The biomechanical changes during sport-specific tasks and different commercially available footwear in individuals following meniscectomy

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Abbreviations

°	Degrees
2D	Two dimensional
3D	Three dimensional
ADL	Activity of daily living
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Spine
BF	Biceps Femoris
BMI	Body Mass Index
BW	Body Weight
CAST	Calibrated Anatomical System Technique
CCR	Co-contraction ratio
CI	Confidence Interval
CMC	Correlation of multiple coefficient
COM	Centre of Mass
COP	Centre of Pressure
DOF	Degree of Freedom
EKAM	External knee adduction moment
EMG	Electromyography
ES	Effect Size
Ext	Extension
Flx	Flexion
GRF	Ground-reaction force
KAAI	Knee adductor angular impulse
KFM	Knee flexion moment
kg	Kilogram
KOOS	Knee injury and osteoarthritis outcome score
LHS	Left heel strike
LOFF	Left off
LON	Left on
LTO	Left toe off
m	Metre
mA	Milliampere
MDD	Minimal detectable difference
mm	Millimetre
MRI	Magnetic resonance imaging
ms	Millisecond
MIHP	Manchester Institute of Health and Performance
MVC	Maximal voluntary contraction
NHS	National Health Service
Nm	Newton metre
OA	Osteoarthritis
PSIS	Posterior superior iliac spine

QOL	Quality of life
QTM	Qualisys track manager
RHS	Right heel strike
RMS	Root mean square
ROFF	Right off
ROM	Range of motion
RON	Right on
RTO	Right toe off
SD	Standard deviation
SEBT	Star excursion balance test
SEM	Standard error of the measurement
sEMG	Surface electromyography
SENIAM	Surface Electromyography for the Non-Invasive Assessment of muscles
SPSS	Statistical Package for the Social Sciences
ST	Semitendinosus
TSK	Tampa Scale of Kinesiophobia
VAS	Visual analogue scale
VGRF	Vertical ground-reaction force
VL	Vastus lateralis
VM	Vastus medialis

Abstract

Injuries to the meniscus are common particularly in sporting individuals. Traumatic meniscal tears typically occur due to a high impact twisting action on a planted foot, which can be seen in sports such as basketball, football and skiing. Competitive athletes generally agree to having a meniscectomy surgery with the objective of returning to the same level of activity as was considered normal before the injury, however the effect of returning to sport and performing sport-specific tasks has not been researched in depth following meniscectomy. Altered knee mechanics and increased knee loading, like those seen in knee osteoarthritis (OA), have been observed following a meniscectomy, therefore identifying ways to reduce knee loading and slow the progression of OA are a priority. Individuals following meniscectomy have been reported to be 15 times more likely to develop knee OA compared to the general healthy population. Whilst it is well researched that medial partial meniscectomies result in the onset of medial (OA), little is known about the biomechanical effects following lateral meniscectomy in comparison to individuals following medial meniscectomy. Therefore, an improved understanding of biomechanical changes following medial and lateral meniscectomy, specifically during both functional and sport-specific tasks is vital and whether approaches such as the use of different footwear have an influence to aid in offloading the knee.

To develop a robust and reliable test protocol for the investigation of the biomechanical outcomes in individuals following meniscectomy, a repeatability study was performed, which enabled the development of a protocol that was applied in the following studies of the thesis. The BOOM study investigated biomechanical and clinical outcomes following meniscectomy surgery in 29 individuals following both medial and lateral meniscectomy in comparison to 20 healthy controls. It was found that there were few differences when comparing individuals following medial and lateral meniscectomy, therefore the sub-groups were combined to analyse the knee joint loading. Knee loading was increased in the early stages of rehabilitation during walking, running and landing, highlighting initial effects of non-effective rehabilitation with muscle weakness, stiffness in joint motion and kinesiophobia, which may have the potential to lead on to knee joint degeneration.

Lastly, the Meni-Foot study looked at the use of three different types of footwear including cushioning footwear, stability footwear and lateral wedge footwear in comparison to neutral footwear, to find a way to offload the affected compartment of the knee and slow the risk of OA progression, specifically in a young active population. Lateral wedge footwear was found to offload the medial compartment of the knee and aid individuals following medial meniscectomy, however further research needs to be done looking at a more comfortable shoe with a lateral wedge to offload the medial compartment and a greater medial arch support to offload the lateral compartment whilst considering pain and motion during dynamic tasks.

To summarise the findings in this thesis, other than greater trunk lean in the lateral meniscectomy during walking, there were no significant differences in knee loading between individuals following a medial meniscectomy and individuals following a lateral meniscectomy. The lack of differences in knee loading between medial and lateral meniscectomy groups was unexpected, however it suggested combining groups in the short-term period following surgery was applicable. Individuals on average 6 months post-meniscectomy showed reduced balance, isometric strength and self-reported function. Individuals showed a quadriceps avoidance strategy, with altered muscle activation, stiffer movement patterns and greater kinesiophobia compared to healthy controls. Non-invasive interventions such as lateral wedge footwear can be used to offload the medial compartment of the knee during walking and therefore, could be beneficial for individuals following medial meniscectomy. Further research needs to be done on sport specific tasks and different footwear conditions depending on which compartment of the knee it aims to offload.

Chapter 1 - **Introduction**

The meniscus plays a vital part of knee joint health as it aids in stabilising the knee, acting as a shock absorber, and transmitting load, with the lateral meniscus taking as much as 70% of the load in the lateral compartment and the medial meniscus carrying approximately 50% of the medial load (Fox et al., 2015; Kurosawa et al., 1980). Injury to the knee, specifically the meniscus is one of the most common problems in competitive sports, due to high demand that is placed on the meniscus in high impact movements such as running, change of direction and landing movements (Stanley et al., 2016; Mitchell et al., 2016). Meniscal injuries are responsible for over 500,000 injuries every year in the USA (Kim et al., 2011; Englund et al., 2016) and an estimated 25,000 hospital admissions each year in the UK (Snoeker et al., 2013). Medial meniscal tears are twice as likely to occur than those on the lateral side, due to the inability of the medial meniscus to move with the joint (Campbell et al., 2001).

Altered knee mechanics have been reported following surgery, including reduced joint contact area and significantly increased joint contact force (Bae et al., 2012), resulting in reduced ability to transmit load through the knee (Badlani et al., 2013; Edd et al., 2015; Willy et al., 2016). These alterations in biomechanics can induce composition changes of the articular cartilage that can lead to degeneration of the menisci and gradual development of knee osteoarthritis (OA) (Dieppe and Lohmander., 2005). Sustaining a meniscal injury significantly increases the risk of developing knee OA, with studies finding that 80% of individuals develop OA 5 to 10 years after a meniscectomy, further resulting in a 15-fold increased risk of requiring total knee reconstruction (Englund et al., 2004; Petty et al., 2011; Papalia et al., 2011; Hall