-sectional study of Chinese individuals, quadriceps weakness was found to be associated with increased risk of both patellofemoral and tibiofemoral knee OA in women, for men the trend was only seen for patellofemoral OA (K. R. Baker et al., 2004). Specifically, quadriceps weakness increased the odds ratio for lateral patellofemoral OA, more so than medial. It was suggested that vastus medialis dysfunction might cause abnormal loading of the lateral patellofemoral joint, leading to greater likelihood of degeneration. Similar findings regarding the relationship between knee extensor strength and symptomatic incidence of knee OA have been demonstrated in systematic reviews and meta-analyses (Culvenor et al., 2017; Øiestad et al., 2015).

There is evidence to suggest that females are at greater risk of developing knee OA due to decreases in knee extensor strength. Even after normalizing strength to body weight, a significant relationship between decreased knee extensor strength and risk of knee OA was only found for females (Slemenda et al., 1998), this was also true for persons with history of meniscal pathology (Thorlund et al., 2016). In a large longitudinal study, examining knee extensor strength in community dwelling adults, in which knee extensor strength was not normalized to body weight, strength did not predict risk of developing knee pain symptoms in both males and females (Segal et al., 2010).

In vitro research involving chemically induced unilateral quadriceps weakness in the knees of rabbits demonstrated that greater joint degeneration occurred in the experimental group compared to controls (Rehan Youssef et al., 2009). Both groups showed evidence of degeneration, however the Mankin grades, a histological scale used to measure articular cartilage, found different patterns of degeneration between the two groups, with the experimental group having significantly greater degeneration on the distal patellar surface, and the control group having greater degeneration in the proximal region. However, the Mankin scores for the entire tibiofemoral joint were not significantly different between the two groups. This may be considered an extreme example, as the experimental group had an 80% decrease in quadriceps weakness compared to the unaffected limb. The greatest degeneration was found in the medial tibial and patellar cartilage. Although, the exact reason for degeneration of the knee joint was compounded by the multifaceted nature of loading at the knee.

There is currently not a consensus on how quadriceps muscle weakness influences the progression of radiographic and symptomatic knee OA. Radiographic knee OA is thought to progress at 3-4% per year on the KL Grade (Felson et al., 1995). A recent longitudinal study over the course of 34 years based on a Japanese cohort found that after adjusting for age and body mass index, quadriceps weakness was strongly related with increased risk of radiographic knee OA in both sexes but not with progression (Takagi et al., 2017). Palmieri-Smith et al. (2010) found that females with no or doubtful signs of OA, based on K-L scores had greater quadriceps strength than those classified with minimal or moderate/severe OA. However, the relationship was not linear, as they failed to find evidence of an increased deficit in strength between females with minimal OA and those with moderate/severe radiographic OA.

Conversely, an American-based longitudinal 5-year study found that there was a significant progression of knee pain, as measured by the WOMAC pain scale, associated with decreased quadriceps strength from baseline in females but not males (Glass et al., 2013). Glass et al. (2013), explicitly did not rely on radiographic measures to evaluate progression of knee OA, and used a symptomatic definition of the disease, arguing that pain and radiographic evidence are not always correlated. Additionally, greater knee extensor strength at baseline was found to be associated with greater progression of radiographic tibiofemoral knee OA in participants who were classified as having varus-valgus misalignment and greater knee laxity (Sharma, Dunlop, Cahue, Song, & Hayes, 2003). Participants in the malalignment group had greater progression of knee OA than the neutral alignment group, regardless of their knee extensor strength. Within the malalignment group, having "high" quadriceps strength nearly doubled the rate of progression. For patellofemoral radiographic OA the authors did not find a relationship between knee extensor strength and disease progression. Another possible reason for the discrepancy in the findings may be that knee extensor strength may affect different areas of knee cartilage. A 2009 study found that greater quadriceps strength may be protective for the patellofemoral joint but have no association with the tibiofemoral joint (Amin et al., 2009). This again highlights the importance of past literature in defining both their criteria used to define knee OA, as well as distinguishing between patellofemoral and tibiofemoral types of the disease.

3.2.2 Knee Extensor Power

There is evidence to suggest that knee extensor power may be more important than knee extensor strength for the development and progression of knee OA. Lower leg power is correlated with poorer mobility and performance of activities of daily living in an elderly population (Bassey et al., 1992; Foldvari et al., 2000; Puthoff, Janz, & Nielson, 2008; Skelton et al., 1994) as well as those with knee OA (Accettura et al., 2015; Berger, McKenzie, Chess, Goela, & Doherty, 2012). The role that knee extensor power plays in the progression and development of knee osteoarthritis is inconclusive. Reduced knee extensor power has been associated with increased incidence of knee pain, although the trend was not statistically significant (D. J. Hunter, March, & Sambrook, 2003). There is evidence to suggest that knee extensor power may be a better predictor of knee osteoarthritis and function than knee extensor strength (Accettura et al., 2015; Berger et al., 2012; Calder et al., 2014; Puthoff et al., 2008). Confounding the research is debate over the best methodology to study the influence of lower limb power on knee osteoarthritis. Power measured at lower loads appears to be a better indicator of knee pain and mobility, although there is no consensus on what intensities are ideal (Berger et al., 2012; Puthoff et al., 2008).

Discrepancies may be partially explained by inconsistency in measurement, as a standardized method does not exist (Tevald et al., 2016). Previous literature has measured power through the use of a leg press, knee extensor machines or dynamometers, additionally it has been measured unilaterally or bilaterally. One study comparing leg press and knee extensor machines found that bilateral leg press was a stronger predictor of physical functioning in an OA population than unilateral knee extensor, although there was not a significant difference (Tevald et al., 2016). Knee extension is a single-joint exercise, while the leg press can be considered multi-joint. Therefore, the leg press may include activation of less targeted knee muscles than the knee extension movement, thereby activating knee and hip extensors/flexors.

Knee power may also be measured by the use of a vertical jump. This technique is also sensitive to methodological concerns. Primarily the adoption of a countermovement during the vertical jump can influence results. With maximal vertical jumps, the inclusion of a countermovement significantly increases the vertical height (Bobbert & Casius, 2005). Additionally, the use of arms during jumping has been shown to increase peak power values by a larger margin for male participants than females (M. S. Walsh, Böhm, Butterfield, & Santhosam, 2007).

3.2.3 Neuromuscular Control

The goal of neuromuscular control is for the nervous system to optimally control dynamic joint stability (Risberg, Mørk, Jenssen, & Holm, 2001). For the purposes of this literature review, two components of neuromuscular control will be investigated; muscle activation patterns and frontal plane motion. Those with knee OA, patellofemoral pain syndrome (PFPS) or ACL deficiency have exhibited abnormal muscle activation patterns, both in terms of onset and amplitude, and excessive frontal plane motion (Bley et al., 2014; Cavazzuti et al., 2010; Chester et al., 2008; Cowan, Bennell, Hodges, Crossley, & McConnell, 2001; Hughes, Watkins, & Owen, 2008; Myer et al., 2015). Neuromuscular control deficits have also been linked to increased risk of injury (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Myer, Ford, Khoury, Succop, & Hewett, 2011). Vertical jump protocols have been used to assess neuromuscular control in healthy participants (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007). High knee flexion postures may lead to decreased neuromuscular control because these movements create a reduction in muscular blood flow to the lower extremities. This reduction or possibly complete occlusion of blood flow to muscles of the lower limb impairs the functioning of the muscles and places an increased burden on the knee joint to withstand forces acting upon it.

3.2.4 Muscle Activation Patterns

Asymmetric onset of the lower limb musculature can cause abnormal loading on the knee joint. Activation of the vastus lateralis and vastus medialis cause the patella to be pulled in the lateral or medial direction, respectively (Miao, Xu, Pan, Liu, & Wang, 2015). Therefore, if there is delayed onset of activation between the two muscles it could lead to abnormal patellar tracking. Based on *in vitro* research, reduced vastus medialis muscle activation has been found to cause an increased patellar lateral shift (Sakai, Luo, Rand, & An, 2000). However, the clinical relevance of the magnitude of the shift created by asymmetric vastii activation is questioned (Lorenz et al., 2012; Sawatsky, Bourne, Horisberger, Jinha, & Herzog, 2012). It is important to note that neither study specifically measured patellar tracking in high knee flexion.

Previous research has shown that the activation patterns of the quadriceps muscles are influenced by pain and knee disorders. Specifically, a delayed onset of activation of the vastus medialis compared to the vastus lateralis has been associated with knee OA, patellofemoral pain syndrome (Cavazzuti et al., 2010; Cowan et al., 2001), and anterior knee pain (Chester et al., 2008). However, the findings are not unanimous as several studies have failed to find a difference in activation patterns between symptomatic and asymptomatic PFPS individuals (Bolgla, Malone, Umberger, & Uhl, 2011; Karst & Willett, 1995). Inconclusive findings may be due to the fact that there is not a standardized method to calculate muscle onset (Hodges & Bui, 1996), as well as differences in the movement used to elicit activation (Cowan et al., 2001), or the physical activity level of the participant (Briani et al., 2016).

Individuals with knee OA have exhibited altered neuromuscular activation patterns in different activities, although neuromuscular responses in gait have been the most extensively researched. Those with mild to moderate knee OA have been shown to have greater activation of the vastus lateralis and reduced activity of the medial head of the gastrocnemius (Hubley-Kozey, Deluzio, Landry, McNutt, & Stanish, 2006). The study population may not be entirely representative of the overall OA group, as inclusion criteria targeted high functioning individuals and the majority of the participants had a K-L grade of II, which is considered mild OA. A requirement for participation in the study was being able to jog 5 meters, a task that would be difficult for those with severe OA. Research that has compared moderate and severe OA groups, have shown that different muscle activation strategies are used between the groups (Astephen, Deluzio, Caldwell, Dunbar, & Hubley-Kozey, 2008; Rutherford, Hubley-Kozey, & Stanish, 2013). Severe OA has been associated with greater medial gastrocnemius activity in early stance (Astephen et al., 2008; Rutherford et al., 2013) and reduced activation of vastus medialis and greater vastus lateralis activation (Rutherford et al., 2013). Additionally, a 2004 study investigating the duration of muscle activity showed that participants with grade II OA or greater activated their vastus lateralis muscles for a longer duration than the control participants (Childs, Sparto, Fitzgerald, Bizzini, & Irrgang, 2004). The walking speed with which gait trials were collected has been shown to influence the results (Hunt, Wrigley, Hinman, & Bennell, 2010; Zeni, Rudolph, & Higginson, 2010). The vastus medialis is important during the descent phase of squatting, as it is activated to a greater extent than the other quadriceps muscles (Dionisio, Almeida, Duarte, & Hirata, 2008). Abnormal activation of this muscle may lead to detrimental movement patterns.

Characteristics of muscle activation such as magnitude and duration are also important for risk of knee injury. Several studies have investigated muscle activation patterns during landing tasks

(Ebben et al., 2010; Gehring, Melnyk, & Gollhofer, 2009). For the quadriceps muscles, peak activation was found to occur within the first 100 ms after initial contact (Cowling & Steele, 2001; Fagenbaum & Darling, 2003). Although, the researchers did find quadriceps activation prior to landing. Greater overall activation (peak, and integrated EMG) of the quadriceps during the landing phase is believed to increase the vertical ground reaction force and reduce energy absorption at landing (Hewett, Myer, & Ford, 2006). More specifically, a reduction in medial quadriceps activation and greater lateral quadriceps activity is thought to put the knee at greater risk of ACL injury by placing the knee in a greater valgus position (Myer, Ford, & Hewett, 2005). Increased vastus lateralis integrated EMG during the preparatory phase of landing has been determined as a predictor of proximal tibia anterior shear force (Sell et al., 2007). Activation of the knee extensors in the time immediately following initial contact (deceleration phase) is required to reduce knee flexion occurring at impact (Fagenbaum & Darling, 2003). The knee joint is reported to contribute from 31 to 37% of the work needed to decelerate the body in landing (Devita & Skelly, 1992). Less knee flexion during the deceleration phase of landing is associated with increased normalized vastus lateralis activity, decreased energy absorption at the knee and increased frontal plane motion (Pollard, Sigward, & Powers, 2010). Greater vastus lateralis iEMG has also been found in females with PFPS compared to healthy subjects during the propulsion phase of a single leg triple hop task (Bley et al., 2014). Based on this information, an increase in iEMG, determined as an increase from baseline values to post squat exposure values for the purposes of the current study, will be considered as a muscle activation pattern potentially leading to increased risk of knee injury.

Sex differences have been found for muscle activation patterns during jumping protocols. At landing, females exhibit greater MVIC normalized quadriceps muscle EMG activity than males (Chappell et al., 2007; Fagenbaum & Darling, 2003). Additionally, it has been shown that vastus lateralis activation was delayed and occurred closer to initial contact in females than males (Gehrig, 2009). However, the lateral thigh muscles were more likely to be activated prior to medial thigh muscles. The researchers failed to find any statistical differences in integrated EMG during the preparatory phase between the sexes for the vastii or hamstring muscles. Greater asynchrony of lateral and medial quadriceps activation was found in female participants, which the researchers suggest may reduce control of frontal plane motion. Several studies have failed to find significant sex differences in jumping and landing (Cowling & Steele, 2001; Medina, Valovich, Howell, & Kingma, 2008).

3.2.5 Frontal Plane Motion

Excessive frontal plane motion is a second component of neuromuscular control related to knee disorders. Greater frontal plane knee motion has been associated with increased risk of non-contact anterior cruciate ligament (ACL) injuries (Hughes et al., 2008; Paterno et al., 2010; Quatman & Hewett, 2009) and patellofemoral pain syndrome (Myer et al., 2015). Frontal plane knee motion has been used as an assessment tool to indicate athletes who may be at greater risk of injury (Myer et al., 2011). A longitudinal study found that female athletes who sustained non-contact ACL injuries displayed greater knee abduction angles and had larger knee abduction moments during landing tasks (Hewett, Myer, et al., 2005). Females are reported to be up to eight times more likely to sustain a non-contact ACL injury than their male counterparts in comparable sports (Hughes & Watkins, 2006). An increased prevalence of ACL injury is important as a history of ACL injuries places individuals at a higher risk for developing knee osteoarthritis (Lohmander et al., 2004).

Patellofemoral pain syndrome incidence rates are also greater in females (Boling et al., 2010; Lankhorst et al., 2012). One possible explanation for these gender differences in injury prevalence is that females produce significantly greater maximum knee valgus angles than males (Hughes et al., 2008; Nakagawa, Moriya, Maciel, & Serrão, 2012). However, when exposed to a fatiguing protocol, peak knee abduction was found to increase for both males and females (McLean et al., 2007). Excessive frontal plane motion may place additional stress on the patellofemoral joint. Patellofemoral joint contact area was found to increase as knee flexion increased (Besier, Draper, Gold, Beaupré, & Delp, 2005). Force on the patellofemoral joint also was greater when the knee was flexed at 90º (Escamilla et al., 2009). Therefore, the patellofemoral joint may be at greater risk of injury during movements of deep flexion in individuals with poor neuromuscular control. Findings on the relationship between frontal plane motion and PFPS are inconclusive. No differences in frontal plane motion were found between controls and those with PFPS during an eccentric leg press (Liebensteiner et al., 2008). Conversely, a study involving recreational athletes performing a weight-bearing stepping task, found that females had greater knee abduction compared to males, and those with patellofemoral pain syndrome exhibited even larger angles than healthy controls (Nakagawa et al., 2012).

3.3 Physiological Mechanisms

3.3.1 Influence of Squatting on Cardiovascular Measures

Exposure to high knee flexion postures is not only potentially harmful from a biomechanical perspective, but also from a physiological one. Squatting specifically has been extensively examined from a cardiovascular standpoint. Multiple studies have demonstrated that squatting is associated with an increase in systolic blood pressure, pulse pressure, and mean arterial pressure (Krediet et al., 2005; Murakami, 2002; O'Donnell & McIlroy, 1962; Rossberg & Peňaz, 1988; Sharpey-Schafer, 1956; R. Zhang et al., 2009). The opposite effects have been shown when returning to a standing following squatting (Rossberg & Peňaz, 1988).

Higher systolic blood pressure (Lo et al., 2017; Yoshimura et al., 2012) and pulse pressure (Lo et al., 2017) have been found to be associated with a greater occurrence of radiographic incidence of knee OA. Pulse pressure is the difference between systolic and diastolic blood pressure, and is believed to be an indication of arterial stiffness (Steppan, Barodka, Berkowitz, & Nyhan, 2011). A 2016 study found that arterial stiffness was associated with increased severity of hip OA (Tootsi, Kals, Zilmer, Paapstel, & Märtson, 2016). However, the study failed to find a significant relationship for knee OA, which may have been partially due to the small sample size.

The squatting protocols used in previous research have varied greatly. Tschakovsky et al. (2011) investigated how squat durations influence hemodynamic responses by comparing three different sustained squat durations (10-seconds, 1-minute and 5-minutes). They found that there were significant differences from baseline measures dependent on the length of the squat; as squatting duration increased, mean arterial pressure (MAP) and cardiac output also increased. The 5-minute squat also had the greatest decrease in MAP following the squat. However, at one minute post-squat there were no statistical difference in MAP between the different squats.

3.3.2 Cartilage Health

Articular cartilage is an avascular structure (Sophia Fox, Bedi, & Rodeo, 2009). However, vascularization may occur due to abnormal angiogenesis, which would impair the structural integrity of the cartilage putting it at increased risk for degeneration (Haywood & Walsh, 2001; D. A. Walsh, 1999). An *in vitro* study examining rabbit knees demonstrated that occlusion of the popliteal artery caused a decrease in blood flow and in partial pressure of oxygen (PsO2) in the synovial fluid of the knee joint (Ferrell & Najafipour, 1992). The researchers suggested that low PsO2 could be detrimental to metabolic processes occurring in the knee cartilage, putting the cartilage at increased risk for damage and degeneration. Anastomosis of the knee joint is impacted by articular degeneration, with increasing articular damage causing more abnormal vascular structures at the patella (Björkström & Goldie, 1980).

The exact relationship between intra-articular pressure and osteoarthritis remains unclear. However, there appear to be several manners in which they are related. For example, a known risk factor for osteoarthritis is obesity (Toivanen et al., 2010), obesity can also cause increased intra-articular pressure (Findlay, 2007). Inflammation of the knee joint has been shown to raise intra-articular pressure, which could lead to decreases of blood flow to the synovial membrane (Haywood & Walsh, 2001). Additionally, acute bouts of increased intra-articular pressure lead to hypoxia in subchondral bone (Grølund, Kofoed, & Svalastoga, 1984). There is evidence to suggest that subchondral bone blood flow disruption may be detrimental to nutrient diffusion in articular cartilage as well as potentially leading to osteocyte death, bone resorption and articular damage in those with OA (Findlay, 2007). These mechanisms could create an increasingly detrimental environment in the articular cartilage. An important note is that maximal intra-articular pressure occurs at full flexion, this provides a potential vascular influence for why occupational high knee flexion is related to harmful knee health (Nade & Newbold, 1983; Pedowitz et al., 1989).

3.3.3 Impact of Squatting on Blood Flow

The impact of a squatting position on blood flow of the lower limb has been extensively studied, using a variety of squatting durations (Brotmacher, 1957; Sharpey-Schafer, 1956; Tschakovsky, Matusiak, Vipond, & McVicar, 2011). One study that compared different durations of squats, found that 1 minute post-squat, the 5-min squat had significantly greater two-leg blood flow than following a 1-minute or 10-second squat (Tschakovsky et al., 2011). This was found despite the fact that, at their lowest point post-squat, two-leg blood flow did not significantly differ between the squat durations. This finding suggests that the recovery response of lower limb blood flow post-squat was influenced by the duration of the occlusion. Increasing squatting duration caused an increase in the reactive hyperemic response, this overcompensation of blood flow into the limb could be due to the longer exposure of the lower limb to hypoxic conditions. Tschakovsky et al., (2011) did not report blood flow during the squat. Blood flow was determined from the resting diameter of the right common femoral artery while in supine and the mean blood velocity obtained during 1-minute post squat from pulsed Doppler ultrasound. This value was then doubled to determine two-leg blood flow. Previous studies have also found that there was a lack of blood flow or an undetectable amount in the peripheral arteries of the lower leg during squatting (Raghavendra, 2012). Pilot research from the Biomechanics of Human Mobility Lab (2017), using an ultrasound Doppler determined that although blood flow was reduced in high knee flexion postures, there remained an inflow of blood. The assumption that there is complete occlusion of blood flow in squatting might be due to lower resolution of previous imaging devices used in past research.

Occupational exposure to high knee flexion movements could cause ischemia to the knee joint. There is evidence to suggest that PFPS may be caused by abnormal vascular pathology, although the evidence is inconclusive in knee OA (Waryasz & McDermott, 2008). Venous stress in the knee joint has also been shown to alter the rate of bone and cartilage formation (Brookes & Helal, 1968). The role that ischemic events play in the development and progression of knee joint pathophysiology needs to be further explored.

3.3.4 The Influence of Reduced Blood Flow on Strength, Power, and Fatigue

Blood flow occlusion resistance training, also known as Kaatsu, has been used as a means to improve muscular strength. Kaatsu training involves either intermittent or continuous occlusion of blood flow of a limb. The occlusion may occur during exercise or prior to. The goal of Kaatsu training is to place additional stress on the muscular system in order to achieve greater improvements in strength, power or muscle size. The safety of Kaatsu protocols has been questioned. Some studies have suggested that the duration of ischemia in blood flow restriction training is significantly less than that expected to result in muscle tissue damage; it is the combination of ischemia with muscular contractions that places the tissue at risk of damage (Umbel et al., 2009). Although, most studies investigating this issue have based their conclusions on the development of delayed onset muscle soreness (DOMS), and it is unclear the exact mechanism for why DOMS occurs.

Complete occlusion of blood flow to the brachial artery resulted in greater decreases in maximal voluntary isometric contractions and integrated EMG activity (Yasuda et al., 2009). Additionally, participants were physically unable to complete the final phase of the experiment under complete occlusion, despite the load being at 20% 1RM. Continuously applied occlusion, whether partial or complete, resulted in greater fatigue measured as volitional task failure on a knee extension task, than intermittently applied manual occlusion (Cook, Clark, & Ploutz-Snyder, 2007). Intermittent low pneumatic compression (~ 70 mmHg) of the lower leg during muscle relaxation has also been found to cause elevated blood flow during exercise and recovery (Zuj et al., 2018). Furthermore, after exposure to a continuous blood flow restriction protocol, tissue oxygenation saturation of the vastus lateralis did not return to baseline during a 90-second rest period, whereas it returned to baseline following non-restricted blood flow trials (Downs et al., 2014). The authors argued that oxygen was depleted following the first set of leg press exercises completed under blood flow restriction, with this reduced availability of oxygen limiting the work done in the subsequent sets. This suggests that there may be an optimal level of occlusion of blood flow that is beneficial for muscle growth, occlusion outside of this range may impair neuromuscular function.

There are several limitations with the Kaatsu research. First, the amount of venous or arterial occlusion applied is not standard between protocols. Occlusion pressures may be determined based on baseline blood pressure rates, a predetermined range, or individualized based on imagining techniques (Fahs, Loenneke, Rossow, Thiebaud, & Bemben, 2012). Second, there is evidence to suggest that the width of the occlusion cuff can influence the results (Loenneke et al., 2012; Neto et al., 2016). Third, the duration of occlusion has also varied greatly between studies, with several studies failing to report the actual durations, others noting that it was applied as tolerated. Lastly, participants tend to be young, active, males. However, there may be a sex effect for blood flow restrictive training. Young healthy females have been found to have greater endurance during a low intensity knee extension protocol with restricted blood flow than males (Labarbera, Murphy, Laroche, & Cook, 2013). Therefore, a more standardized protocol is required to allow for precise comparisons between research studies, as well as the inclusion of a broader population. Kaatsu training is not a perfect correlate to the effects of occupational squatting. Kaatsu training involves systematically applying a reduction in blood flow to the lower limbs, which is also a consequence of squatting. However, in occupational settings individuals may be engaging in postures that result in blood flow occlusion far more frequently than exhibited in a typical Kaatsu training program.

3.4 Occupational Squatting

Previous research on occupational high knee flexion postures has shown that individuals who are exposed to high knee flexion postures such as squatting or kneeling, are at an increased risk of developing knee osteoarthritis, meniscal injury or knee pain (P. Baker et al., 2003; Coggon et al., 2000; Cooper et al., 1994; Rytter, Jensen, & Bonde, 2008). Additionally, frequent knee bending was associated with a greater risk of cartilage knee lesions, especially in the patellofemoral region (Teichtahl et al., 2010; Virayavanich et al., 2013). However, there is not a consensus on whether the increased risk is due to the time spent in the postures, the number of transitions through these postures or the estimated lifetime exposure. Further confounding the issue is that previous studies often do not differentiate between the type of high knee flexion activities, for example squatting and kneeling exposures are largely included together. Analyses that have separately reported the two movements have shown differences in risk rates between them. Several studies have shown that squatting has a higher odds ratio than kneeling (Cooper et al., 1994; McWilliams, Leeb, Muthuri, Doherty, & Zhang, 2011), although other studies have found no significant difference between the two (Lau et al., 2000; Yoshimura et al., 2004).

Of the studies that do examine squatting specifically there is no consensus on what durations place individuals at increased risk for knee osteoarthritis. The daily exposure elevated risk threshold defined in studies has varied from 30 minutes/day to over 2 hours/day (Manninen, Heliövaara, Riihimäki, & Suomalainen, 2002). Research that investigated daily exposure to high flexion movements found that time spent in squatting differed vastly between occupations with high knee flexion activities. Unsupported kneeling was found to be the most common activity overall, however squatting accounted for up to 80% of the work shift for cobblestone layers (Ditchen, Ellegast, Gawliczek, Hartmann, & Rieger, 2014). Squatting for over 5 minutes an hour is associated with increased risk for musculoskeletal pain in the lower limbs (Andersen, Haahr, & Frost, 2007).

Exposure to squatting postures in occupational settings has been thoroughly investigated from an epidemiological perspective. Past research has reported odds ratio of increased risk of developing knee OA based on estimated length of time spent in squatting/kneeling postures or the number of times that a person knelt or squatted. Wide ranges of odds ratios have been reported from under one to seven times greater risk of developing knee osteoarthritis, implying that in some cases, squatting may potentially be beneficial to reducing knee osteoarthritis. Findings may change depending on the adjustments made to the analysis. Studies have adjusted odds ratio for age, sex, obesity, presence of Heberden's nodes and/or previous knee injury (Yoshimura et al., 2004). A meta-analysis showed that unadjusted odds ratios resulted in higher odds ratios than when the analysis was adjusted for potentially confounding variables (McWilliams et al., 2011).

Few studies have directly compared duration and frequency of exposure. Baker et al. (2003), determined odds ratios for developing meniscal injury and knee pain based on posture durations as well as the number of transitions through high knee flexion postures that individuals completed in a day. The study included over 1400 men between the ages of 20-59 years. The researchers found that squatting for over an hour during the course of a workday was associated with an OR of 2.5 (95% CI 1.2-4.9), while transitioning from a kneeling or squatting posture over 30 times per workday had an OR of 1.9 (95% CI 1.0-3.8), providing preliminary support that longer duration may be more detrimental to knee health than higher frequency.

Another limitation of the literature is that there is a heavy reliance on self-reporting of exposures to deep flexion positions. Participants are required to recall the occurrence of certain movements performed over the course of decades or their entire lifetime. A 2009 study demonstrated that when asked to self-report the amount of time spent in different postures during a workday, individuals tended to overestimate all postures other than standing, specifically mean time spent in a crouched, kneeling or squatting posture was self-reported as over three times the actual amount of time spent in the pose (Teschke et al., 2009). In the study, observational data were collected every minute and then summed, then compared to self-reports. This relationship of overestimation of durations in knee-straining postures has been previously found (Ditchen et al., 2013). The researchers showed that even immediately following a collection period, participants often overestimated duration, whereas they had good to moderate ability to recall total number of exposures to the postures. Six-months post observations, overestimation of durations in knee-straining postures was even greater. Therefore, this demonstrates that ability to recall completion of postures over decades is suspect to misrepresentation.

There is conflicting evidence to suggest that the relationship between the risk of developing knee osteoarthritis due to occupational exposure to kneeling and squatting is linear. Multiple studies have found as exposure to occupational kneeling and squatting increased, the risk of developing radiographic knee OA also increased (Jensen & Kirkeskov Jensen, 2005; Seidler et al., 2008). The rate at which exposure doubled the risk for males ranged from 12,900 hours cumulatively spent in these positions, when adjusted for age, area, BMI, and lifting (Seidler et al., 2008) to between 3,474 to 12,244 hours when using a regression formula that accounted for more potentially confounding variables (Klussmann et al., 2010). Females in the study had increased risk at lower cumulative exposures than males. Males reported greater occupational exposure kneeling/squatting than the females, resulting in different exposure categories between the two groups. However, a recent meta-analysis found that the relationship was better explained by a quadratic fit (Verbeek et al., 2017).

Historically, the focus has been on occupational exposures of male workers to high knee flexion, despite the fact that females may be exposed to these postures in their workplaces as well. A 2010 study, found that of over 100 female controls contacted, 37.3% had been exposed to kneeling or squatting in the workplace (Klussmann et al., 2010). Of females who went on to develop symptomatic knee osteoarthritis, 49.1% reported being exposed to these knee-stressing postures. Females who engaged in occupations with regular squatting, knee bending or heavy lifting showed greater risk of cartilage defects, especially in the patellar region (Teichtahl et al., 2010). Housekeeping, although not statistically significant was found to be positively associated with knee OA (Dahaghin et al., 2009).

3.5 Summary of Literature Review

This literature review has established the following main points and provides motivation for the proposed study:

1. Decreased knee extensor strength and power are risk factors for the development and progression of radiographic and symptomatic knee OA and PFPS (Accettura et al., 2015; Lankhorst et al., 2012; Øiestad et al., 2015; Palmieri-Smith, Thomas, Karvonen-Gutierrez, & Sowers, 2010).
2. Impaired neuromuscular control, such as a delay in onset of the vastus medialis compared to the vastus lateralis is associated with knee OA, PFPS and anterior knee pain (Cavazzuti et al., 2010; Chester et al., 2008; Cowan et al., 2001). Additionally, greater vastus lateralis iEMG and peak activity compared to vastus medialis in the preparatory phase of landing (Myer, Ford, & Hewett, 2005; Sell et al., 2007), and excessive frontal plane motion of the knee joint are risk factors for non-contact ACL injuries, and patellofemoral pain syndrome (Hughes et

al., 2008; Myer et al., 2015). These injuries are also related to an increased incidence of knee OA (Lohmander et al., 2004).

3. Decreased limb blood flow (through the use of Kaatsu training) has resulted in greater development of DOMS (Umbel et al., 2009), reduced iEMG activity (Yasuda et al., 2009), delayed recovery of blood flow post exercise (Downs et al., 2014), and greater fatigue (Cook et al., 2007).
4. Squatting causes an increase in several cardiovascular measures related to the development of knee OA such as systolic blood pressure and pulse pressure (Lo et al., 2017; O'Donnell & McIlroy, 1962; Sharpey-Schafer, 1956). Increasing squatting duration caused an increase in the reactive hyperemic response post-squat (Tschakovsky et al., 2011).
5. Occupational exposure to high knee flexion activities has been linked to increased risk of developing knee OA and other knee injuries (Cooper et al., 1994). There is inconclusive evidence on whether it is the amount of time spent in high knee flexion postures or the total number of transitions made through these postures that is more detrimental to knee joint health (P. Baker et al., 2003).

Chapter 4: Methods

4.1 Study Population

Fifteen female and fifteen male participants were recruited for the study (Table 4.1). Participants were recruited from the university population. All participants were between 18-30 years old. Previous literature on occupational high knee flexion tasks has largely focused on males (P. Baker et al., 2003; Jensen, Rytter, Marott, & Bonde, 2012; McWilliams et al., 2011; Rytter et al., 2008; Seidler et al., 2008), neglecting to highlight the fact that females are also exposed to these positions in their activities of daily living, leisure pursuits or in their work environments (Yoshimura et al., 2004). It is also important to include both male and female participants as they exhibit different muscle activation and movement patterns, as well as different rates of knee osteoarthritis (Hughes et al., 2008; Nakagawa et al., 2012; Palmieri-Smith, McLean, Ashton-Miller, & Wojtys, 2009).

Participants were excluded if they had a current lower-limb injury or had sustained a previous injury to a knee ligament or the meniscus. They were also excluded if they had a current medical problem related to cardiovascular disease, deep vein thrombosis, Raynaud's disease, pulmonary embolism, peripheral vascular disease or diabetes.

Table 4.1 Participant demographics

	Female	Male	All
Age (years)	21.7 (± 1.7)	22.8 (± 2.6)	22.3 (± 2.2)
Mass (kg)	58.6 (± 7.0)	75.2 (± 7.9)	66.88 (± 11.16)
Height (m)	1.64 (± 0.05)	1.76 (± 0.06)	1.70 (± 0.09)
Adipose Tissue Thickness (mm)	8.9 (± 1.4)	4.6 (± 2.0)	6.7 (± 2.8)

4.2 Experiment Design

4.2.1 Experimental Set-up

4.2.1.1 ***Kinematic***

Kinematic data were collected using an 18 camera; 6-bank 3D motion capture system (Optotrak, Northern Digital Inc., Waterloo, ON, Canada) at a sampling rate of 100 Hz. The collection space was calibrated through the use of a rigid cube fitted with 16 infrared diodes using a 60-second calibration trial. A digitizing probe consisting of four infrared markers was used to define the global coordinate system (GCS) according to International Society of Biomechanics standards (Wu & Cavanagh, 1995). The laboratory setup is illustrated in Figure 1.1.

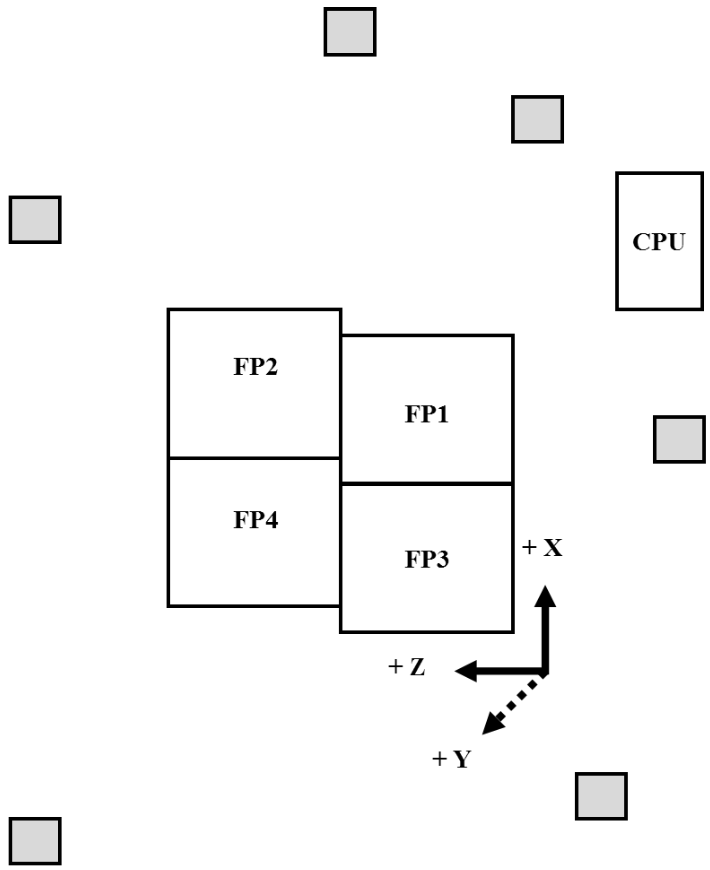


Figure 4.1 Laboratory setup

Note: the global coordinate system is represented by a positive XYZ coordinate system, with its origin relative to the force plates. The grey squares indicate motion capture cameras. FP indicates the force plate and its number.

Rigid body clusters were attached to the lateral side of the participant's dominant leg at the foot, shank, thigh, and also on the pelvis. Bony landmarks of the lower limb were digitized and used to define the segment coordinate systems (Figure 4.4).

4.2.1.2 Electromyography (EMG)

EMG was recorded using a wireless system (Wave Plus, Cometa, Cistalano, Italy). The system contains a built-in 1000x signal amplification that is non-modifiable and has a band pass filter of 10-1000 Hz. EMG was collected at a sampling rate of 2000 Hz on the right lower limb at two different sites, vastus medialis, and vastus lateralis muscles (Figure 4.2). Ag-AgCl surface electrodes (Ambu Blue Sensor N, Denmark) were used, and placed with an interelectrode distance of 2 cm (De Luca, 1997). Prior to placement of the electrodes, the areas of interest were shaved using a disposable safety razor, exfoliated, and sterilized with isopropyl alcohol. Double-sided tape was used to adhere the wireless EMG acquisition units to the limb of the participant.

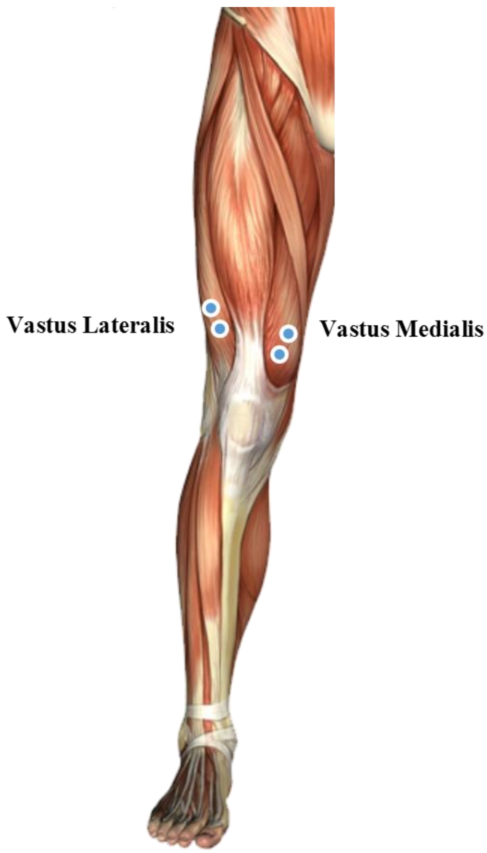


Figure 4.2 EMG electrode placement.

4.2.1.3 Kinetics

Kinetic data were collected from two embedded force plates at 2000 Hz (OR6-7, AMTI, Watertown, MA, USA). Kinetic data were used to determine force and moments during the countermovement jumps. Prior to collection, the force plates were zeroed.

4.2.2 Experimental Protocol

Prior to arrival at the laboratory, participants were sent an informational letter outlining the study. Participants were asked to remove any outdoor footwear upon entering the Biomechanics of Human Motion Mobility laboratory. Upon entry to the laboratory, participants received an overview of the procedures and then were asked to review the informational letter and provide informed consent. Participants wore shorts and athletic footwear. Height, weight and age were recorded prior to testing. Adipose tissue thickness (ATT) was found by measuring skinfold thickness above the muscle belly of the vastus medialis. Two measurements were taken at the site. ATT was calculated by taking the average skinfold thickness measurement and halving it. Brachial blood pressure was collected on the left arm of the participant. Leg dominance was determined by asking the participant to perform a series of tests including tracing a shape with their foot on the floor, stamping out an imaginary fire, and kicking a ball (Schneiders et al., 2010). Electromyography (EMG) and near-infrared spectroscopy (NIRS) data were collected from the dominant leg. Participants were familiarized with the instrumentation and movements required for the study. The study protocol is outlined in Figure 4.3.

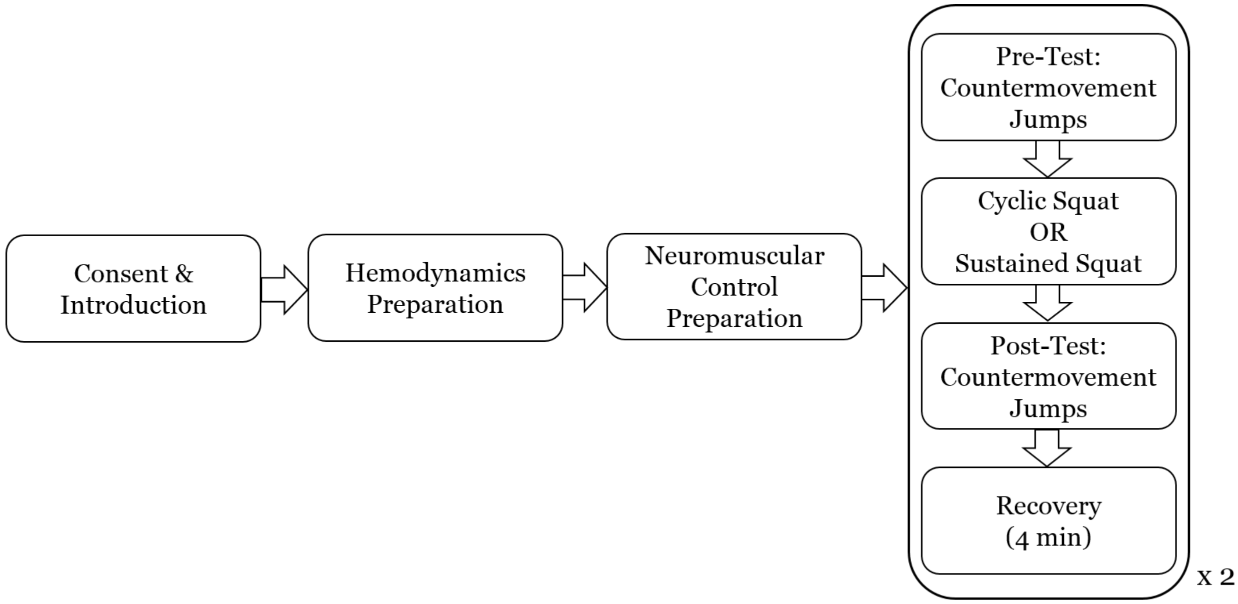


Figure 4.3 Outline of study protocol

Baseline hemodynamic trials consisted of quiet standing, seated and maximal occlusion trials. These took place following familiarization with the equipment. Participants were instrumented with one NIRS probe (PortaLite, Artinis, The Netherlands) placed on the vastus medialis muscle body. The differential pathlength factor for vastus medialis was set at 5.89. Once all equipment had been secured, the participant completed a series of baseline tests. This consisted of an approximately 3-minute seated baseline. A pneumatic cuff was placed around the proximal thigh region of the dominant leg. While the participant was seated, the cuff was set to a pressure of 300 mmHg for a duration of 5 minutes. Arterial occlusion was confirmed by observing a decrease in oxyhemoglobin concentration in the NIRS signal. The cuff was rapidly deflated upon conclusion of the maximal occlusion trial and participants remained seated for 10 minutes of recovery. During the seated recovery, participants were instrumented with EMG electrodes (Table 4.2, Figure 4.2) and motion capture markers (Table 4.3, Figure 4.4). EMG electrodes were placed following SENIAM guidelines (SENIAM, 1999).

Table 4.2 EMG electrode placement

Muscle	Location	Orientation
Vastus Medialis	Approximately 80% of the line created between the ASIS and the medial aspect of the patella.	In the same direction as the muscle fibers. Around, perpendicular to line between ASIS and medial side of patella.
Vastus Lateralis	Approximately 67% of the line created from the ASIS to lateral aspect of patella.	In the same direction as the muscle fibers. Around, perpendicular to line between ASIS and lateral side of patella.

Based on SENIAM guidelines (1999)

Prior to collection of kinematic data, bony landmarks were digitized on the participant while standing in the anatomical position (Figure 4.4). Calibration trials were collected to improve the definition of the lower segments. These trials consisted of a static reference trial as well as functional joint centre calibration trials to define both hip and knee joints for processing in Visual 3D (Schwartz & Rozumalski, 2005). A 3-second static reference trial was collected with the participant standing stationary in the anatomical position. Functional hip centre calibration trials involved the participant performing hip abduction, adduction, flexion, extension and circumduction of the hip for a total of 20 seconds on their dominant side (Besier, Sturnieks, Alderson, & Lloyd, 2003; Camomilla, Cereatti, Vannozzi, & Cappozzo, 2006). The participant also completed a functional knee joint centre calibration trial on their dominant limb, which consisted of standing on one leg and flexing and extending the other limb to approximately 100º repeatedly for 20 seconds (Besier et al., 2003).

Table 4.3 Anatomical landmarks for digitization and rigid body locations

Segment	Digitized Points	Rigid Body Location
Pelvis	R/L IC – Right/Left Iliac Crest R/L ASIS – Right/Left Anterior superior iliac spine R/L PSIS – Right/Left Posterior superior iliac spine Sacrum	Securely attached by a strap placed around the waist, and affixed over the sacrum.
Thigh	GT – Greater trochanter MEDFC – Medial femoral condyle LATFC –Lateral femoral condyle	Attached on the lateral aspect at approximately the midpoint of the region between the greater trochanter and the lateral femoral condyle.
Shank	MEDTC – Medial tibial condyle LATTC – Lateral tibial condyle MEDMAL – Medial malleolus LATMAL - Lateral malleolus TIBTUB – Tibial Tuberosity	Attached to the lateral aspect of the midpoint of the region between the lateral tibial condyle and the lateral malleolus.
Foot	HEEL – Right Calcaneus 1ST – Head of 1st metatarsal 5TH – Head of 5th metatarsal TOE – Tip of great toe	Secured to the lateral aspect of the foot below the lateral malleolus.

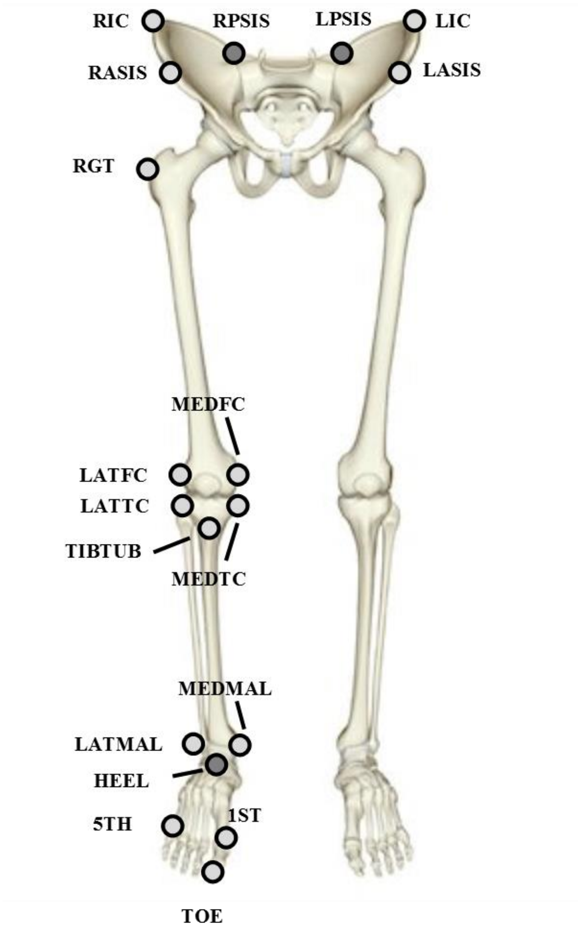


Figure 4.4 Location of digitized landmarks. Kinematic data were collected on the dominant leg, (right leg in this example).

Pre-testing consisted of two countermovement jumps. To begin the jumps, participants stood with hands akimbo, with one foot on each of the force plates. Foot width placement was not standardized; however, most participants stood approximately hip width apart. Participants were instructed to jump as high as possible. Countermovement jumps were completed without an arm swing as this is thought to limit the influence of the upper body on lower-limb force production (Feltner, Bishop, & Perez, 2004). The countermovement jump was demonstrated by the researcher, prior to any attempts by the participant.

Participants completed one to three practice jumps before the beginning of collections to become familiar with the movement. There was a 30-second standing recovery between countermovement jumps. Foot placement was not controlled between squats. Previous work has shown that foot placement and foot angle during a squat did not cause significantly different muscle activation for the vastii (Escamilla et al., 2001). Participants lowered to a self-selected depth during the countermovement. It was considered a successful jump if participants kept their arms akimbo, and landed with one foot fully on each force plate. If a jump was unsuccessful, participants completed an additional jump. No further instructions were given regarding landing technique, as this has been shown to cause acute changes to landing patterns of individuals (Mizner, Kawaguchi, & Chmielewski, 2008). Countermovement jumps were chosen as they enabled all biomechanical outcomes measures to be collected during one test. This limited the time between completion of the squat exposure and collection of the post-exposure outcome measures, thus allowing for the measurement of the acute effects of the squat exposure with minimal potential for washout. Additionally, countermovement jumps have been used previously to assess neuromuscular control in order to help identify individuals who may be at greater risk of sustaining lower limb injuries (Chappell et al., 2007).

Once all baseline measures had been collected, participants performed either a sustained or cyclic squats; the order was fully randomized. The sustained squat involved descending into a static squat position for 4 minutes whereas the cyclic squat protocol consisted of performing a series of six static squats for a duration of 40 seconds, with a 20-second standing rest between squats. The cyclic squat intervals were chosen to allow a 2:1 work to rest ratio, as well as to have the total time spent in a deep squat equivalent between the two conditions. Participants were instructed to choose either a flatfoot or heels-up squat, squatting to the lowest depth possible. They were also instructed to cross their arms across their chests and to remain as stationary as possible for the duration of the squat. Participants were requested not to use their arms for balance.

Upon completion of the squat, the participants stood quietly for 30 seconds. They then completed two countermovement jumps. After the post-tests were collected, the participant completed a 4-minute standing recovery. They then completed the other squat type (sustained or cyclic), followed by another set of post-tests.

4.2.3 Data Processing

All hemodynamic, EMG and kinematic and strength data were processed using custom Matlab (Mathworks, Natick, MA, USA) code and Visual 3D (C-Motion, Germantown, MD, USA). Biomechanical outcome measures were collected during countermovement jumps (Figure 4.5). Knee joint power was determined by taking the product of the flexion moment for the knee joint and instantaneous angular velocity of the knee (Winter, 2009).

Knee power (W) reported was the maximal value attained during the takeoff phase of the countermovement jump for each squat type. Power measures were normalized to body mass. The average over the two pre or post trials was used. Change in power was determined as the difference in power between pre and post-test values.

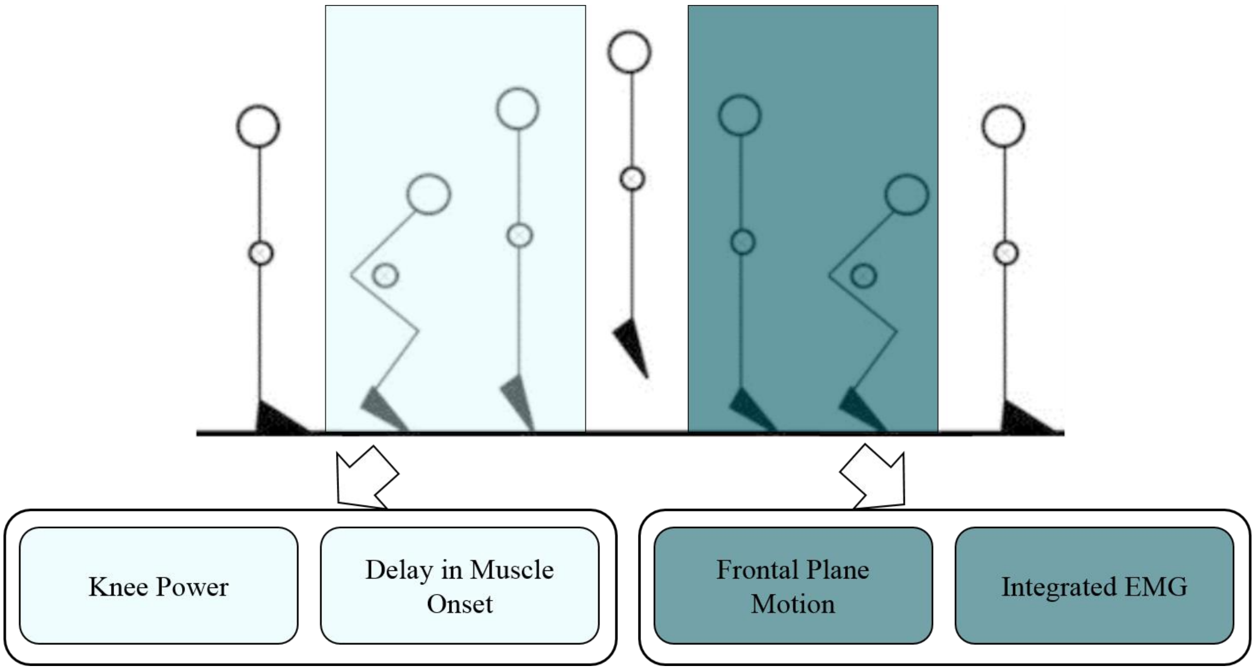


Figure 4.5 Countermovement jump outcome measures are indicated at the bottom of the figure for the associated countermovement jump phase. The light shaded area indicates the takeoff phase; the dark shaded area indicated the landing phase. Figure adapted from (Padulo et al., 2013).

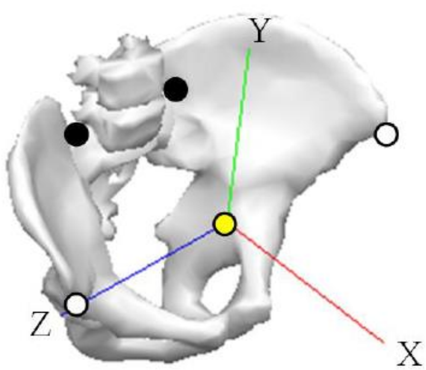
4.2.3.1 Kinematic Data

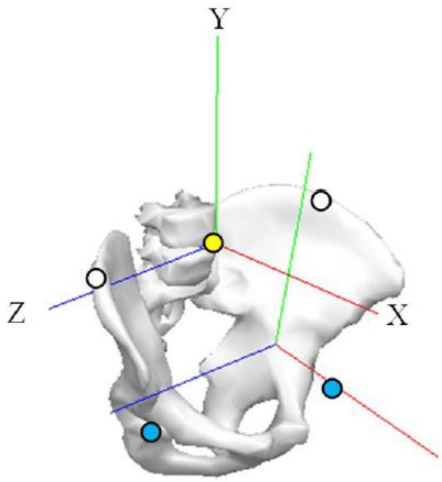
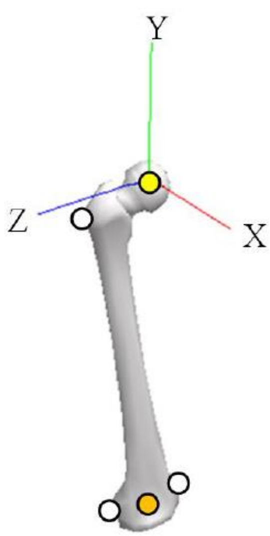
Kinematic data were filtered at 10 Hz using a dual-pass 4^{th} order Butterworth filter (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Longpré, Potvin, & Maly, 2013). Joint angles were calculated in Visual 3D using a Z-Y-X Cardan sequence, as suggested by ISB standards (Wu & Cavanagh, 1995). The coordinate systems for all of the body segments were defined following ISB recommendations (Wu & Cavanagh, 1995), as outlined in Table 4.4.

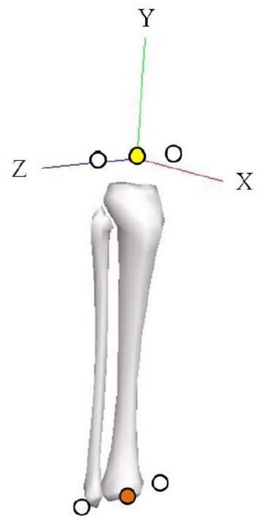
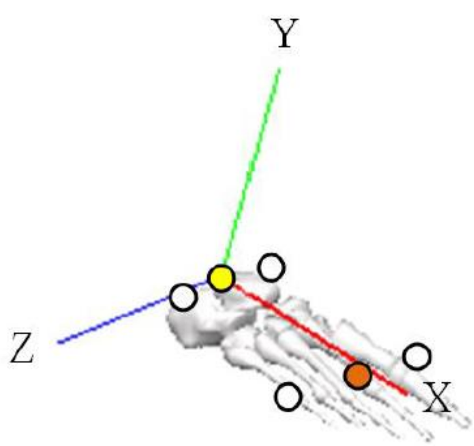
Hip angles were calculated using the virtual pelvis and the thigh segment, with the virtual pelvis designated as the reference segment. Knee angles were calculated using the joint coordinate system. Ankle angles were calculated using the virtual foot and the shank, with the shank as the reference segment. All kinematic data were padded to ensure a minimum of 1 second of data were collected before and after the squat protocols and squat transitions (Howarth & Callaghan, 2009).

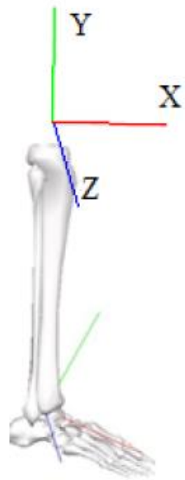
Table 4.4 Body segment coordinate system

Note: adapted from Chong, 2016; Tennant, 2016 and Visual 3D Documentation. Lines denote the positive direction of the axes. Bony landmarks (anterior/posterior), segment origins, midpoints and joint centres are represented by white/black, yellow, orange and blue circles respectively.

Segment	Coordinate System Definition
Pelvis (Coda) 	The standard pelvis system used in Visual 3D. Uses ASIS and PSIS markers to define the segment. Origin: The midpoint between the right and left ASIS markers. XZ-plane: Plane created by the right and left ASIS, and the midpoint of the right and left PSIS. Y-axis: Perpendicular to the XZ-plane Z- axis: Vector from the origin to the right ASIS. X-axis: Cross product of Y by Z. (Visual 3D documentation – Coda Pelvis)
Pelvis (Virtual)	Origin: Midpoint between right and left IC markers, created based on functional hip joint centres (highlighted in blue) are based on estimations from the Coda pelvis.

	YZ-plane: Plane created by the right and left iliac crest markers and hip joint centres. Y-axis: Vector created by the midpoint of the right and left hip joint centres to the midpoint of the iliac crest markers. X-axis: Perpendicular to the YZ-plane. Z-axis: Cross product of X by Y.
Thigh 	Origin: Hip joint centre, as calculated by functional hip trials. YZ-plane: Plane defined by the greater trochanter, lateral and medial femoral epicondyles. Y-axis: Vector between the hip joint centre and the midpoint of the medial and lateral epicondyles. Z-axis: Perpendicular to Y-axis, along the plane defined by the hip joint centre and femoral epicondyles, oriented towards the right. X-axis: Perpendicular to YZ plane, oriented anteriorly.
Shank	Origin: Midpoint between the medial and lateral tibial plateau and the medial and lateral malleoli.

	YZ-plane: Plane defined by the medial and lateral knee markers, and the medial and lateral malleoli. Y-axis: Vector defined by the midpoint of the medial and lateral malleoli and the medial and lateral tibial plateau. X-axis: Perpendicular to the YZ-plane, oriented anteriorly. Z-axis: Cross product of X by Y.
Foot 	Origin: Midpoint between the medial and lateral malleoli markers. YZ-plane: Plane defined by the medial and lateral malleoli, and the 1st and 5th metatarsals. Y-axis: Vector from midpoint of 1st and 5th metatarsals to the midpoint of medial and lateral malleoli markers. X-axis: Perpendicular to the YZ-plane, oriented anteriorly. Z-axis: Cross product of X by Y. The LCS will then be rotated manually, so that the frontal plane is the YZ-plane.
Foot (Virtual)	The virtual foot was defined based on the same coordinate system of the shank, and was tracked by the foot cluster. A neutral ankle angle was defined as when the foot is flat to the ground and the shank

	segment is in a vertical position. The position of the ankle during the static standing trial was expressed as 0º. Dorsiflexion resulted in positive values and plantarflexion resulted in negative values.

4.2.3.2 Kinetic Data

Kinetic data were collected during countermovement jumps and squat trials. All kinetic data were filtered with a low-pass second order dual-pass Butterworth filter, with a cutoff frequency of 10 Hz (Kristianslund, Krosshaug, & van den Bogert, 2012; Tomescu, Bakker, Beach, & Chandrashekar, 2018). It is recommended that kinematic and kinetic data be filtered using matching cut-off frequencies to minimize the introduction of non-physiological artefacts to hip abduction and flexion moments (Kristianslund et al., 2012; Kristianslund, Krosshaug, & van den Bogert, 2013; Tomescu et al., 2018). Kinetic data were used to determine initial contact of the countermovement jumps, and was defined as when vertical ground reaction force exceeded 10 N (Myer, Ford, Khoury, Succop, & Hewett, 2010).

4.2.3.3 Frontal Plane Motion

Neuromuscular control was assessed from EMG and kinematic data collected during the countermovement jump trials. This was partially determined as the magnitude of deviations of the functional knee joint center from a body-fixed reference plane during squat transitions (Tennant, 2016). Post-squat exposure absolute peak deviations of the knee joint centre from the plane was compared to pre-test measures. A body-fixed reference plane was created for the dominant side that includes the distal foot, ankle joint and functional hip joint centre (Frost, Beach, Callaghan, & McGill, 2015). The distal foot was defined as the midpoint between the first and fifth metatarsal heads. The perpendicular distance of the functional knee joint centre to the body-fixed plane was used to calculate deviations.

4.2.3.4 Onset of Muscle Activation

Raw EMG data were processed using the following steps: the signal was full-wave rectified; and low-pass filtered at 50 Hz using a 6^{th} order Butterworth filter (Cowan et al., 2000). The countermovement jump trials were used to calculate EMG onset, with the average being taken across the two pre and post-tests. Differences between EMG onset during the takeoff phase of the countermovement jump was determined (Figure 4.6).

Onset of activation between the paired muscle responses (vastus lateralis/vastus medialis) was determined as occurring when the signal was three standard deviations from the standing baseline value for at least 25 ms (Briani et al., 2016; Cowan et al., 2000; Hinman, Bennell, Metcalf, & Crossley, 2002; Hodges & Bui, 1996). As the Cometa wireless EMG system introduces a built-in delay of 14 ms, this was accounted for when determining muscle onset. Onsets determined automatically using the three standard deviation threshold were verified with visual inspection.

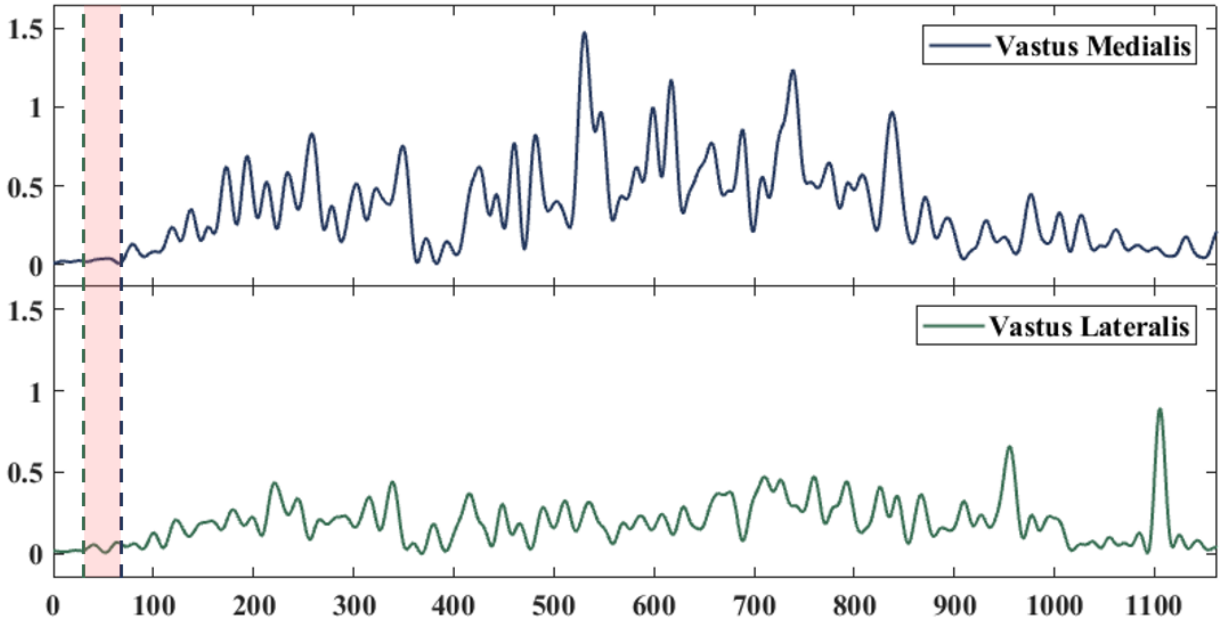


Figure 4.6 Method used to identify the onset of muscle activation. The shaded area indicates the delay between onset of vastus medialis and vastus lateralis. The dashed line indicates time point where three standard deviation threshold has occurred for the muscle.

4.2.3.5 Integrated EMG

Raw kinetic and raw, full-wave rectified EMG data were used to determine intervals over which integrated EMG was determined during the countermovement jumps. Raw force and EMG data were used to ensure synchronization between these measures in the integrated EMG calculation. Two phases were examined, a preparatory phase, occurring 150 ms before initial contact, and a deceleration phase occurring from initial contact to 150 ms post initial contact (Figure 4.7).

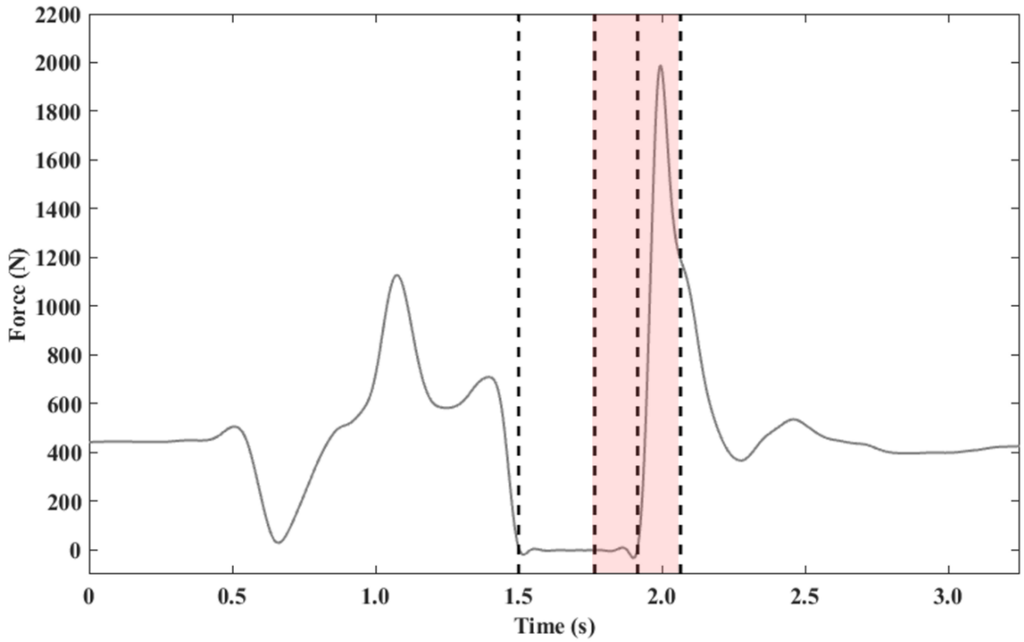


Figure 4.7 Method used to identify phases for integrated EMG. Red shaded area indicates preparatory (left) and deceleration (right) phases.

4.2.3.6 Hemodynamics

The following hemodynamics variables were measured during the study, tissue saturation index (TSI%), and oxyhemoglobin concentration (O_2Hb). All hemodynamics variables were collected at 50 Hz. Oxygenation concentration levels from the manual occlusion trial were used to determine minimal Oxygenation, with experimental values being normalized to this value. Change in TSI% was determined as the absolute change from the mean values occurring over the last 5 seconds before squat exposure to the TSI% measured during the last 5 seconds of the squat (Figure 4.8). For the cyclic squat exposures, changes were expressed as the mean of the last 5 seconds of the sixth squat compared to the pre squat values (Figure 4.9). Change in TSI% and minimal oxygenation values were chosen to reflect potentially detrimental decreases in muscle blood flow and muscle oxygenation concentrations. Although, NIRS is not a direct measure of blood flow, it can be used as a surrogate to measure variables of interest. TSI% has been shown to closely follow similar trends as blood flow measures (Gibbons, 2017)**.** NIRS was also chosen as the preferred tool to measure blood flow as pilot testing indicated that the dynamic nature of the movements made it difficult to ensure placement of the ultrasound probe over the superficial femoral artery for the entire duration of the protocol. The probe was required to be constantly repositioned, or was only able to capture the artery of interest during one phase of the squat position (either static standing or static squatting, but not both and not the entire dynamic transition phase).

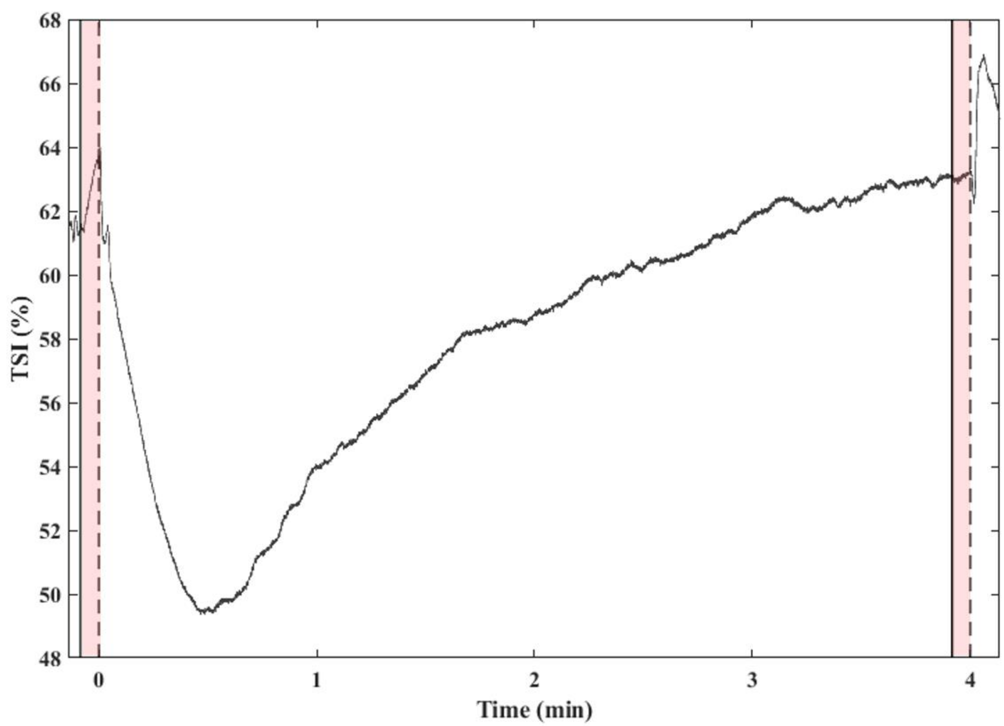


Figure 4.8 Method used to determine change in TSI% during sustained squat. Dashed lines indicate start and end of squat, respectively. Solid lines indicate five seconds from start or end of squat. Shaded areas indicate five-second period used to quantify mean change.

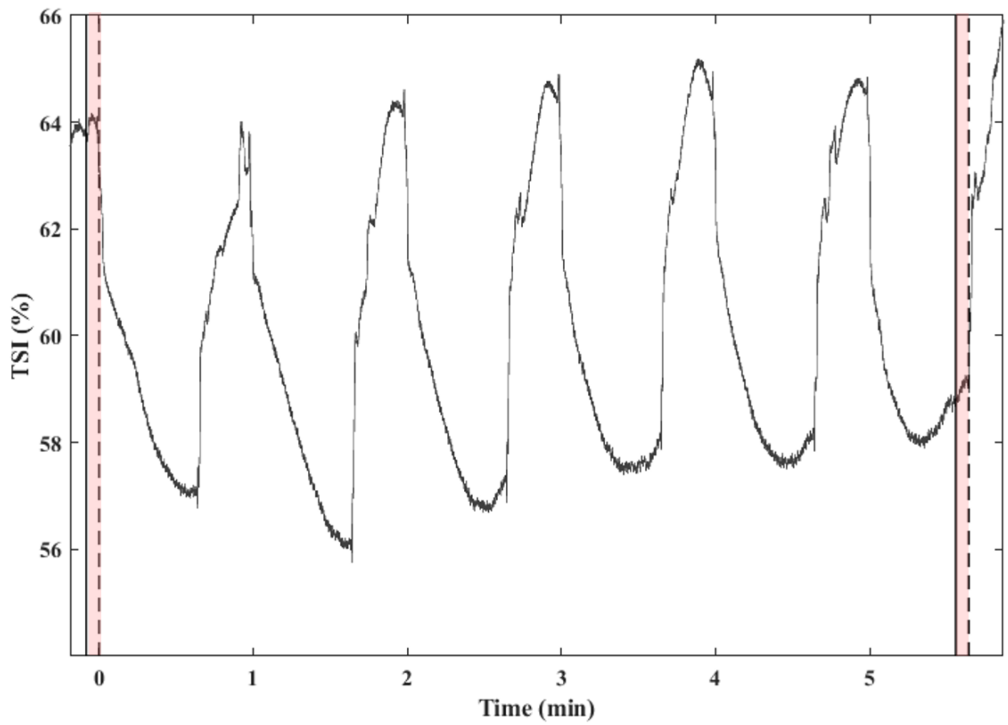


Figure 4.9 Method used to determine change in change in TSI% during cyclic squats. Dashed lines indicate start of first squat, and end of sixth squat respectively. Solid lines indicate five seconds from start or end of squat. Shaded areas indicate five-second period used to quantify mean change.

4.2.4 Statistical Analyses

To test the proposed hypotheses (Table 2.1), SPSS (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY) statistical analysis software was used. A mixed general linear model design was used for all ANOVA tests conducted (outlined in Tables 4.5 through 4.8). Levene's test for equality of variances was completed to assess variances across the different groups. Mauchly's test of sphericity was also performed. Greenhouse-Geisser p-values were used when the assumption of sphericity was violated.

Table 4.5 Statistical analysis for knee power

Factor Type	Independent Variables Factor	 Level	Dependent Variables	Statistical Model
Between	Sex	Female Male	Knee Power	Mixed General Linear Model Two-way ANOVA (2x2)
Within	Squat Exposure	Cyclic Sustained		

Table 4.6 Statistical analysis for neuromuscular control

Factor Type	Independent Variables Factor	 Level	Dependent Variables	Statistical Model
Between	Sex	Female Male	Deviation of knee joint centre Muscle Onset Delay	Mixed General Linear Model Two-way ANOVA (2x2)
Within	Squat Exposure	Cyclic Sustained		

Table 4.7 Statistical analysis for integrated EMG

Factor Type	Independent Variables Factor	Level	Dependent Variables	Statistical Model
Between	Sex	Female Male	Integrated EMG	Mixed General Linear Model Four-way ANOVA (2x2x2x2)
Within	Squat Exposure	Cyclic Sustained		
Within	Phase	Preparatory Deceleration		
Within	Muscle	Vastus Medialis Vastus Lateralis		

Table 4.8 Statistical analysis for hemodynamic variables

Factor Type	Independent Variables Factor	Level	Dependent Variables	Statistical Model
Between	Sex	Female Male	% Minimal Oxygenation TSI%	Mixed General Linear Model Two-way ANOVA (2x2)
Within	Squat Exposure	Cyclic Sustained		

Chapter 5: Results

Beyond the 30 participants reported in Table 4.1, some participants were excluded from the analysis for the following reasons. Four participants were unable to complete the sustained squat exposure, and the collection was therefore aborted. An additional four participants were removed due to instrumentation issues. Three participants were excluded from the muscle onset analysis due to processing issues. This was determined as when the onset algorithm determined delays of over 150 ms between onset of the vastus lateralis and vastus medialis muscles due to noisy signal during the quiet standing phase. Lastly, five participants were excluded from the analysis of % minimal oxygenation due to not attaining arterial occlusion during the maximal occlusion trial. In these five participants, it appears that venous occlusion occurred, based on an observed increase in oxyhemoglobin and deoxyhemoglobin concentration values during the occlusion trial (Figure 5.1). In the included participants, arterial occlusion was confirmed by an increase in deoxyhemoglobin concentration and a decrease in oxyhemoglobin concentration during the occlusion trial (Figure 5.2). Unless otherwise stated, thirty participants were included in the analyses. Eight participants were required to complete additional countermovement jump trials. Five were due to restarting a squat exposure; the other three were due to unsuccessfully completed jumps, either due to not landing fully on the force plate or losing their balance.

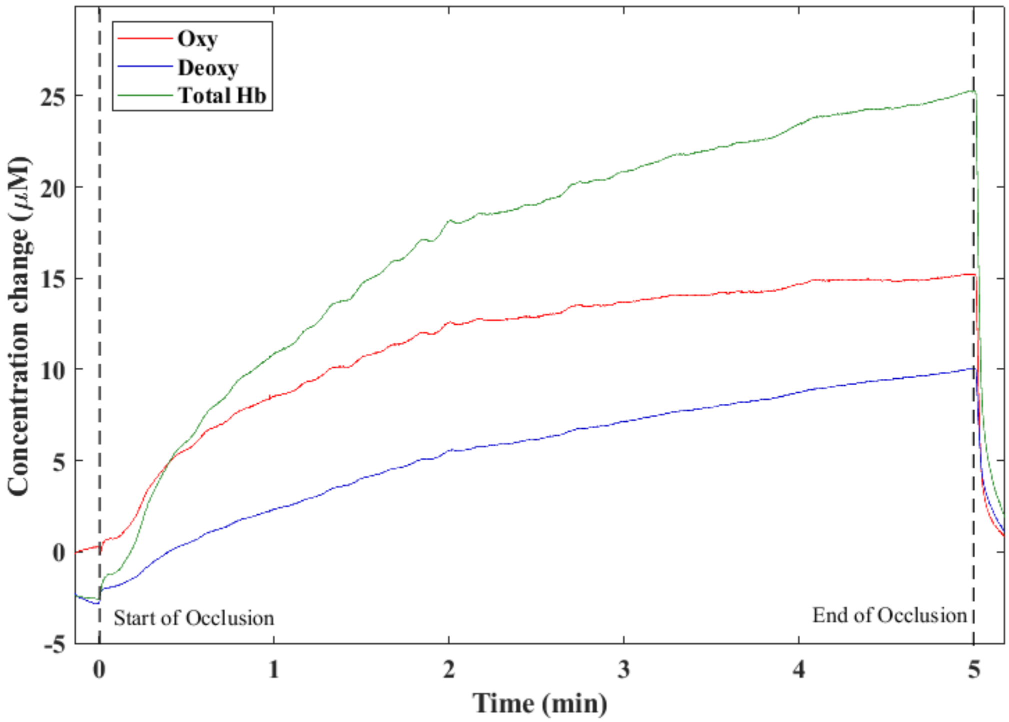


Figure 5.1 Example of venous occlusion that resulted in exclusion of this participant from the % minimal oxygenation analyses. Red line indicates oxyhemoglobin concentration, blue line indicates deoxyhemoglobin concentration, green line indicates total hemoglobin concentration. Dashed lines signifying start and ending of occlusion trial, respectively.

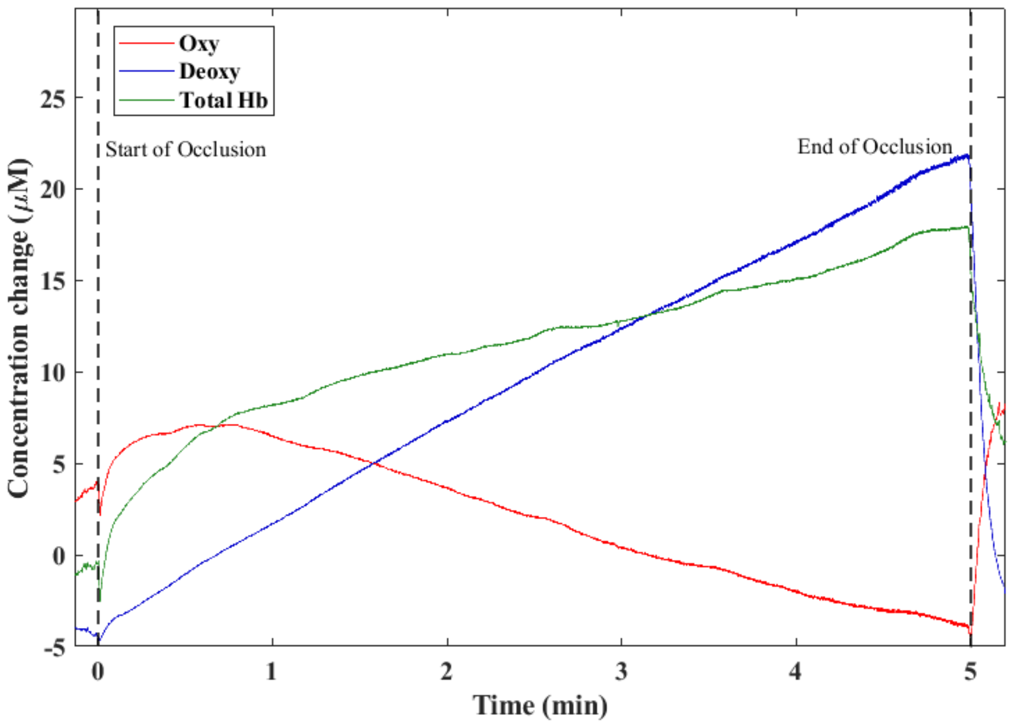


Figure 5.2 Example of arterial occlusion. Red line indicates oxyhemoglobin concentration, blue line indicates deoxyhemoglobin concentration, green line indicates total hemoglobin concentration. Dashed lines signifying start and ending of occlusion trial, respectively.

5.1 Knee Power

There was a significant main effect for squat exposure type on change in peak knee power during the takeoff phase of a countermovement jump ($F_{1,28} = 6.55$, $p = .016$) (Table 5.1). This result supports hypothesis 1 that exposure to the sustained squat would cause greater decreases in power generation than the cyclic squat exposure (−0.71 W/kg vs. −0.33 W/kg). Additionally, a significant main effect for sex was found ($F_{1,28} = 6.99$, $p = .013$). Males had greater decreases in knee power after squatting exposure than females (−0.73 W/kg vs. −0.32 W/kg). There was not a significant interaction effect between exposure type and sex ($F_{1,28} = 2.68$, $p = .113$).

Table 5.1 Peak knee power values normalized to W/kg (± standard deviation).

	Cyclic	Sustained
Female	−0.25 (± 0.40)	−0.38 (± 0.46)
Male	−0.42 (± 0.64)	−1.04 (± 0.77)
All	−0.33 (± 0.53)	−0.71 (± 0.71)

5.2 Neuromuscular Control

5.2.1 Frontal Plane Motion

No significant main effects were found for squat exposure type ($F_{1,28} = 1.24$, $p = .275$) or sex ($F_{1,28} = 0.99$, $p = .328$). It had been hypothesized that sustained squatting would result in greater deviation of the knee joint centre from the body-fixed plane at initial contact of the countermovement jump than following exposures to a cyclic squat. The interaction between squat exposure and sex was also not significant ($F_{1,28} = 1.02$, $p = .321$). Mean values are reported in Table 5.2.

Table 5.2 Mean deviation of knee joint centre from body-fixed plane in cm (± standard deviation). Negative values indicate less deviation from baseline values.

	Cyclic	Sustained
Female	−1.82 (± 4.53)	0.45 (± 4.07)
Male	0.36 (± 4.60)	0.13 (± 3.81)
All	−0.73 (± 4.62)	0.29 (± 3.88)

5.2.2 Onset of Muscle Activation

Three male participants were excluded from the analysis due to noisy EMG signals. No significant main effects were found for squat exposure type ($F_{1,25}$ = 3.28, p = .082) or sex ($F_{1,25}$ = 0.53, p = .475) (Table 5.3). On average, during the cyclic squatting exposure vastus medialis onset occurred prior to vastus lateralis onset (6.20 ms ± 48.68 ms). There was not a significant interaction between squat exposure type and sex ($F_{1,25}$ = 0.76, p = .392).

Table 5.3 Mean muscle onset delay between vastus lateralis and vastus medialis in ms (± standard deviation). Negative values indicate vastus medialis onset occurred later than vastus lateralis.

	Cyclic	Sustained
Female (n = 15)	−2.27 (± 45.69)	−13.50 (± 37.53)
Male (n = 12)	16.79 (± 52.18)	−15.25 (± 38.30)
All	6.20 (± 48.68)	−14.28 (± 37.15)

5.2.3 Integrated EMG

There were no significant main effects found for squat exposure type ($F_{1,28}$ = 2.76, p = .108), muscle ($F_{1,28}$ = 2.95, p = .097), phase ($F_{1,28}$ = 2.58 , p = .120) or sex ($F_{1,28}$ = 3.49, p = .072) on integrated EMG

Table 5.4). This was contrary to hypotheses 2b that stated that sustained squatting would cause a greater decrease in integrated EMG than cyclic squatting. A significant interaction occurred between muscle and phase ($F_{1,28}$ = 4.80, p = .037) (Figure 5.3). Although not statistically significant, a trend was observed where during the deceleration phase females experienced reductions in iEMG for both muscles, and after both exposure types, whereas males tended to have increased iEMG activation. For both vastus medialis and vastus lateralis, iEMG values decreased following squat exposures during the deceleration phase (−4.83 mV·s vs. −0.12 mV·s, respectively), whereas overall there was greater activation during the preparatory phase (0.86 mV·s vs. 0.38 mV·s, respectively) following squat exposures compared to pre exposure values.

Table 5.4 Mean integrated EMG values by squat exposure, phase and muscle (mV·s)

		Preparatory Phase		Deceleration Phase	
		Cyclic	Sustained	Cyclic	Sustained
Females					
	VM	0.011 (± 3.77)	0.235 (±4.15)	−14.578 (± 23.84)	−5.949 (±17.05)
	VL	− 1.152 (± 7.58)	0.543 (± 2.90)	−2.140 (± 15.74)	−0.008 (± 12.22)
Males					
	VM	0.601 (± 4.88)	2.574 (± 3.10)	−5.013 (± 27.07)	6.209 (± 16.66)
	VL	0.622 (± 2.30)	1.487 (± 2.23)	1.055 (± 14.08)	0.617 (± 11.58)
All					
	VM	0.306 (± 4.29)	1.404 (± 3.79)	−9.795 (± 25.53)	0.130 (± 17.68)
	VL	−0.265 (± 5.58)	1.015 (± 2.59)	−0.542 (± 14.76)	0.305 (± 11.70)

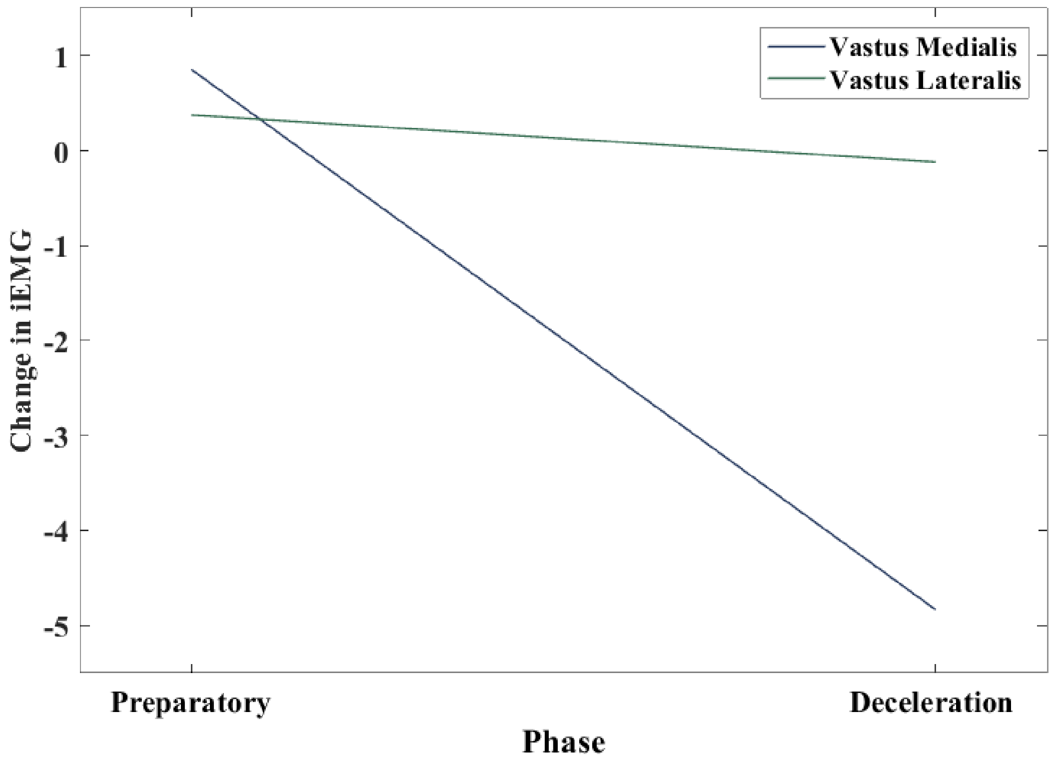


Figure 5.3 Interaction between muscle and phase for integrated EMG. Blue line indicates vastus medialis, green line indicates vastus lateralis.

5.3 Hemodynamics

Due to five participants not achieving arterial occlusion during the maximal occlusion trial, changes in % minimum oxygenation during squat exposures is based on data from 25 participants (12 female/13 male). Minimal oxygenation values were normalized to oxyhemoglobin concentration levels attained during the occlusion trial; therefore, greater minimal oxygenation values indicate lower oxygenation levels in the muscle. No significant main effects were found for exposure type ($F_{1,23}$ = 0.037, p = .849) or sex ($F_{1,23}$ = 1.48, p = .236) on changes in % minimum oxygenation during squatting exposures (Table 5.5). There was also no significant interaction effect between exposure type and sex determined for % minimum oxygenation ($F_{1,23} = 0.001$, $p = .980$). A non-significant trend was observed where on average male participants attained nearly twice the minimal oxygenation values at the end of the squat exposures than females.

Tissue saturation index was used as a surrogate for muscle blood flow; negative values indicate a decrease in tissue saturation index from baseline, with positive values indicating an increase. A significant main effect of squat exposure type was not found for change in TSI% during squat exposures ($F_{1,28} = 0.128$, $p = .723$). However, a significant main effect of sex on change in TSI% was determined ($F_{1,28} = 7.29$, $p = .012$). Males tended to experience greater decreases in TSI% from pre-test values than females (mean: −1.97 ± 5.56% vs. 2.60 ± 4.25%). The trends were in opposite directions, with TSI% values increasing from baseline for female participants and decreasing for males. There was not a significant interaction effect between exposure and sex.

Table 5.5 Hemodynamics mean values

	% Minimal Oxygenation		TSI%	
	Cyclic	Sustained	Cyclic	Sustained
Females	34.81 (± 66.91)	32.52 (± 90.59)	2.40 (± 4.49)	2.79 (± 4.15)
Males	63.12 (± 55.67)	60.14 (± 48.64)	−2.03 (± 6.12)	−1.92 (± 5.15)
All	49.53 (± 61.72)	46.88 (± 71.71)	0.18 (± 5.73)	0.44 (± 5.18)

Chapter 6: Discussion

The primary objective of the thesis was to investigate the effects of cyclic and sustained squatting exposures on lower-limb biomechanics and hemodynamics measures. Occupational exposure to high knee flexion postures, such as squatting, has been linked to an increased risk of developing knee osteoarthritis. By systematically and quantitatively comparing the effects of squatting exposures on power, neuromuscular control variables and hemodynamic outcomes, it was expected that any significant results could lead to a better understanding of whether one type of squatting was more detrimental to knee joint health than the other. It was hypothesized that sustained squatting exposures would cause greater decreases to knee power, neuromuscular control and hemodynamics.

6.1 Knee Power

Mean changes to peak knee power generation during the takeoff phase of a countermovement jump were analyzed. This outcome measure was chosen as a means to investigate potentially detrimental acute changes to power generation. The adequate generation of power is vital to accomplishing activities of daily living and mobility (Bean et al., 2002). Following sustained squatting exposures, a greater decrease in knee power was observed from pre-test values, than following cyclic squatting exposures. Knee power decreased from pre-test values by −0.71 W/kg vs. −0.33 W/kg, for sustained and cyclic squatting respectively. These changes equated to a decrease in power of approximately 7.5% and 3.7% from baseline values. These results support the hypothesis that sustained squatting would cause greater reductions to the generation of knee power during the takeoff phase of a countermovement jump. It is important to note that although the relative changes in power demonstrated in the current study may appear nominal to a healthy, young population, even minimal changes in knee power may significantly influence the ability of an older population to complete activities of daily living or affect their mobility. In a chronic care population over 85 years of age, a change of power of just under one W/kg was the difference between those who needed to use aids to perform tasks of daily living, such as needing to use their arms to rise from a chair, or required a walking frame (Bassey et al., 1992). However, a change of one W/kg represented nearly 50% of their total power.

Knee extensor power has been shown to decrease by 3.5% per year after the age of 65 (Skelton et al., 1994). In elderly women living in a community-based setting, leg power had the greatest correlation with self-reported functional status (Foldvari et al., 2000). Previous research which investigated knee extensor power generated during vertical jumps across a wide-range of ages, determined that healthy individuals in their early 70s generated approximately 20 to 25% of the average power than individuals in their 20s (Bosco & Komi, 1980). Furthermore, participants completed two squatting exposures for a total of eight minutes in the high knee flexion posture, and saw significant decreases in power.

A main effect for sex was also found for changes to knee power following squat exposures. Males displayed greater decreases following squat exposures than females (−0.73 W/kg vs. −0.32 W/kg, respectively). One potential explanation for this finding is due to sex differences in muscle fiber type composition. Females may potentially be more resistant to fatigue due to a greater percentage of slow twitch muscle fibers. By possessing a smaller percentage of fast twitch fibers, females may be at a disadvantage in terms of force or power production, however, they may have an advantage in endurance or generating force once fatigued (Wüst, Morse, Haan, Jones, & Degens, 2008). Although, females have a greater percentage of skeletal mass concentrated in the lower body than males 57.7% vs. 54.9%, respectively (Janssen, Heymsfield, Wang, & Ross, 2000). Females have been shown to have greater endurance during an isometric knee extension fatigue protocol following moderate occlusion of the lower-limb (Labarbera et al., 2013), although this trend was not confirmed during full occlusion, where no sex differences were found (Clark, Collier, Manini, & Ploutz-Snyder, 2005). There was not a significant interaction between squat exposure and sex in the study (p = .113).

Consistent with previous work, males in our study generated greater power during the countermovement jumps than females (Marquez, Alegre, Jaén, & Aguado, 2017). This could imply that males had the potential to lose power by a greater degree than females. Additionally, males have been found to attain a larger propulsive impulse than females during the propulsive and takeoff phase of the jump when normalized to mass (McMahon, Rej, & Comfort, 2017). The authors suggest that this led to a reduced velocity achieved throughout the propulsive and takeoff phases, potentially explaining differences in jump height and peak concentric power attained. Differences in the depth of the countermovement jump between the sexes have also been highlighted in previous literature. Male participants tend to go to a greater depth during the countermovement jump than females (McMahon et al., 2017), which has been suggested as a possible reason for sex differences in power generation. In the current study, squat depth during countermovement jumps was not standardized. Participants chose a self-selected squat depth for the jumps.

6.2 Neuromuscular Control

It was hypothesized that neuromuscular control, defined as deviation of the knee joint centre from a body-fixed plane and delays in muscle onset between vastii muscles, would see greater deficits from the sustained squat exposure than compared to the cyclic squat exposure. Specifically, it was hypothesized that there would be a greater delay between the vastii following squat exposures, with the vastus medialis having a greater delay in onset than vastus lateralis after an acute sustained squat exposure. Effective neuromuscular control is vital to reduce the risk of injury (Lim et al., 2009; Mandelbaum et al., 2005; Myer, Ford, Palumbo, & Hewett, 2005). Females have been reported as four to eight times more likely to sustain a non-contact ACL injury than males in comparable sports (Arendt & Dick, 1995; Hughes & Watkins, 2006). In order to reduce the likelihood of sustaining this type of injury, it is suggested that individuals land with greater hip and knee flexion (Leppänen et al., 2016; Pollard et al., 2010). Landing with a larger vertical ground reaction force is thought to also increase injury risk (Hewett, Myer, et al., 2005). Reducing the frontal plane motion of the knee joint has also been suggested as a way to minimize injury (Munro, Herrington, & Comfort, 2012). Lastly, muscle activation patterns have been determined to contribute to poor neuromuscular control (Hewett, Zazulak, Myer, & Ford, 2005).

6.2.1 Frontal Plane Motion

The ability of the lower limb musculature to maintain dynamic stability of the knee joint is an important element of neuromuscular control. Knee valgus motion is one of the predictors for non-contact ACL injury risk (Myer et al., 2010). Therefore, deviation of the knee joint centre from a body-fixed plane was used as one of the determinants of dynamic stability, with greater deviation indicating poorer neuromuscular control, and thereby placing the knee joint at increased risk of injury. Failure to adequately control dynamic stability of the knee during high impact tasks has implications for injury risk. A study that investigated neuromuscular control outcome measures in over 200 female athletes in sports with an increased risk of ACL injury, found that those who went on to sustain injury had greater knee valgus angles at landing of a drop vertical jump task (Hewett, Myer, et al., 2005). Deviation of the knee joint centre from a body-fixed plane was predicted to increase by a larger degree following the sustained squat protocol. However, no statistical differences were determined.

Our findings that neuromuscular control was not impaired following potentially fatiguing squat exposures is somewhat contrary to the literature. Following exposure to a different high flexion posture, a 30 minute simulated occupational kneeling task, caused significant changes to frontal plane motion during squatting (Tennant, Chong, & Acker, 2018). Previous work examining landing tasks, found that after exposure to a fatiguing protocol, peak knee abduction and knee abduction moments increased in collegiate athletes (McLean et al., 2007), indicating poorer frontal plane neuromuscular control following a fatiguing activity. Similar results for increased frontal plane motion at landing were confirmed with recreationally active participants (Chappell et al., 2005; Gehring et al., 2009). Possible differences in findings may be due to the methodology. In the study with collegiate athletes, ten drop vertical jumps were completed before and after a four minute, continuous fatiguing protocol that represented activities commonly performed in basketball, soccer and volleyball (Chappell et al., 2005). The investigators analysis was based on the mean the first five jumps, whereas our analysis involved two jumps post exposure. In their work, the initial jump following the fatiguing protocol was approximately 60-65% of max pre-fatigue jump height, and increased to approximately 70% for the second jump. Jump height gradually increased on subsequent jumps, reaching roughly 85% of pre-fatigue values by the fifth trial. Changes to jump height were not measured in our study, although, decreases in knee power generation were found, which could imply participants were not achieving similar jump heights to pre exposure values. This may indicate that participants in our study, if reaching reduced jump heights, were not creating vertical ground reaction forces to the same magnitude of those seen by the collegiate athletes, reducing the amount of frontal plane motion. Chappell et al. (2005), had participants complete repetitions of five consecutive vertical jumps, followed by a 30-m sprint to volitional exhaustion. Outcome measures were collected on three separate stop-jump tasks that involved a multi-step approach, followed by a one-legged takeoff, two-foot landing then the completion of either a forward, vertical or a backward jump. As a forward momentum component was included in the jumping task, the comparability to the current study may be restricted, as in our study the emphasis was on vertical movement. Chappell et al. (2005) used recreationally active participants, but had them complete a potentially more complicated experimental task was more typical of an approach to the net, as performed in volleyball. Our study provided a more simplistic movement, by focusing on the vertical component of the jump, that participants were potentially more comfortable performing.

The current study did not directly compare the degree of knee abduction between males and females, but compared changes in frontal plane motion before and after squatting exposures. Therefore, direct comparisons between our work and previous literature in regards to sex differences that occur may be limited and must be interpreted with caution. However, contrary to previous work, our study failed to demonstrate significant sex differences. Females tend to display greater valgus angles at landing (Carson & Ford, 2011; Russell, Palmieri, Zinder, & Ingersoll, 2006). Additionally, females exhibit greater total valgus knee motion than males (Ford, Myer, & Hewett, 2003). This inability to control frontal plane motion is believed to place females at increased risk for ACL injuries (Krosshaug et al., 2006). An analysis of mechanisms of ACL injury in basketball players from high school to professional level players, found that females were over five times more likely to experience valgus collapse, which they defined as the knee collapsing medially during landing (Krosshaug et al., 2006).

6.2.2 Onset of Muscle Activation

Onset of muscle activation of the vastus medialis and vastus lateralis was investigated during the takeoff phase of the countermovement jump. The knee extensor muscles are important for dynamic stability of the knee joint (Hewett, Zazulak, et al., 2005). A greater delay between onset of vastus medialis and lateralis was predicted. Specifically, it was hypothesized that following the sustained squat exposure, vastus medialis activation would show a significantly greater delay with respect to the vastus lateralis, than the cyclic squat exposure. However, the study failed to show any significant differences in muscle onset activation between the vastii. A trend did emerge in that muscle onset of the vastus medialis tended to occur later following the sustained squat compared to the cyclic squat (-14.28 ± 37.15 ms and 6.20 ± 48.68 ms, respectively), wherein on average vastus lateralis onset tended to occur later.

A possible explanation for the lack of significant findings for delay in muscle onset may be due to methodological reasons. In the current study, we investigated the initiation of the countermovement jump. An algorithm determined when muscle activity had reached three standard deviations of the baseline standing values for a minimum of 25 ms, during the period before takeoff had occurred. Onset prior to landing was infeasible using this method, as participants demonstrated a large degree of variability in EMG activity during the flight phase of the countermovement jump. To our knowledge, few studies have investigated delays in muscle onset during the takeoff phase of a countermovement jump. Gehring et al., (2009) were also unable to find significant differences in muscle onset of the vastii following a fatigue inducing protocol.

There are conflicting results surround sex differences in activation of quadriceps during landing tasks. Preparatory phase sex differences have been previously demonstrated in studies (Ebben et al., 2010; Gehring et al., 2009). Contrary to the current study, following a fatiguing protocol onset of the vastus lateralis was delayed compared to the vastus medialis in females (Gehring et al., 2009). The opposite effect was found by Ebben et al., (2010) who found that males had earlier activation of both the vastus lateralis and vastus medialis compared to females during the preparatory phase of the jump. Female participants in the study tended to activate the vastus medialis prior to the vastus lateralis during the preparatory phase of the jump; however, these differences were not statistically analyzed. No significant sex differences were found during the deceleration phase. Cowling & Steele (2001) were unable to find significant sex differences in muscle onset of the vastii during a single-limb landing task that simulated a common netball movement. Similarly, work comparing female and male athletes, and non-athlete females found no sex differences in vastus medialis onset during a single leg controlled drop landing task, however non-athlete females displayed significantly slower vastus medialis activation compared to female athletes (Medina et al., 2008). Although vastus medialis onset of non-athlete females was nearly twice as slow as male athletes, the trend was not statistically different.

6.2.3 Integrated EMG

It was hypothesized that integrated EMG activity in the vastus medialis and vastus lateralis during the preparatory and deceleration landing phases of the countermovement jump would differ significantly from baseline values between exposure types. Specifically, integrated EMG during the deceleration phase of landing was predicted to be significantly reduced following the sustained squatting exposure, compared to the cyclic squat. This hypothesis was not confirmed, as a significant difference did not occur. No significant exposure type, muscle, phase or sex main effects were found. A significant interaction did occur between muscle and phase, wherein, iEMG values for the vastus medialis were changed to a greater degree during the preparatory and deceleration phases of landing

(0.855 mV·s and −4.833 mV·s, respectively) compared to the vastus lateralis (0.375 mV·s and –0.119 mV·s, respectively). Our results show that there is the potential for vastii to be exhibiting opposite trends depending on the phase of landing investigated (Figure 5.3). In the current study, the vastus lateralis was activated to a lesser extent than vastus medialis.

No significant exposure type main effect on changes to integrated EMG during the preparatory or deceleration phase for the vastus lateralis or vastus medialis was found in our study. There is conflicting evidence on whether external occlusion results in greater muscle activation. Yasuda et al., (2009) found that complete and moderate occlusion to the brachial artery caused greater increases in integrated EMG recorded in the arm flexors compared to the control during cyclic unilateral elbow flexion at 20% MVIC. In contrast, a negative correlation was found between iEMG of the rectus femoris and blood volume, in participants who completed a 60-minute, sustained single-limb knee extension contraction at 2.5% MVIC, however no correlation was determined for vastus lateralis activity (Kouzaki et al., 2003). A lack of signifcant differences for the vastii was also confirmed during cyclic knee extension. Completing physical activity with partial occlusion to the lower limb did not result in increased maximal muscle activity measured during a low intensity (30% MVIC) dynamic unilateral knee extension to failure compared to that found with no occlusion (Wernbom, Järrebring, Andreasson, & Augustsson, 2009). These results suggest that at low intensity, muscle activity in the vastii is not significantly changed during cyclic or sustained contractions of the knee extensors.

In the preparatory phase, lower limb musculature is important for modifying landing stiffness. A stiff landing is associated with reduced hip and knee flexion, which places the knee at risk of increased joint loads (Pollard et al., 2010). Greater quadriceps activation may also contribute to reduced energy absorption in landing, and increased ground reaction forces (Hewett et al., 2006).

A prospective study that followed young female basketball and floorball players, found that those who landed with less knee flexion and a greater vertical ground reaction force were more likely to sustain an ACL injury (Leppänen et al., 2016).

Adequate activation of the knee extensors in the deceleration phase is required to reduce knee flexion at impact (Fagenbaum & Darling, 2003). Landing in a more extended position, with reduced knee flexion, is associated with increased normalized vastus lateralis activity, reduced energy absorption at the knee, and greater frontal plane motion (Pollard et al., 2010). This combined neuromuscular control strategy is also believed to put individuals at a greater risk of ACL injury. Although, the study investigated only young female soccer players, aged 11 to 20 years, therefore it is unclear how this relates to injury risk in young adults and males. Nevertheless, males in the current study displayed increased vastus lateralis iEMG following squat exposures in both the preparatory and deceleration phases. With the greatest increases occurring following the sustained squat exposure. This neuromuscular control strategy is most detrimental when combined with reduced knee flexor activity in the preparatory phase or decreased glute activity during the deceleration phase (Zazulak, Straub, Medvecky, Avedisian, & Hewett, 2005; Zebis, Andersen, Bencke, & Kjaer, 2009). Medial activation of the hamstring muscles acts as an antagonist to lateral quadriceps activity. Hip extensor and knee flexor activity was not measured in the current study.

A significant main effect of sex was not found in our study for changes to integrated EMG ($p = .072$) this is contrary to the expected findings. Previous work has shown signficicant sex differencs in terms of muscle activation patterns in the lower limb musculature in high risk activities such as landing and cutting tasks (Chappell et al., 2007; Ebben et al., 2010; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Padua et al., 2006; Pollard et al., 2010; Shultz, Nguyen, Leonard, & Schmitz, 2009). The research explicitly focusing on muscle activation patterns during jump landings is somewhat inconclusive. Ebben et al. (2010) found no signficant sex differences during preparatory or deceleration phases for vastii in terms of muscle activation levels. However, males exhibited earlier onset of both lateral and medial vastii in the preparatory phase. Their classification of the preparatory and deceleration phase was not based on a time frame from when initial contact occured, but determined as when muscle burst EMG exceeded 150% of baseline values before and after initial contact. Additionally, they reported % MVIC and not iEMG. Conversely, a sex effect was demonstrated, where females displayed greater quadriceps activation during landing from a vertical stop-jump than males (Chappell et al., 2007). Greater quadriceps activation during the preparatory phase could place females at an increased risk of knee injury, due to increased ACL loading caused by a greater quadriceps force during landing. Additionally, during single-leg drop landings, collegiate female athletes exhibited greater peak rectus femoris activation during the preparatory and deceleration phases of landing (Zazulak et al., 2005). The authors found that males had greater activation of the hip musculature. A hamstring dominant strategy sex effect has been demonstated in other work (Ebben et al., 2010). Although, during a vertical stop-jump task with a running approach, females were found to have greater hamstring activation during the preparatory phase, but less activation during deceleration (Chappell et al., 2007). A hamstring dominant strategy is thought to cause peak activation of the hamstrings to occur closer to peak tibiofemoral shear force, increasing stabilization of the lower leg, through joint compression (Cowling & Steele, 2001). In contrast, employing a quadriceps dominant strategy is associated with increased ACL injury risk, by increasing anterior shear force (Hewett, Zazulak, et al., 2005; Hughes & Watkins, 2006; Malinzak et al., 2001). Other work has shown that energy absorption at the knee joint was greater in female participants during a drop jump landing task (Decker et al., 2003; Schmitz & Shultz, 2010).

An inability of the lower leg musculature to adequately absorb the body's kinetic energy during the landing phase may also lead to poor frontal plane control of the knee joint. Decreased medial quadriceps activity is theorized to reduce the ability of the lower leg to create dynamic knee stability along with passive joint restraints (Myer, Ford, Palumbo, et al., 2005). Additionally, greater lateral quadriceps activity and reduced medial activity during initial deceleration of the landing phase can place the knee in a valgus position, which may increase the risk of ACL injury (Bencke, Aagaard, & Zebis, 2018; Myer, Ford, Palumbo, et al., 2005). Greater frontal plane motion, defined as peak knee valgus angle, has been associated with increased vastus lateralis activity in the preparatory phase, whereas a lower peak valgus angle was associated with greater preparatory vastus medialis activity in female participants (Palmieri-Smith, Wojtys, & Ashton-Miller, 2008). Correlations between frontal plane motion and muscle activity were not investigated in the current study. Direct comparisons between landing studies may be difficult as different methodologies were employed. There have been reported differences in muscle activation patterns between unilateral and bilateral landings, instruction, as well as when drop height is changed (Etnoyer, Cortes, Ringleb, Van Lunen, & Onate, 2013; Herrington, 2011; Yeow, Lee, & Goh, 2010). Differences in iEMG may be partially due to differences in the operational definitions of the preparatory and deceleration phases of landing. Studies have defined these time frames as occuring 50 ms before to 250 ms after initial contact (Fagenbaum & Darling, 2003; Gehring et al., 2009; Zazulak et al., 2005).

6.3 Hemodynamics

Hemodynamics measures were collected during the squat exposures. Increases in % minimal oxygenation (normalized to occlusion trial values) and decreases in % tissue saturation index from the onset of the squat exposure to the end were analyzed to represent potentially detrimental effects of the squat exposures. Sustained squatting was hypothesized to create greater detriments in hemodynamics variables during squatting exposures than cyclic squatting. Specifically, sustained squatting was hypothesized to result in a greater increase in % minimal oxygenation levels and greater decreases to tissue saturation index from baseline values (Table 2.1). The study failed to find a significant main effect of squatting exposure for changes to minimal oxygenation (sustained: 46.88 ± 71.71%, cyclic: 49.53 ± 61.72%). The high variability of the outcome measure may have influenced the lack of significant findings. Additionally, the skin temperature under the NIRS probe may have affected the outcome measures. No significant main effect of squat exposure was found for changes to tissue saturation index either (sustained: 0.44 ± 5.18%, cyclic: 0.18 ± 5.73%).

The lack of significant differences in changes in hemodynamic measures in the current study between the cyclic and sustained squats contradicts earlier work that found greater oxygen consumption during sustained exercise, compared to cyclic exposures (van Beekvelt, Orbon, van Engelen, Wevers, & Colier, 2003). A possible reason for the lack of statistically significant findings may be because the durations of the squatting exposures were not adequate to create large effects on the hemodynamic measures. Theoretically, maintaining a sustained contraction should cause a gradual increase in intramuscular pressure which would then cause greater ischemia within the muscle. Although, this relationship is dependent on the level of contraction required, as at lower %MVIC intramuscular pressure may not cause a cessation in muscle perfusion (Sjøgaard, Savard, & Juel, 1988).

Intermittent compression of the lower leg during single-leg plantar flexion exercise resulted in elevated blood flow to the superficial femoral artery during exercise as well as during recovery (Zuj et al., 2018). The extent of compression attained in that study was low (70 mmHg) and may not be representative of mechanical compressions that occur in the leg due to thigh-calf contact.

However, the current study supports the concept that cyclic compression compared to sustained compression may provide a physiological benefit (assessed through hemodynamic measures and exercise performance). Differences may be present between our study and this previous work, as they used an external compression system, and timed compressions to coincide with the diastolic phase of the cardiac cycle. In the current study, the vascular compression occurred due to thigh-calf contact. While the degree of compression would vary between participants, it should remain relatively consistent within an individual, although this was not controlled for in our study. A study that directly compared blood flow during sustained isometric contractions and repeated short cyclic contractions (5 s contraction, followed by 5 s rest) at equivalent %MVIC during a hand grip task found that blood flow was similar during the contraction phases, however blood flow increased by a greater magnitude during the relaxation phase of the cyclic contractions (Sjøgaard et al., 1988). These findings were based on the responses of only two young healthy male participants, so caution should be taken in interpreting these results.

A sex main effect was determined for changes to TSI%, with males showing greater decreases following squatting exposures than females (−1.97 ± 5.56% vs. 2.60 ± 4.25%). While females tended to experience an increase in tissue saturation index compared to baseline values, males did not return to baseline values during the squat exposure. There are several factors that may be producing the contrasting responses. First, differences in muscle morphology, such as muscle fiber type composition and/or muscle size, may exist between the sexes. Males have larger proportional knee extensor and flexor muscles cross-sectional areas (Behan, Maden-Wilkinson, Pain, & Folland, 2018). Therefore, when the greater muscle mass is contracted during the squatting exposure this may create more vascular occlusion and negatively influence oxygen delivery. Additionally, dissimilarities have been found in vasodilation responses to lower-limb exercise, with females exhibiting a greater vasodilation response to dynamic knee extension exercises (Parker et al., 2007).

Sex differences in flexibility may also have influenced the results. Females have been shown to achieve a larger max knee angle and thigh-calf force in high knee flexion postures (Kingston & Acker, 2018). Thigh-calf contact that occurs in high knee flexion postures may allow for the unloading of knee joint and thus reduce activation required by the knee extensors. thereby reducing the level of contraction required to maintain the squatting exposure. Intramuscular tissue pressure increases as both % maximal voluntary contraction and external pressure increase (Sadamoto, Bonde-Petersen, & Suzuki, 1983). These differences may be greater at lower intensities, since as maximal intensities are reached the amount of muscle occlusion by contraction and mechanical compression should be similar (S. K. Hunter, 2009; Yoon, Schlinder Delap, Griffith, & Hunter, 2007). When strength was matched, during a fatiguing task, males exhibited greater active hyperemia following a 4 minute sustained forearm contraction than females, but similar rates of blood flow during a task failure trial (S. K. Hunter et al., 2006). Although, conflicting evidence has been found for whether sex differences in fatigue remain when the muscle is exposed to ischemic conditions. These differences may be due to the muscle group investigated and methodology. No sex effects were found during muscle ischemia when examining calf muscles in a volitional activation task (Russ & Kent-Braun, 2003), however they were present when electrical stimulation was used in the quadriceps (Wüst et al., 2008). Furthermore, a significant interaction effect occurred for squat exposure and sex was not found in our study. A review of studies investigating sex differences between sustained and cyclic contractions found that muscle fatigue sex differences may be greater during cyclic contractions than sustained (S. K. Hunter, 2009). This implies that males may be less adaptable to intermittent insults to the musculature, such as temporary decreases in blood flow, or accumulation of metabolites, leading to greater reductions in performance.

Integration of Results:

A statistical analysis of correlations between biomechanical and hemodynamics variables was not investigated. However, the results of the current study may help to partially elucidate the interplay between biomechanics and hemodynamic measures. A major finding was that the squatting exposures appeared to affect the sexes differently. Compared to females, males experienced greater reductions in generation of knee power (− 0.73 W/kg vs. −0.32 W/kg) and decreases in TSI% following squat exposures (−1.97 ± 5.56% vs. 2.60 ± 4.25%). A relationship between tissue saturation index and changes to knee power may exist wherein, during the squat exposures, males experienced less muscle perfusion due to greater muscle mass, thus they were more negatively affected by the squat exposures than females, leading to a greater reduction in knee power in subsequent tasks. In contrast, females experienced an increase in tissue saturation index from baseline values, and were thus less affected by the squatting protocol, due to adequate muscle perfusion. Females are more resistant to fatigue, which may be in part due to an advantage in their ability to maintain adequate muscle blood flow during relatively low intensity sustained exercise. Recovery rates of hemodynamic measures were not investigated, however females have been shown to experience a greater hyperemic response to incremental increases of workload during dynamic leg exercises (Parker et al., 2007). Although the opposite effect was seen after 4 minutes of a low intensity forearm isometric fatiguing protocol, both with and without matching for strength (S. K. Hunter et al., 2006). We had proposed that decreased lower limb blood following exposures to high knee flexion postures led to reductions in quadriceps strength (Figure 1.1). However, in the current study, we were unable to find a significant link between changes in lower limb blood flow during squat exposures and reductions in quadriceps strength, as measured by deceases in knee power during takeoff of a countermovement jump. Due to the inability to identify the mechanisms leading to decreases in quadriceps strength, we revised our proposed mechanisms leading to the development of knee osteoarthritis to reflect that decreases in lower limb blood flow and reductions in quadriceps strength might be independent of one another (Figure 6.1).

Summary

One of the goals of this thesis was to systematically compare the acute effects of frequency and duration of high knee flexion postures on outcome measures potentially detrimental to knee joint health. The findings are slightly inconclusive as to whether intermittent or sustained exposure to high knee flexion activities is more damaging, however a trend did occur. When a significant exposure main effect occurred, sustained squatting led to greater negative changes from baseline. From this, for acute exposures, we would recommend that when completing a task while in a high knee flexion posture, it would be beneficial to implement recovery periods throughout the task. Incorporating recovery periods during squatting led to lower knee power losses following the exposures than seen during sustained squatting. Males tended to be more significantly affected by the squatting exposures than females, experiencing greater reductions in knee power on average than females did. Therefore, ensuring that high knee flexion postures are completed with ample rest, (2:1 ratio in the current study) could be especially important for males.

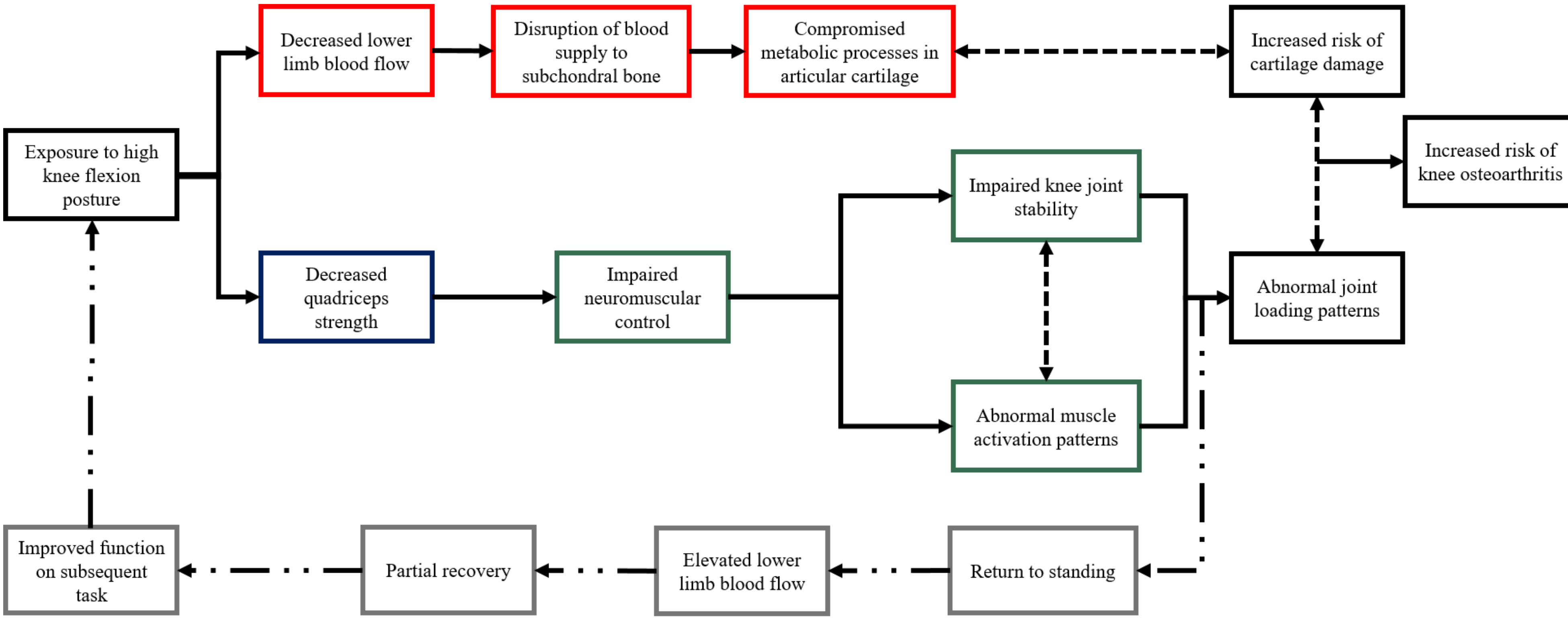


Figure 6.1 Revised mechanisms to the development of knee osteoarthritis. Top left quadrant has been revised to reflect that decreased lower limb blood flow and decreases to quadriceps strength are independent pathways. Red boxes indicate hemodynamics mechanisms. Blue box indicates muscular changes. Green boxes indicate neuromuscular control mechanisms. Grey boxes indicate cyclic squat exposure outcomes. Solid lines indicate typical squat exposure pathway. Dashed arrows with two arrow heads indicate two-way or cyclic processes. Dot-dashed lines indicate cyclic squat exposure pathway.

Chapter 7: Limitations

There were several limitations to the study. The global objective of the study was to gain insight into proposed mechanisms of risk for the development of knee osteoarthritis, patellofemoral pain, or poor knee health; however, the current study was not longitudinal in nature, and did not include a diseased population. Therefore, the generalizability of the findings to special populations may be limited. However, the study was able to demonstrate that even acute exposures to high knee flexion postures can cause significant decreases to the generation of knee power on subsequent tasks, and it is predicted that the effects would be amplified in a diseased or older population, as well as with longer total exposure durations.

Plantar flexion muscles such as the gastrocnemius and soleus muscles were not investigated in the current study. These muscles have been shown to play a role in power generation during takeoff, as well as having implications for landing mechanics. The focus on knee extensor muscles exclusively was determined based on the strong link between function of the knee extensor muscles and risk of knee osteoarthritis, patellofemoral pain syndrome, and non-contact ACL injury.

Participants had the option to perform either a flat foot squat or heels up squat. They were instructed to use the same type of squat for both exposures. Twenty-four participants employed a heels up squat, and the remaining six chose a flat foot squat. Heels up squatting should hypothetically allow for greater thigh-calf contact during the squatting exposure. Achieving thigh-calf contact theoretically allows for greater unloading of the knee joint during high flexion postures, thus reducing the amount of knee extensor activation required. Thigh-calf contact increases with knee flexion angle, which was not standardized during squats. There is the potential that participants varied the amount of thigh-calf contact achieved and flexion angles during the two squat exposures, although they were instructed to squat as low as possible for both exposures. Knee flexion angles during squat exposures can be found in Appendix A. Anecdotally, participants who failed to successfully complete the sustained squatting exposure appeared to have less thigh-calf contact and greater muscle activity during the squats.

Menstruation cycle phase, hormone levels, and oral contraceptive use was not measured in our study. Differences in hormone levels, have been postulated as a reason for sex effects in neuromuscular control, however, the results are inconclusive. Several studies investigating neuromuscular control in female collegiate athletes failed to find significant changes to ACL laxity over the course of their menstrual cycle (Belanger et al., 2004; Hertel, Williams, Olmsted-kramer, Leidy, & Putukian, 2006). Additionally, work comparing high school basketball players showed no differences in ACL laxity between sexes, although there were indications of differences in PCL laxity and compliance index (Weesner, Albohm, & Ritter, 1986). The authors speculated that disparity in ACL injury rates might be due to disparities in conditioning levels. Supporting this theory, is evidence that female collegiate level athletes displayed a quadriceps dominant muscle activation pattern that recreationally active females did not possess (Huston, Edward, & Arbor, 1996). Conversely, multiple studies have reported differences in neuromuscular control based on fluctuations in hormone levels (Deie, Sakamaki, Sumen, Urabe, & Ikuta, 2002). A recent systematic review determined that the use of oral contraceptives, which reduces hormonal fluctuations across the cycle, was found to have a protective effect and reduce ACL injury risk by up to 20% (Herzberg et al., 2016).

Activity level in the study was not controlled. The population consisted of mostly recreationally active individuals, with all but four participants indicating that they were currently participating in some form of physical activity or sport. The participants who indicated they were not currently active were female. Level of training may have an influence on landing muscle activation. Comparisons between collegiate level basketball players found that muscle activation patterns were more similar, although females still tended to have greater overall normalized quadriceps activity compared to male athletes (Fagenbaum & Darling, 2003). Additionally, activity level has been shown to influence the timing of quadriceps activation (Medina et al., 2008).

The current study relied on near-infrared spectroscopy to measure hemodynamics during squatting exposures. Although the device does not directly measure blood flow, it was considered a surrogate, and because of this, inferences needed to be made. An additional limitation concerning the use of NIRS is that the signal is significantly affected by adipose tissue thickness (van Beekvelt, Borghuis, van Engelen, Wevers, & Colier, 2001).

The changes seen from baseline for several of the outcome measures were small, often with variations larger than the values found. This variability in participants on outcomes could be confounding potentially meaningful results.

Chapter 8: Contributions and Future Directions

This study was the first to systematically compare the effects of sustained and intermittent high knee flexion activities on biomechanical and hemodynamic measures. The total time in the high knee flexion posture was controlled between exposures, allowing for a direct comparison of whether maintaining or cycling through the posture was potentially more detrimental to the knee. The study provided preliminary support for sustaining high knee flexion activities having more detrimental acute effects on knee health.

The current study provided more hemodynamics data on females. Previous studies have often used small female sample sizes or excluded them altogether. Our findings suggest possible sex differences in high knee flexion postures, highlighting the need to ensure representation of females in hemodynamic studies to clarify any sex differences that may occur.

We also provided evidence that even acute exposures to high knee flexion activities can hinder subsequent performance following exposure. These findings add preliminary support to our proposed pathway for a mechanism of knee OA development due to exposure to high knee flexion activities.

Building on the findings of the current study, there are many future directions that the research could pursue. The current study investigated above-knee hemodynamics and muscle activity. Future work could examine how above and below knee hemodynamics and muscle activity are collectively affected by high knee flexion postures. Hemodynamics may be affected differently above and below knee. Previous work has suggested minimal blood flow occurs below the knee during high flexion activities, however, there is limited research on this area. Pilot work by our lab has shown that blood flow does continue during these postures. However, it may be affected by whether individuals have a sufficiently redundant arterial network surrounding the knee joint. Proper timing and activation of the gastrocnemius and soleus muscles are important for knee flexion during activities of daily living. Additionally, knee extensors were the focus of the current study, however knee flexors also play an important role in knee health, so should also be investigated. An imbalance in the magnitude and timing of knee extensors to knee flexors is associated with an increased risk for ACL injury. Co-contraction of these muscle groups is needed to maintain proper stability of the knee joint.

Anecdotally, participants who were unable to achieve thigh-calf contact during the squatting exposures were more likely to be unable to complete the task. Exploring the relationship between amount of thigh-calf contact and performance could be beneficial. Greater thigh-calf contact could allow the movement to become more passive, requiring less muscle activity, but potentially at the cost of greater occlusion of blood flow.

Lastly, studying under a more occupationally relevant setting would also be a valuable future direction. In the current study, we did not explicitly attempt to faithfully replicate an occupational exposure to high knee flexion postures. Our focus was on a systematic comparison between intermittent and sustained squatting, where duration in the posture was strictly controlled. Squatting while carrying a load has been associated with greater risk of developing knee osteoarthritis and this relationship could be further explored.

References

Accettura, A. J., Brenneman, E. C., Stratford, P. W., & Maly, M. R. (2015). Knee Extensor Power Relates to Mobility Performance in People With Knee Osteoarthritis: Cross-Sectional Analysis. *Physical Therapy*, *95*(7), 989–995. https://doi.org/10.2522/ptj.20140360

Amin, S., Baker, K., Niu, J., Clancy, M., Goggins, J., Guermazi, A., … Felson, D. T. (2009). Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis. *Arthritis and Rheumatism*, *60*(1), 189–198. https://doi.org/10.1002/art.24182

Amin, S., Goggins, J., Niu, J., Guermazi, A., Grigoryan, M., Hunter, D. J., … Felson, D. T. (2008). Occupation-related squatting, kneeling, and heavy lifting and the knee joint: a magnetic resonance imaging-based study in men. *Journal of Rheumatology*, *35*(9), 2166–2171. https://doi.org/10.1021/nl061786n.Core-Shell

Andersen, J. H., Haahr, J. P., & Frost, P. (2007). Risk factors for more severe regional musculoskeletal symptoms: A two-year prospective study of a general working population. *Arthritis and Rheumatism*, *56*(4), 1355–1364. https://doi.org/10.1002/art.22513

Arden, N., & Nevitt, M. C. (2006). Osteoarthritis: Epidemiology. *Best Practice and Research: Clinical Rheumatology*, *20*(1), 3–25. https://doi.org/10.1016/j.berh.2005.09.007

Arendt, E. A., & Dick, R. (1995). Knee Injury Patterns Among Men and Women in Collegiate Basketball and Soccer. *The American Journal of Sports Medicine*, *23*(6), 694–701. https://doi.org/10.1177/036354659502300611

Arthritis Alliance of Canada. (2011). *The impact of arthritis in Canada: today and over the next 30 years*. *Arthritis Alliance of Canada* (Vol. Fall). Retrieved from http://www.arthritisalliance.ca

Astephen, J. L., Deluzio, K. J., Caldwell, G. E., Dunbar, M. J., & Hubley-Kozey, C. L. (2008). Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels. *Journal of Biomechanics*, *41*(4), 868–876. https://doi.org/10.1016/j.jbiomech.2007.10.016

Baker, K. R., Xu, L., Zhang, Y., Nevitt, M., Niu, J., Aliabadi, P., … Felson, D. (2004). Quadriceps weakness and its relationship to tibiofemoral and patellofemoral knee osteoarthritis in Chinese: The Beijing osteoarthritis study. *Arthritis and Rheumatism*, *50*(6), 1815–1821. https://doi.org/10.1002/art.20261

Baker, P., Coggon, D., Reading, I., Barrett, D., McLaren, M., & Cooper, C. (2002). Sports injury, occupational physical activity, joint laxity, and meniscal damage. *Journal of Rheumatology*, *29*(3), 557–563.

Baker, P., Reading, I., Cooper, C., & Coggon, D. (2003). Knee disorders in the general population and their relation to occupation. *Occupational and Environmental Medicine*, *60*, 794–798.

Bassey, E. J., Fiatarone, M. A., O'Neill, E. F., Kelly, M., Evans, W. J., & Lipsitz, L. a. (1992). Leg extensor power and functional performance in very old men and women. *Clinical Science*, *82*(3), 321–327. https://doi.org/10.1042/cs0820321

Bean, J. F., Kiely, D. K., Herman, S., Leveille, S. G., Mizer, K., Frontera, W. R., & Fielding, R. A. (2002). The relationship between leg power and physical performance in mobility-limited older people. *Journal of the American Geriatrics Society*, *50*(3), 461–467. https://doi.org/10.1046/j.1532-5415.2002.50111.x

Behan, F. P., Maden-Wilkinson, T. M., Pain, M. T. G., & Folland, J. P. (2018). Sex differences in muscle morphology of the knee flexors and knee extensors. *PLoS ONE*, *13*(1).

Belanger, M. J., Moore, D. C., Iii, J. J. C., Fadale, P. D., Hulstyn, M. J., & Ehrlich, M. G. (2004). Knee Laxity Does Not Vary With the Menstrual Cycle, Before or After Exercise. *American Journal of Sports Medicine*, *32*(5), 1150–1157. https://doi.org/10.1177/0363546503261360

Bencke, J., Aagaard, P., & Zebis, M. K. (2018). Muscle activation during ACL injury risk movements in young female athletes: A narrative review. *Frontiers in Physiology*, *9*(MAY), 1–10. https://doi.org/10.3389/fphys.2018.00445

Berger, M. J., McKenzie, C. A., Chess, D. G., Goela, A., & Doherty, T. J. (2012). Quadriceps neuromuscular function and self-reported functional ability in knee osteoarthritis. *Journal of Applied Physiology*, *113*(2), 255–262. https://doi.org/10.1152/japplphysiol.00947.2011

Besier, T. F., Draper, C. E., Gold, G. E., Beaupré, G. S., & Delp, S. L. (2005). Patellofemoral joint contact area increases with knee flexion and weight-bearing. *Journal of Orthopaedic Research*, *23*(2), 345–350. https://doi.org/10.1016/j.orthres.2004.08.003

Besier, T. F., Sturnieks, D. L., Alderson, J. A., & Lloyd, D. G. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*, *36*(8), 1159–1168. https://doi.org/10.1016/S0021-9290(03)00087-3

Björkström, S., & Goldie, I. F. (1980). A study of the arterial supply of the patella in the normal state, in chondromalacia patellae and in osteoarthrosis. *Acta Orthop Scand*, *51*(1), 63–70. https://doi.org/10.3109/17453678008990770

Blagojevic, M., Jinks, C., Jeffery, A., & Jordan, K. P. (2010). Risk factors for onset of osteoarthritis of the knee in older adults: a systematic review and meta-analysis. *Osteoarthritis and Cartilage*, *18*(1), 24–33. https://doi.org/10.1016/j.joca.2009.08.010

Bley, A. S., Correa, J. C. F., Dos Reis, A. C., Rabelo, N. D. D. A., Marchetti, P. H., & Lucareli, P. R. G. (2014). Propulsion Phase of the single leg triple hop test in women with patellofemoral pain syndrome: A biomechanical study. *PLoS ONE*, *9*(5), 1–7. https://doi.org/10.1371/journal.pone.0097606

Bobbert, M. F., & Casius, L. J. R. (2005). Is the Effect of a Countermovement on Jump Height due to Active State Development? *Medicine & Science in Sports & Exercise*, *37*(3), 440–446. https://doi.org/10.1249/01.MSS.0000155389.34538.97

Bolgla, L. A., Malone, T. R., Umberger, B. R., & Uhl, T. L. (2011). Comparison of hip and knee strength and neuromuscular activity in subjects with and without patellofemoral pain syndrome. *International Journal of Sports Physical Therapy*, *6*(4), 285–296. https://doi.org/10.1016/j.ptsp.2014.11.001

Boling, M., Padua, D. A., Marshall, S., Guskiewicz, K., Pyne, S., & Beutler, A. (2010). Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scandinavian Journal of Medicine and Science in Sports*, *20*(5), 725–730. https://doi.org/10.1111/j.1600-0838.2009.00996.x

Bosco, C., & Komi, P. V. (1980). Physiology Influence of Aging on the Mechanical Behavior. *European Journal of Applied Physiology*, *219*(8318), 209–219.

Briani, R. V., de Oliveira Silva, D., Pazzinatto, M. F., Ferreira, A. S., Ferrari, D., & de Azevedo, F. M. (2016). Delayed onset of electromyographic activity of the vastus medialis relative to the vastus lateralis may be related to physical activity levels in females with patellofemoral pain. *Journal of Electromyography and Kinesiology*, *26*, 137–142. https://doi.org/10.1016/j.jelekin.2015.10.012

Brookes, M., & Helal, B. (1968). Primary osteoarthritis, venous engorgement and osteogenesis. *Journal of Bone and Joint Surgery*, *50*(3), 493–504.

Brotmacher, L. (1957). Hæmodynamic Effects of Squatting During Recovery From Exertion. *British Heart Journal*, *19*(4), 567–573. https://doi.org/10.1136/hrt.19.4.567

Calder, K. M., Acker, S. M., Arora, N., Beattie, K. A., Callaghan, J. P., Adachi, J. D., & Maly, M. R. (2014). Knee power is an important parameter in understanding medial knee joint load in knee osteoarthritis. *Arthritis Care and Research*, *66*(5), 687–694. https://doi.org/10.1002/acr.22223

Camomilla, V., Cereatti, A., Vannozzi, G., & Cappozzo, A. (2006). An optimized protocol for hip joint centre determination using the functional method. *Journal of Biomechanics*, *39*(6), 1096–1106. https://doi.org/10.1016/j.jbiomech.2005.02.008

Carson, D. W., & Ford, K. R. (2011). Sex Differences in Knee Abduction During Landing : A Systematic Review. *Sports Health*, *3*(4), 373–382. https://doi.org/10.1177/1941738111410180

Cavazzuti, L., Merlo, A., Orlandi, F., & Campanini, I. (2010). Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome. *Gait and Posture*, *32*(3), 290–295. https://doi.org/10.1016/j.gaitpost.2010.06.025

Chappell, J. D., Creighton, R. A., Giuliani, C., Yu, B., & Garrett, W. E. (2007). Kinematics and electromyography of landing preparation in vertical stop-jump: Risks for noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine*, *35*(2), 235–241. https://doi.org/10.1177/0363546506294077

Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., Yu, B., & Carolina,

N. (2005). Effect of Fatigue on Knee Kinetics and Kinematics in Stop-Jump Tasks. *American Journal of Sports Medicine*, *33*(7), 1022–1029. https://doi.org/10.1177/0363546504273047

Chester, R., Smith, T. O., Sweeting, D., Dixon, J., Wood, S., & Song, F. (2008). The relative timing of VMO and VL in the aetiology of anterior knee pain: a systematic review and meta-analysis. *BMC Musculoskeletal Disorders*, *9*(1), 64. https://doi.org/10.1186/1471-2474-9-64

Childs, J. D., Sparto, P. J., Fitzgerald, G. K., Bizzini, M., & Irrgang, J. J. (2004). Alterations in lower extremity movement and muscle activation patterns in individuals with knee osteoarthritis. *Clinical Biomechanics*, *19*(1), 44–49. https://doi.org/10.1016/j.clinbiomech.2003.08.007

Clark, B. C., Collier, S. R., Manini, T. M., & Ploutz-Snyder, L. L. (2005). Sex differences in muscle fatigability and activation patterns of the human quadriceps femoris. *European Journal of Applied Physiology*, *94*(1–2), 196–206. https://doi.org/10.1007/s00421-004-1293-0

Coggon, D., Croft, P., Kellingray, S., Barrett, D., McLaren, M., & Cooper, C. (2000). Occupational Physical Activities and Osteoarthritis of the Knee. *Arthritis & Rheumatism*, *43*(7), 1443–1449. https://doi.org/10.1002/1529-0131(200007)43:7<1443::AID-ANR5>3.0.CO;2-1

Cook, S. B., Clark, B. C., & Ploutz-Snyder, L. L. (2007). Effects of exercise load and blood-flow restriction on skeletal muscle function. *Medicine and Science in Sports and Exercise*, *39*(10), 1708–1713. https://doi.org/10.1249/mss.0b013e31812383d6

Cooper, C., McAlindon, T. E., Coggon, D., Egger, P., & Dieppe, P. (1994). Occupational activity and osteoarthritis of the knee. *Annals of the Rheumatic Diseases*, *53*(2), 90–93. https://doi.org/10.1136/ard.53.2.90

Cowan, S. M., Bennell, K. L., & Hodges, P. W. (2000). The test–retest reliability of the onset of concentric and eccentric vastus medialis obliquus and vastus lateralis electromyographic activity in a stair stepping task. *Physical Therapy in Sport*, *1*(4), 129–136. https://doi.org/10.1054/ptsp.2000.0036

Cowan, S. M., Bennell, K. L., Hodges, P. W., Crossley, K. M., & McConnell, J. (2001). Delayed Onset of Electromyograpic Activity of Vastus Medialis Obliquus Relative to Vastus Lateralis in Subjects with Patellofemoral Pain Syndrome. *Archives of Physical Medicine and Rehabilitation*, *82*(2), 183–189.

Cowling, E. J., & Steele, J. R. (2001). Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *Journal of Electromyography and Kinesiology*, *11*(4), 263–268. https://doi.org/10.1016/S1050-6411(00)00056-0

Culvenor, A. G., Ruhdorfer, A., Juhl, C., Eckstein, F., & Øiestad, B. E. (2017). Knee Extensor Strength and Risk of Structural, Symptomatic, and Functional Decline in Knee Osteoarthritis: A Systematic Review and Meta-Analysis. *Arthritis Care and Research*, *69*(5), 649–658. https://doi.org/10.1002/acr.23005

Dahaghin, S., Tehrani-Banihashemi, S. A., Faezi, S. T., Jamshidi, A. R., & Davatchi, F. (2009). Squatting, sitting on the floor, or cycling: Are life-long daily activities risk factors for clinical knee osteoarthritis? Stage III results of a community-based study. *Arthritis Care and Research*, *61*(10), 1337–1342. https://doi.org/10.1002/art.24737

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*(July 1993), 135–163. https://doi.org/citeulike-article-id:2515246

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing.

Clinical Biomechanics, *18*(7), 662–669. https://doi.org/10.1016/S0268-0033(03)00090-1

Deie, M., Sakamaki, Y., Sumen, Y., Urabe, Y., & Ikuta, Y. (2002). Anterior knee laxity in young women varies with their menstrual cycle. *International Orthopaedics*, *26*(3), 154–156. https://doi.org/10.1007/s00264-001-0326-0

Devita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine & Science in Sports & Exercise*, *24*(1), 108–115.

Ding, C., Martel-Pelletier, J., Pelletier, J.-P., Abram, F., Raynauld, J.-P., Cicuttini, F., & Jones, G. (2007). Meniscal tear as an osteoarthritis risk factor in a largely non-osteoarthritic cohort: A cross-sectional study. *Journal of Rheumatology*, *34*(4), 776–784.

Dionisio, V. C., Almeida, G. L., Duarte, M., & Hirata, R. P. (2008). Kinematic, kinetic and EMG patterns during downward squatting. *Journal of Electromyography and Kinesiology*, *18*, 134–143. https://doi.org/10.1016/j.jelekin.2006.07.010

Ditchen, D. M., Ellegast, R. P., Gawliczek, T., Hartmann, B., & Rieger, M. A. (2014). Occupational kneeling and squatting: development and validation of an assessment method combining measurements and diaries. *International Archives of Occupational and Environmental Health*, *88*(2), 153–165. https://doi.org/10.1007/s00420-014-0946-5

Ditchen, D. M., Ellegast, R. P., Hartmann, B., & Rieger, M. A. (2013). Validity of self-reports of knee-straining activities at work: A field study with 6-month follow-up. *International Archives of Occupational and Environmental Health*, *86*(2), 233–243. https://doi.org/10.1007/s00420-012-0758-4

Downs, M. E., Hackney, K. J., Martin, D., Caine, T. L., Cunningham, D., O'Connor, D. P., & Ploutz-

Snyder, L. L. (2014). Acute vascular and cardiovascular responses to blood flow-restricted exercise. *Medicine and Science in Sports and Exercise*, *46*(8), 1489–1497. https://doi.org/10.1249/MSS.0000000000000253

Ebben, W. P., Fauth, M. L., Petushek, E. J., Garceau, L. R., Hsu, B. E., Lutsch, B. N., & Feldmann, C. R. (2010). Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *Journal of Strength and Conditioning Research*, *24*(2), 408–415.

Englund, M., Guermazi, A., Roemer, F. W., Aliabadi, P., Yang, M., Lewis, C. E., … Felson, D. T. (2009). Meniscal tear in knees without surgery and the development of radiographic osteoarthritis among middle-aged and elderly persons: The multicenter osteoarthritis study. *Arthritis and Rheumatism*, *60*(3), 831–839. https://doi.org/10.1002/art.24383

Escamilla, R. F., Fleisig, G. S., Zheng, N., Lander, J. E., Barrentine, S. W., Andrews, J. R., … Moorman, C. T. (2001). Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine & Science in Sports & Exercise*, *33*(9), 1552–1566. https://doi.org/10.1097/00005768-200109000-00020

Escamilla, R. F., Zheng, N., Macleod, T. D., Brent Edwards, W., Imamura, R., Hreljac, A., … Andrews, J. R. (2009). Patellofemoral joint force and stress during the wall squat and one-leg squat. *Medicine and Science in Sports and Exercise*, *41*(4), 879–888. https://doi.org/10.1249/MSS.0b013e31818e7ead

Etnoyer, J., Cortes, N., Ringleb, S. I., Van Lunen, B. L., & Onate, J. A. (2013). Instruction and Jump-Landing Kinematics in College-Aged Female Athletes Over Time. *Journal of Athletic Training*, *48*(2), 161–171. https://doi.org/10.4085/1062-6050-48.2.09

Fagenbaum, R., & Darling, W. G. (2003). Jump Landing Strategies in Male and Female College

Athletes and the Implications of Such Strategies for Anterior Cruciate Ligament Injury. *Am J Sports Med*, *31*(2), 233–240.

Fahs, C. A., Loenneke, J. P., Rossow, L. M., Thiebaud, R. S., & Bemben, M. G. (2012). Methodological considerations for blood flow restricted resistance exercise. *Journal of Trainology*, *1*, 14–22. https://doi.org/10.17338/trainology.1.1_14

Felson, D. T., Zhang, Y., Hannan, M. T., Naimark, A., Weissman, B., Aliabadi, P., & Levy, D. (1995). The incidence and natural history of knee osteoarthritis in the elderly, the framingham osteoarthritis study. *Arthritis & Rheumatism*, *38*(10), 1500–1505. https://doi.org/10.1002/art.1780381017

Feltner, M. E., Bishop, E. J., & Perez, C. M. (2004). Segmental and kinetic contributions in vertical jumps performed with and without an arm swing. *Research Quarterly for Exercise and Sport*, *75*(3), 216–230. https://doi.org/10.1080/02701367.2004.10609155

Ferrell, W. R., & Najafipour, H. (1992). Changes in synovial PO2 and blood flow in the rabbit knee joint due to stimulation of the posterior articular nerve. *Journal of Physiology*, *449*, 607–617.

Findlay, D. M. (2007). Vascular pathology and osteoarthritis. *Rheumatology*, *46*(12), 1763–1768. https://doi.org/10.1093/rheumatology/kem191

Foldvari, M., Clark, M., Laviolette, L. C., Bernstein, M. A., Kaliton, D., Castaneda, C., … Singh, M. A. F. (2000). Association of Muscle Power With Functional Status in Community-Dwelling Elderly Women. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *55*(4), M192–M199. https://doi.org/10.1093/gerona/55.4.m192

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus Knee Motion during Landing in High

School Female and Male Basketball Players. *Medicine & Science in Sports & Exercise*, *35*(10), 1745–1750. https://doi.org/10.1249/01.MSS.0000089346.85744.D9

Frost, D. M., Beach, T. A. C., Callaghan, J. P., & McGill, S. M. (2015). The influence of load and speed on individuals' movement behavior. *Journal of Strength and Conditioning Research*, *29*(9), 2417–2425.

Gehring, D., Melnyk, M., & Gollhofer, A. (2009). Gender and fatigue have influence on knee joint control strategies during landing. *Clinical Biomechanics*, *24*, 82–87. https://doi.org/10.1016/j.clinbiomech.2008.07.005

Gelber, A. C., Hochberg, M. C., Mead, L. A., Wang, N., Wigley, F. M., & Klag, M. J. (2000). Joint injury in young adults and risk for subsequent knee and hip osteoarthritis. *Annals of Internal Medicine*, *133*(5), 321–328.

Gibbons, T. (2017). *Hemodynamic effects of intermittent compression as a countermeasure to orthostatic stress*. University of Waterloo. Retrieved from http://hdl.handle.net/10012/12318

Glass, N. A., Torner, J. C., Frey Law, L. A., Wang, K., Yang, T., Nevitt, M. C., … Segal, N. A. (2013). The relationship between quadriceps muscle weakness and worsening of knee pain in the MOST cohort: a 5-year longitudinal study. *Osteoarthritis and Cartilage*, *21*(9), 1154–1159. https://doi.org/10.1086/498510.Parasitic

Grølund, J., Kofoed, H., & Svalastoga, E. (1984). Effect of increased knee joint pressure on oxygen tension and blood flow in subchondral bone. *Acta Physiologica Scandinavica*, *121*, 127–131.

Haywood, L., & Walsh, D. A. (2001). Vasculature of the normal and arthritic synovial joint. *Histology and Histopathology*, *16*(1), 277–284.

Herrington, L. C. (2011). Knee Valgus Angle During Landing Tasks in Female Volleyball and Basketball Players. *Journal of Strength and Conditioning Research*, *25*(1), 262–266. https://doi.org/10.1519/JSC.0b013e3181b62c77

Hertel, J., Williams, N. I., Olmsted-kramer, L. C., Leidy, H. J., & Putukian, M. (2006). Neuromuscular performance and knee laxity do not change across the menstrual cycle in female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, *14*, 817–822. https://doi.org/10.1007/s00167-006-0047-4

Herzberg, S. D., Motu'apuaka, M. L., Lambert, W., Fu, R., Brady, J., & Guise, J.-M. (2016). The Effect of Menstrual Cycle and Contraceptives on ACL Injuries and Laxity A Systematic Review and Meta-analysis. *Orthopaedic Journal of Sports Mediicine*, *5*(7), 1–10. https://doi.org/10.1177/2325967117718781

Hewett, T. E., Lindenfeld, T. N., Riccobene, J. V, & Noyes, F. R. (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *The American Journal of Sports Medicine*, *27*(6), 699–706. https://doi.org/10.1177/03635465990270060301

Hewett, T. E., Myer, G. D., & Ford, K. R. (2006). Anterior Cruciate Ligament Injuries in Female Athletes Part 1, Mechanisms and Risk Factors. *The American Journal of Sports Medicine*, *34*(2), 299–311. https://doi.org/10.1177/0363546505284183

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., … Succop, P. (2005). Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *American Journal of Sports Medicine*, *33*(4), 492–501.

https://doi.org/10.1177/0363546504269591

Hewett, T. E., Zazulak, B. T., Myer, G. D., & Ford, K. R. (2005). A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *British Journal of Sports Medicine*, *39*(6), 347–350. https://doi.org/10.1136/bjsm.2005.018572

Hinman, R. S., Bennell, K. L., Metcalf, B. R., & Crossley, K. M. (2002). Delayed onset of quadriceps activity and altered knee joint kinematics during stair stepping in individuals with knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation*, *83*(8), 1080–1086. https://doi.org/10.1053/apmr.2002.33068

Hodges, P. W., & Bui, B. H. (1996). A Comparision of Computer-Based Methodes for the Determination of Onset of Muscle Contration Using Electromyography. *Electroencephalo Clin Neurophysiol*, *101*(6), 511–519. https://doi.org/10.1016/S0921-884X(96)95190-5

Howarth, S. J., & Callaghan, J. P. (2009). The rule of 1 s for padding kinematic data prior to digital filtering: Influence of sampling and filter cutoff frequencies. *Journal of Electromyography and Kinesiology*, *19*, 875–881. https://doi.org/10.1016/j.jelekin.2008.03.010

Hubley-Kozey, C. L., Deluzio, K. J., Landry, S. C., McNutt, J. S., & Stanish, W. D. (2006). Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *16*(4), 365–378. https://doi.org/10.1016/j.jelekin.2005.07.014

Hughes, G., & Watkins, J. (2006). A risk-factor model for anterior cruciate ligament injury. *Sports Medicine (Auckland, N.Z.)*, *36*(5), 411–428. https://doi.org/10.2165/00007256-200636050-00004

Hughes, G., Watkins, J., & Owen, N. J. (2008). Gender differences in lower limb frontal plane kinematics during landing. *Sports Biomechanics*, *7*(3), 333–341. https://doi.org/10.1080/14763140802233215

Hunt, M. A., Wrigley, T. V., Hinman, R. S., & Bennell, K. L. (2010). Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain. *Arthritis Care and Research*, *62*(10), 1426–1432. https://doi.org/10.1002/acr.20248

Hunter, D. J., March, L., & Sambrook, P. N. (2003). The association of cartilage volume with knee pain. *Osteoarthritis and Cartilage*, *11*(10), 725–729. https://doi.org/10.1016/S1063-4584(03)00160-2

Hunter, S. K. (2009). Sex Differences and Mechanisms of Task-Specific Muscle Fatigue. *Exercise and Sport Sciences Reviews*, *37*(3), 113–122. https://doi.org/10.1097/JES.0b013e3181aa63e2.Sex

Hunter, S. K., Schletty, J. M., Schlachter, K. M., Griffith, E. E., Polichnowski, A. J., Ng, A. V, … Ng, A. V. (2006). Active hyperemia and vascular conductance differ between men and women for an isometric fatiguing contraction. *Journal of Applied Physiology*, *101*, 140–150. https://doi.org/10.1152/japplphysiol.01567.2005.

Huston, L. J., Edward, M., & Arbor, A. (1996). Neuromuscular Performance Characteristics in Elite Female Athletes. *The American Journal of Sports Medicine*, *24*(4), 427–436.

Janssen, I., Heymsfield, S. B., Wang, Z., & Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18 – 88 yr. *Journal of Applied Physiology*, *89*(1), 81–88.

Jensen, L. K., & Kirkeskov Jensen, L. (2005). Knee-straining work activities, self-reported knee disorders and radiographically determined knee osteoarthritis. *Scandinavian Journal of Work, Environment and Health*, *31*(SUPPL. 2), 68–74.

Jensen, L. K., Rytter, S., Marott, J. L., & Bonde, J. P. (2012). Relationship between years in the trade and the development of radiographic knee osteoarthritis and MRI-detected meniscal tears and bursitis in floor layers. A cross-sectional study of a historical cohort. *BMJ Open*, *2*(3), e001109. https://doi.org/10.1136/bmjopen-2012-001109

Karst, G. M., & Willett, G. M. (1995). Onset Timing of Electromyographic Activity in the Vastus Medialis Oblique and Vastus Lateralis Muscles in Subjects With and Without Patellofemoral Pain Syndrome. *Physical Therapy*, *75*(9), 813–823. Retrieved from http://ptjournal.apta.org/content/75/9/813.abstract

Kellgren, J. H., & Lawrence, J. S. (1957). Radiological Assessment of Osteo-Arthrosis. *Annals of the Rheumatic Diseases*, *16*(4), 494–502. https://doi.org/10.1136/ard.16.4.494

Kingston, D. C., & Acker, S. M. (2018). Thigh-calf contact parameters for six high knee flexion postures: Onset, maximum angle, total force, contact area, and center of force. *Journal of Biomechanics*, *67*(23), 46–54. https://doi.org/10.1016/j.jbiomech.2017.11.022

Kivimaki, J., Riihimäki, H., & Hanninen, K. (1992). Knee disorders in carpet and floor layers and painters. *Scandinavian Journal of Work, Environment and Health*, *18*(5), 310–316. https://doi.org/10.5271/sjweh.1571

Klussmann, A., Gebhardt, H., Nübling, M., Liebers, F., Quirós Perea, E., Cordier, W., … Rieger, M. A. (2010). Individual and occupational risk factors for knee osteoarthritis: results of a case-control study in Germany. *Arthritis Research & Therapy*, *12*(3), R88.

https://doi.org/10.1186/ar3015

Kouzaki, M., Shinohara, M., Masani, K., Tachi, M., Kanehisa, H., & Fukunaga, T. (2003). Local blood circulation among knee extensor synergists in relation to alternate muscle activity during low-level sustained contraction. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *95*(1), 49–56. https://doi.org/10.1152/japplphysiol.00671.2002

Krediet, C. T. P., de Bruin, I. G. J. M., Ganzeboom, K. S., Linzer, M., van Lieshout, J. J., & Wieling, W. (2005). Leg crossing, muscle tensing, squatting, and the crash position are effective against vasovagal reactions solely through increases in cardiac output. *Journal of Applied Physiology*, *99*, 1697–1703. https://doi.org/10.1152/japplphysiol.01250.2004.

Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics : Implications for injury prevention. *Journal of Biomechanics*, *45*(4), 666–671. https://doi.org/10.1016/j.jbiomech.2011.12.011

Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2013). Artefacts in measuring joint moments may lead to incorrect clinical conclusions : the nexus between science (biomechanics) and sports injury prevention ! *British Journal of Sports Medicine*, *47*(8), 470–473.

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., … Bahr, R. (2006). Mechanisms of Anterior Cruciate Ligament Injury in Basketball: Video Analysis of 39 Cases. *The American Journal of Sports Medicine*, *35*(3), 359–367. https://doi.org/10.1177/0363546506293899

Labarbera, K. E., Murphy, B. G., Laroche, D. P., & Cook, S. B. (2013). Sex differences in blood flow restricted isotonic knee extensions to fatigue. *Journal of Sports Medicine and Physical Fitness*, *53*(4), 444–452. https://doi.org/10.1002/14651858.CD003793.pub2.7.

Lankhorst, N. E., Bierma-Zeinstra, S. M. A., & van Middelkoop, M. (2012). Risk Factors for Patellofemoral Pain Syndrome: A Systematic Review. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(2), 81-A12. https://doi.org/10.2519/jospt.2012.3803

Lau, E. C., Cooper, C., Lam, D., Chan, V. N. H., Tsang, K. K., & Sham, A. (2000). Factors associated with osteoarthritis of the hip and knee in Hong Kong Chinese: Obesity, joint injury, and occupational activities. *American Journal of Epidemiology*, *152*(9), 855–862. https://doi.org/10.1093/aje/152.9.855

Leppänen, M., Pasanen, K., Kujala, U. M., Vasankari, T., Kannus, P., Äyrämö, S., … Parkkari, J. (2016). Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *The American Journal of Sports Medicine*, *45*(2), 386–393. https://doi.org/10.1177/0363546516665810

Liebensteiner, M. C., Szubski, C., Raschner, C., Krismer, M., Burtscher, M., Platzer, H. P., … Dirnberger, E. (2008). Frontal plane leg alignment and muscular activity during maximum eccentric contractions in individuals with and without patellofemoral pain syndrome. *Knee*, *15*(3), 180–186. https://doi.org/10.1016/j.knee.2008.01.009

Lim, B. O., Lee, Y. S., Kim, J. G., An, K. O., Yoo, J., & Kwon, Y. H. (2009). Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *American Journal of Sports Medicine*, *37*(9), 1728–1734. https://doi.org/10.1177/0363546509334220

Lo, G. H., McAlindon, T. E., Katz, J. N., Driban, J. B., Price, L. L., Eaton, C. B., … Suarez-Almazor, M. E. (2017). Systolic and pulse pressure associate with incident knee osteoarthritis: data from the Osteoarthritis Initiative. *Clinical Rheumatology*, 1–8.

https://doi.org/10.1007/s10067-017-3656-z

Loenneke, J. P., Fahs, C. A., Rossow, L. M., Sherk, V. D., Thiebaud, R. S., Abe, T., … Bemben, M. G. (2012). Effects of cuff width on arterial occlusion: Implications for blood flow restricted exercise. *European Journal of Applied Physiology*, *112*(8), 2903–2912. https://doi.org/10.1007/s00421-011-2266-8

Lohmander, L. S., Östenberg, A., Englund, M., & Roos, H. (2004). High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis and Rheumatism*, *50*(10), 3145–3152. https://doi.org/10.1002/art.20589

Longpré, H. H. S., Potvin, J. J. R., & Maly, M. R. M. (2013). Biomechanical changes at the knee after lower limb fatigue in healthy young women. *Clinical Biomechanics*, *28*(4), 441–447. https://doi.org/10.1016/j.clinbiomech.2013.02.010

Lorenz, A., Müller, O., Kohler, P., Wünschel, M., Wülker, N., & Leichtle, U. G. (2012). The influence of asymmetric quadriceps loading on patellar tracking - An in vitro study. *Knee*, *19*(6), 818–822. https://doi.org/10.1016/j.knee.2012.04.011

Macdonald, K. V, Sanmartin, C., Langlois, K., & Marshall, D. A. (2014). Symptom onset, diagnosis and management of osteoarthritis. *Health Report*, *25*(9), 10–17.

Malinzak, R. a, Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics*, *16*(5), 438–445.

Mandelbaum, B. R., Silvers, H. J., Watanabe, D. S., Knarr, J. S., Thomas, S. D., Griffin, L. Y., …

Garrett Jr, W. (2005). Effectiveness of a Neuromuscular and Proprioceptive Training Program in Preventing Anterior Cruciate Ligament Injuries in Female Athletes: 2-Year Follow-up. *American Journal of Sports Medicine*, *33*(7), 1003–1010. https://doi.org/10.1177/0363546504272261

Manninen, P., Heliövaara, M., Riihimäki, H., & Suomalainen, O. (2002). Physical workload and the risk of severe knee osteoarthritis. *Scandinavian Journal of Work, Environment and Health*, *28*(1), 25–32. https://doi.org/10.5271/sjweh.643

Marquez, G., Alegre, L. M., Jaén, D., & Aguado, X. (2017). Sex differences in kinetic and neuromuscular control during jumping and landing. *Journal of Musculoskeletal and Neuronal Interactions*, *17*(1), 409–416.

McLean, S. G., Felin, R. E., Suedekum, N., Calabrese, G., Passerallo, A., & Joy, S. (2007). Impact of fatigue on gender-based high-risk landing strategies. *Medicine and Science in Sports and Exercise*, *39*(3), 502–514. https://doi.org/10.1249/mss.0b013e3180d47f0

McMahon, J. J., Rej, S. J. E., & Comfort, P. (2017). Sex Differences in Countermovement Jump Phase Characteristics. *Sports*, *5*(8), 1–11. https://doi.org/10.3390/sports5010008

McWilliams, D. F., Leeb, B. F., Muthuri, S. G., Doherty, M., & Zhang, W. (2011). Occupational risk factors for osteoarthritis of the knee: A meta-analysis. *Osteoarthritis and Cartilage*, *19*(7), 829–839. https://doi.org/10.1016/j.joca.2011.02.016

Medina, J. M., Valovich, T. C., Howell, S. K., & Kingma, J. J. (2008). Timing of neuromuscular activation of the quadriceps and hamstrings prior to landing in high school male athletes , female athletes , and female non-athletes. *Journal of Electromyography and Kinesiology*, *18*(4), 591–597. https://doi.org/10.1016/j.jelekin.2006.11.009

Miao, P., Xu, Y., Pan, C., Liu, H., & Wang, C. (2015). Vastus medialis oblique and vastus lateralis activity during a double-leg semisquat with or without hip adduction in patients with patellofemoral pain syndrome. *BMC Musculoskeletal Disorders*, *16*(1), 289. https://doi.org/10.1186/s12891-015-0736-6

Mizner, R. L., Kawaguchi, J. K., & Chmielewski, T. L. (2008). Muscle Strength in the Lower Extremity Does Not Predict Postinstruction Improvements in the Landing Patterns of Female Athletes. *Journal of Orthopaedic & Sports Physical Therapy*, *38*(6), 353–361. https://doi.org/10.2519/jospt.2008.2726

Munro, A. G., Herrington, L. C., & Comfort, P. (2012). Comparison of landing knee valgus angle between female basketball and football athletes: Possible implications for anterior cruciate ligament and patellofemoral joint injury rates. *Physical Therapy in Sport*, *13*(4), 259–264. https://doi.org/10.1016/j.ptsp.2012.01.005

Murakami, T. (2002). Squatting: The Hemodynamic Change Is Induced By Enhanced Aortic Wave Reflection. *European Heart Journal*, *15*(11), 986–988.

Murphy, L., Schwartz, T. A., Helmick, C. G., Renner, J. B., Tudor, G., Koch, G., … Jordan, J. M. (2008). Lifetime risk of symptomatic knee osteoarthritis. *Arthritis Care and Research*, *59*(9), 1207–1213. https://doi.org/10.1002/art.24021

Myer, G. D., Ford, K. R., Di Stasi, S. L., Foss, K. D. B., Micheli, L. J., & Hewett, T. E. (2015). High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: Is PFP itself a predictor for subsequent ACL injury? *British Journal of Sports Medicine*, *49*(2), 118–122. https://doi.org/10.1136/bjsports-2013-092536

Myer, G. D., Ford, K. R., & Hewett, T. E. (2005). The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology*, *15*(2), 181–189. https://doi.org/10.1016/j.jelekin.2004.08.006

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2010). Clinical correlates to laboratory measures for use in non-contact anterior cruciate ligament injury risk prediction algorithm. *Clinical Biomechanics*, *25*(7), 693–699. https://doi.org/10.1016/j.clinbiomech.2010.04.016

Myer, G. D., Ford, K. R., Khoury, J., Succop, P., & Hewett, T. E. (2011). Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *British Journal of Sports Medicine*, *45*(4), 245–252. https://doi.org/10.1136/bjsm.2009.069351

Myer, G. D., Ford, K. R., Palumbo, J. P., & Hewett, T. E. (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *Journal of Strength and Conditioning Research*, *19*(1), 51–60.

Nade, S., & Newbold, P. J. (1983). Factors determining the level and changes in intra-articular pressure in the knee joint of the dog. *Journal of Physiology*, *338*, 21–36. https://doi.org/10.1113/jphysiol.1983.sp014657

Nakagawa, T. H., Moriya, É. T. U., Maciel, C. D., & Serrão, F. V. (2012). Frontal plane biomechanics in males and females with and without patellofemoral pain. *Medicine and Science in Sports and Exercise*, *44*(9), 1747–1755. https://doi.org/10.1249/MSS.0b013e318256903a

Neto, G. R., Novaes, J. S., Dias, I., Brown, A., Vianna, J., & Cirilo-Sousa, M. S. (2016). Effects of resistance training with blood flow restriction on haemodynamics: A systematic review. *Clinical Physiology and Functional Imaging*, 1–8. https://doi.org/10.1111/cpf.12368

Nonnenmann, M. W., Anton, D. C., Gerr, F., & Yack, H. J. (2010). Dairy Farm Worker Exposure to Awkward Knee Posture During Milking and Feeding Tasks. *Journal of Occupational and Environmental Hygiene*, *7*(8), 483–489. https://doi.org/10.1080/15459624.2010.487036

O'Donnell, T. V, & McIlroy, M. B. (1962). The circulatory effects of squatting. *American Heart Journal*, *64*(3), 347–356. https://doi.org/10.1016/0002-8703(59)90181-4

Øiestad, B. E., Juhl, C. B., Eitzen, I., & Thorlund, J. B. (2015). Knee extensor muscle weakness is a risk factor for development of knee osteoarthritis. A systematic review and meta-analysis. *Osteoarthritis and Cartilage*, *23*(2), 171–177. https://doi.org/10.1016/j.joca.2014.10.008

Padua, D. A., Arnold, B. L., Perrin, D. H., Gansneder, B. M., Carcia, C. R., & Granata, K. P. (2006). Fatigue, Vertical Leg Stiffness, and Stiffness Control Strategies in Males and Females. *Journal of Athletic Training*, *41*(3), 294–304.

Padulo, J., Tiloca, A., Powell, D., Granatelli, G., Bianco, A., & Paoli, A. (2013). EMG amplitude of the biceps femoris during jumping compared to landing movements. *SpringerPlus*, *2*(1), 1–7. https://doi.org/10.1186/2193-1801-2-520

Palmieri-Smith, R. M., McLean, S. G., Ashton-Miller, J. A., & Wojtys, E. M. (2009). Association of quadriceps and hamstrings cocontraction patterns with knee joint loading. *Journal of Athletic Training*, *44*(3), 256–263. https://doi.org/10.4085/1062-6050-44.3.256

Palmieri-Smith, R. M., Thomas, A. C., Karvonen-Gutierrez, C., & Sowers, M. F. (2010). Isometric Quadriceps Strength in Women with Mild, Moderate, and Severe Knee Osteoarthritis. *American*

Journal of Physical Medicine & Rehabilitation, *89*(7), 541–548. https://doi.org/10.1097/PHM.0b013e3181ddd5c3

Palmieri-Smith, R. M., Wojtys, E. M., & Ashton-Miller, J. A. (2008). Association between preparatory muscle activation and peak valgus knee angle. *Journal of Electromyography and Kinesiology*, *18*(6), 973–979. https://doi.org/10.1016/j.jelekin.2007.03.007

Parker, B. A., Smithmyer, S. L., Pelberg, J. A., Mishkin, A. D., Herr, M. D., Proctor, D. N., … Ad, M. (2007). Sex differences in leg vasodilation during graded knee extensor exercise in young adults. *Journal of Applied Physiology*, *103*, 1583–1591. https://doi.org/10.1152/japplphysiol.00662.2007.

Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., Huang, B., & Hewett, T. E. (2010). Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *The American Journal of Sports Medicine*, *38*(10), 1968–1978. https://doi.org/10.1177/0363546510376053

Pedowitz, R. A., Gershuni, D. H., Crenshaw, A. G., Petras, S. L., Danzig, L. A., & Hargens, A. R. (1989). Intraarticular pressure during continuous passive motion of the human knee. *Journal of Orthopaedic Research*, *7*(4), 530–537. https://doi.org/10.1002/jor.1100070410

Pereira, D., Peleteiro, B., Araújo, J., Branco, J., Santos, R. A., & Ramos, E. (2011). The effect of osteoarthritis definition on prevalence and incidence estimates: A systematic review. *Osteoarthritis and Cartilage*, *19*(11), 1270–1285. https://doi.org/10.1016/j.joca.2011.08.009

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, *25*(2), 142–146. https://doi.org/10.1016/j.clinbiomech.2009.10.005

Puthoff, M. L., Janz, K. F., & Nielson, D. (2008). The relationship between lower extremity strength and power to everday walking behaviors in older adults with functional limitations. *Journal of Geriatric Physical Therapy*, *31*(1), 24–31. https://doi.org/10.1519/00139143-200831010-00005

Quatman, C. E., & Hewett, T. E. (2009). The anterior cruciate ligament injury controversy: is "valgus collapse" a sex-specific mechanism? *British Journal of Sports Medicine*, *43*(5), 328–335. https://doi.org/10.1136/bjsm.2009.059139

Raghavendra, G. K. G. (2012). Does Squatting Worsen Lower Limb Ischemia in Patients with Peripheral Arterial Disease? *Indian Journal of Surgery*, *74*(4), 298–300. https://doi.org/10.1007/s12262-011-0364-9

Rehan Youssef, A., Longino, D., Seerattan, R., Leonard, T., & Herzog, W. (2009). Muscle weakness causes joint degeneration in rabbits. *Osteoarthritis and Cartilage*, *17*(9), 1228–1235. https://doi.org/10.1016/j.joca.2009.03.017

Risberg, M. A., Mørk, M., Jenssen, H. K., & Holm, I. (2001). Design and Implementation of a Neuromuscular Training Program Following Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *31*(11), 620–631. https://doi.org/10.2519/jospt.2001.31.11.620

Rossberg, F., & Peňaz, J. (1988). Initial cardiovascular response on change of posture from squatting to standing. *European Journal of Applied Physiology*, *57*, 93–97.

Russ, D. W., & Kent-Braun, J. A. (2003). Sex differences in human skeletal muscle fatigue are eliminated under ischemic conditions. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *94*(6), 2414–2422. https://doi.org/10.1152/japplphysiol.01145.2002

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex Differences in Valgus Knee Angle During a Single-Leg Drop Jump. *Journal of Athletic Training*, *41*(2), 166–171.

Rutherford, D. J., Hubley-Kozey, C. L., & Stanish, W. D. (2013). Changes in knee joint muscle activation patterns during walking associated with increased structural severity in knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *23*(3), 704–711. https://doi.org/10.1016/j.jelekin.2013.01.003

Rytter, S., Jensen, L. K., & Bonde, J. P. (2008). Clinical knee findings in floor layers with focus on meniscal status. *BMC Musculoskeletal Disorders*, *9*(1), 144. https://doi.org/10.1186/1471-2474-9-144

Sadamoto, T., Bonde-Petersen, F., & Suzuki, Y. (1983). Skeletal Muscle Tension, Flow, Pressure, and EMG During Sustained Isometric Contractions in Humans. *European Journal of Applied Physiology*, *51*, 395–408.

Sakai, N., Luo, Z. P., Rand, J. A., & An, K. N. (2000). The influence of weakness in the vastus medialis oblique muscle on the patellofemoral joint: An in vitro biomechanical study. *Clinical Biomechanics*, *15*(5), 335–339. https://doi.org/10.1016/S0268-0033(99)00089-3

Sandmark, H., Hogstedt, C., & Vingård, E. (2000). Primary osteoarthrosis of the knee in men and women as a result of lifelong physical load from work. *Scandinavian Journal of Work, Environment and Health*, *26*(1), 20–25. https://doi.org/10.5271/sjweh.505

Sawatsky, A., Bourne, D., Horisberger, M., Jinha, A., & Herzog, W. (2012). Changes in patellofemoral joint contact pressures caused by vastus medialis muscle weakness. *Clinical*

Biomechanics, *27*(6), 595–601. https://doi.org/10.1016/j.clinbiomech.2011.12.011

Schmitz, R. J., & Shultz, S. J. (2010). Contribution of Knee Flexor and Extensor Strength on Sex-Specific Energy Absorption and Torsional Joint Stiffness During Drop Jumping. *Journal of Athletic Training*, *45*(5), 445–452.

Schneiders, A. G., Sullivan, S. J., O'Malley, K. J., Clarke, S. V., Knappstein, S. A., & Taylor, L. J. (2010). A Valid and Reliable Clinical Determination of Footedness. *PM and R*, *2*(9), 835–841. https://doi.org/10.1016/j.pmrj.2010.06.004

Schwartz, M. H., & Rozumalski, A. (2005). A new method for estimating joint parameters from motion data. *Journal of Biomechanics*, *38*, 107–116. https://doi.org/10.1016/j.jbiomech.2004.03.009

Segal, N. A., Torner, J. C., Felson, D. T., Niu, J., Sharma, L., Lewis, C. E., & Nevitt, M. (2010). Knee extensor strength does not protect against incident knee symptoms at 30 months in the multicenter knee osteoarthritis (MOST) cohort. *Pm&R*, *1*(5), 459–465. https://doi.org/10.1016/j.pmrj.2009.03.005.Knee

Seidler, A., Bolm-Audorff, U., Abolmaali, N., Elsner, G., & knee osteoarthritis study-group. (2008). The role of cumulative physical work load in symptomatic knee osteoarthritis - a case-control study in Germany. *Journal of Occupational Medicine and Toxicology*, *3*(1), 14. https://doi.org/10.1186/1745-6673-3-14

Sell, T. C., Ferris, C. M., Abt, J. P., Tsai, Y. S., Myers, J. B., Fu, F. H., & Lephart, S. M. (2007). Predictors of Proximal Tibia Anterior Shear Force during a Vertical Stop-Jump. *Journal of Orthopaedic Research*, *25*(12), 1589–1597. https://doi.org/10.1002/jor

Sharma, L., Dunlop, D., Cahue, S., Song, J., & Hayes, K. (2003). Quadriceps Strength and Osteoarthritis Progression in Malaligned and Lax Knees. *Annals of Internal Medicine*, *138*(8), 613–620. https://doi.org/200304150-00006 [pii]

Sharpey-Schafer, E. P. (1956). Effects of Squatting on the Normal and Failing Circulation. *British Medical Journal*, *1*(4975), 1072–1074. https://doi.org/10.1136/bmj.1.4975.1072

Shultz, S. J., Nguyen, A., Leonard, M. D., & Schmitz, R. J. (2009). Thigh Strength and Activation as Predictors of Knee Biomechanics during a Drop Jump Task. *Medicine & Science in Sports & Exercise*, *41*(4), 857–866. https://doi.org/10.1249/MSS.0b013e3181e3b3f

Sjøgaard, G., Savard, G., & Juel, C. (1988). Muscle blood flow during isometric activity and its relation to muscle fatigue. *European Journal of Applied Physiology*, *57*, 327–335.

Skelton, D. A., Greig, C. A., Davies, J. M., & Young, A. (1994). Strength, power and related functional ability of healthy people aged 65—89 years. *Age and Ageing*, *23*, 371–377.

Slemenda, C., Hellman, D., Brandt, K., Katz, B., Mazzuca, S., Braunstein, E., & Byrd, D. (1998). Reduced quadrcieps strength relative to body weight a risk factor for knee osteoarthritis in women? *Arthritis and Rheumatism*, *41*(11), 1951–1959.

Sophia Fox, A. J., Bedi, A., & Rodeo, S. A. (2009). The Basic Science of Articular Cartilage: Structure, Composition, and Function. *Sports Health: A Multidisciplinary Approach*, *1*(6), 461–468. https://doi.org/10.1177/1941738109350438

Stålhammar, H. R., Leskinen, T. P. J., Kuorinka, I. A. A., Gautreau, M. H. J., & Troup, J. D. G. (1986). Postural, epidemiological and biomechanical analysis of luggage handling in an aircraft luggage compartment. *Applied Ergonomics*, *17*(3), 177–183. https://doi.org/10.1016/0003-

6870(86)90003-7

Steppan, J., Barodka, V., Berkowitz, D. E., & Nyhan, D. (2011). Vascular Stiffness and Increased Pulse Pressure in the Aging Cardiovascular System. *Cardiology Research and Practice*, *2011*, 1–8. https://doi.org/10.4061/2011/263585

Takagi, S., Omori, G., Koga, H., Endo, K., Koga, Y., Nawata, A., & Endo, N. (2017). Quadriceps muscle weakness is related to increased risk of radiographic knee OA but not its progression in both women and men: the Matsudai Knee Osteoarthritis Survey. *Knee Surgery, Sports Traumatology, Arthroscopy*. https://doi.org/10.1007/s00167-017-4551-5

Takeda, H., Nakagawa, T., Nakamura, K., & Engebretsen, L. (2011). Prevention and management of knee osteoarthritis and knee cartilage injury in sports. *British Journal of Sports Medicine*, *45*(4), 304–309. https://doi.org/10.1136/bjsm.2010.082321

Teichtahl, A. J., Wluka, A. E., Wang, Y., Urquhart, D. M., Hanna, F. S., Berry, P. A., … Cicuttini, F. M. (2010). Occupational activity is associated with knee cartilage morphology in females. *Maturitas*, *66*(1), 72–76. https://doi.org/10.1016/j.maturitas.2010.01.014

Tennant, L. M. (2016). *Neuromuscular Control of Gait and Squatting Following a Simulated Occupational Kneeling Exposure*. University of Waterloo. Retrieved from http://hdl.handle.net/10012/10174

Tennant, L. M., Chong, H. C., & Acker, S. M. (2018). The effects of a simulated occupational kneeling exposure on squat mechanics and knee joint load during gait. *Ergonomics*, *61*(6), 839–852. https://doi.org/10.1080/00140139.2017.1411529

Teschke, K., Trask, C., Johnson, P., Chow, Y., Village, J., & Koehoorn, M. (2009). Measuring posture for epidemiology: Comparing inclinometry, observations and self-reports. *Ergonomics*, *52*(9), 1067–1078. https://doi.org/10.1080/00140130902912811

Tevald, M. A., Murray, A. M., Luc, B., Lai, K., Sohn, D., & Pietrosimone, B. G. (2016). The contribution of leg press and knee extension strength and power to physical function in people with knee osteoarthritis: A cross-sectional study. *Knee*, *23*(6), 942–949. https://doi.org/10.1016/j.knee.2016.08.010

Thorlund, J. B., Felson, D. T., Segal, N. A., Nevitt, M. C., Niu, J., Neogi, T., … Englund, M. (2016). Effect of Knee Extensor Strength on Incident Radiographic and Symptomatic Knee Osteoarthritis in Individuals With Meniscal Pathology: Data From the Multicenter Osteoarthritis Study. *Arthritis Care and Research*, *68*(11), 1640–1646. https://doi.org/10.1002/acr.22889

Toivanen, A. T., Heliövaara, M., Impivaara, O., Arokoski, J. P. A., Knekt, P., Lauren, H., & Kröger, H. (2010). Obesity, physically demanding work and traumatic knee injury are major risk factors for knee osteoarthritis-a population-based study with a follow-up of 22 years. *Rheumatology*, *49*(2), 308–314. https://doi.org/10.1093/rheumatology/kep388

Tomescu, S. S., Bakker, R., Beach, T. A. C., & Chandrashekar, N. (2018). The Effects of Filter Cutoff Frequency on Musculoskeletal Simulations of High-Impact Movements. *Journal of Applied Biomechanics, 34,* 336–341.

Tootsi, K., Kals, J., Zilmer, M., Paapstel, K., & Märtson, A. (2016). Severity of osteoarthritis is associated with increased arterial stiffness. *International Journal of Rheumatology*, *2016*. https://doi.org/10.1155/2016/6402963

Tschakovsky, M. E., Matusiak, K., Vipond, C., & McVicar, L. (2011). Lower limb-localized vascular phenomena explain initial orthostatic hypotension upon standing from squat. *AJP:*

Heart and Circulatory Physiology, *301*(5), H2102–H2112. https://doi.org/10.1152/ajpheart.00571.2011

Umbel, J. D., Hoffman, R. L., Dearth, D. J., Chleboun, G. S., Manini, T. M., & Clark, B. C. (2009). Delayed-onset muscle soreness induced by low-load blood flow-restricted exercise. *European Journal of Applied Physiology*, *107*, 687–695. https://doi.org/10.1007/s00421-009-1175-6

van Beekvelt, M. C. P., Borghuis, M. S., van Engelen, B. G., Wevers, R. A., & Colier, W. N. J. M. (2001). Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle. *Clinical Science*, *28*, 21–28.

van Beekvelt, M. C. P., Orbon, K., van Engelen, B. G. M., Wevers, R. A., & Colier, W. N. J. M. (2003). NIR spectroscopic measurement of local muscle metabolism during rhythmic, sustained, and intermittent handgrip exercise. In *Proc.SPIE* (Vol. 5138, pp. 35–45). https://doi.org/10.1117/12.502380

Verbeek, J., Mischke, C., Robinson, R., Ijaz, S., Kuijer, P., Kievit, A., … Neuvonen, K. (2017). Occupational Exposure to Knee Loading and the Risk of Osteoarthritis of the Knee: A Systematic Review and a Dose-Response Meta-Analysis. *Safety and Health at Work*, *8*(2), 130–142. https://doi.org/10.1016/j.shaw.2017.02.001

Virayavanich, W., Alizai, H., Baum, T., Nardo, L., Nevitt, M. C., Lynch, J. A., … Link, T. M. (2013). Association of frequent knee bending activity with focal knee lesions detected with 3T magnetic resonance imaging: Data from the osteoarthritis initiative. *Arthritis Care and Research*, *65*(9), 1441–1448. https://doi.org/10.1002/acr.22017

Walsh, D. A. (1999). Angiogenesis and arthritis. *Rheumatology (Oxford)*, *38*, 103–112.

Walsh, M. S., Böhm, H., Butterfield, M. M., & Santhosam, J. (2007). Gender bias in the effects of arms and countermovement on jumping performance. *Journal of Strength and Conditioning Research*, *21*(2), 362–366.

Waryasz, G. R., & McDermott, A. Y. (2008). Patellofemoral pain syndrome (PFPS): a systematic review of anatomy and potential risk factors. *Dynamic Medicine*, *7*(1), 9. https://doi.org/10.1186/1476-5918-7-9

Weesner, C. L., Albohm, M. J., & Ritter, M. A. (1986). A Comparison of Anterior and Posterior Cruciate Ligament Laxity Between Female and Male Basketball Players. *The Physician and Sportsmedicine*, *14*(5), 149–154. https://doi.org/10.1080/00913847.1986.11709076

Wernbom, M., Järrebring, R., Andreasson, M. A., & Augustsson, J. (2009). Acute Effects of Blood Flow Restriction on Muscle Activity and Endurance During Fatiguing Dynamic Knee Extensions at Low Load. *Journal of Strength and Conditioning Research*, *23*(8), 2389–2395. https://doi.org/10.1519/JSC.0b013e3181bc1c2a

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement*. *Biomechanics and Motor Control of Human Movement* (4th ed.). Hoboken, NJ: John Wiley & Sons.

Wu, G., & Cavanagh, P. R. (1995). ISB Recommendations in the Reporting for Standardization of Kinematic Data. *Journal of Biomechanics*, *28*(10), 1257–1261. https://doi.org/10.1016/0021-9290(95)00017-C

Wüst, R. C. I., Morse, C. I., Haan, A. De, Jones, D. A., & Degens, H. (2008). Sex differences in contractile properties and fatigue resistance of human skeletal muscle. *Experimental Physiology*, *93*(7), 843–850. https://doi.org/10.1113/expphysiol.2007.041764

Yasuda, T., Brechue, W., Fujita, T., Shirakawa, J., Sato, Y., & Abe, T. (2009). Muscle activation during low-intensity muscle contractions with restricted blood flow. *Journal of Sports Sciences*, *27*(5), 479–489. https://doi.org/10.1080/02640410802626567

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2010). The Knee Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *The Knee*, *17*(2), 127–131. https://doi.org/10.1016/j.knee.2009.07.015

Yoon, T., Schlinder Delap, B., Griffith, E. E., & Hunter, S. K. (2007). Mechanisms of fatigue differ after low- and high-force fatiguing contractions in men and women. *Muscle and Nerve*, *36*(4), 515–524. https://doi.org/10.1002/mus.20844

Yoshimura, N., Muraki, S., Oka, H., Tanaka, S., Kawaguchi, H., Nakamura, K., & Akune, T. (2012). Accumulation of metabolic risk factors such as overweight, hypertension, dyslipidaemia, and impaired glucose tolerance raises the risk of occurrence and progression of knee osteoarthritis: A 3-year follow-up of the ROAD study. *Osteoarthritis and Cartilage*, *20*(11), 1217–1226. https://doi.org/10.1016/j.joca.2012.06.006

Yoshimura, N., Nishioka, S., Kinoshita, H., Hori, N., Nishioka, T., Ryujin, M., … Cooper, C. (2004). Risk Factors for Knee Osteoarthritis in Japanese Women: Heavy Weight, Previous Joint Injuries, and Occupational Activities. *Journal of Rheumatology*, *31*(1), 157–162.

Zazulak, B. T., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender Comparison of Hip Muscle Activity During Single-Leg Landing. *Journal of Orthopaedic & Sports Physical Therapy*, *35*(5), 292–299.

Zebis, M. K., Andersen, L. L., Bencke, J., & Kjaer, M. (2009). Identification of Athletes at Future Risk of Anterior Cruciate Ligament Ruptures by Neuromuscular Screening. *American Journal* *of Sports Medicine*, *37*(10), 1967–1973. https://doi.org/10.1177/0363546509335000

Zeni, J. A., Rudolph, K., & Higginson, J. S. (2010). Alterations in quadriceps and hamstrings coordination in persons with medial compartment knee osteoarthritis. *Journal of Electromyography and Kinesiology*, *20*(1), 148–154. https://doi.org/10.1016/j.jelekin.2008.12.003

Zhang, R., Claassen, J. a H. R., Shibata, S., Kilic, S., Martin-Cook, K., Diaz-Arrastia, R., & Levine, B. D. (2009). Arterial-cardiac baroreflex function: insights from repeated squat-stand maneuvers. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, *297*(1), R116–R123. https://doi.org/10.1152/ajpregu.90977.2008

Zhang, Y., Xu, L., Nevitt, M. C., Aliabadi, P., Yu, W., Qin, M., … Felson, D. T. (2001). Comparison of the Prevalence of Knee Osteoarthritis between the Elderly Chinese Population in Beijing and Whites in the United States: The Beijing Osteoarthritis Study. *Arthritis and Rheumatism*, *44*(9), 2065–2071. https://doi.org/10.1002/1529-0131(200109)44:9<2065::AID-ART356>3.0.CO;2-Z

Zuj, K. A., Prince, C. N., Hughson, R. L., & Peterson, S. D. (2018). Enhanced muscle blood flow with intermittent pneumatic compression of the lower leg during plantar flexion exercise and recovery. *Journal of Applied Physiology*, *124*(2), 302–311. https://doi.org/10.1152/japplphysiol.00784.2017

Appendix A

Table A.1 Average knee angles during the last 5 seconds of the squat exposure (º)

	Cyclic	Sustained	Difference
Female	151.5 (± 3.1)	152.7 (± 3.5)	2.3 (± 1.6)
Male	146.2 (± 11.9)	150.1 (± 6.4)	4.3 (± 6.1)
All	149.0 (± 8.8)	151.4 (± 5.2)	3.3 (± 4.4)

Table A.2 Cyclic squat exposure knee angles (º)

	Cyclic Average	Variation of Cyclic Squat Angles
Female	151.5 (± 3.1)	1.1 (± 0.7)
Male	146.2 (± 11.9)	0.9 (± 0.8)
All	149.0 (± 8.8)	1.0 (± 0.7)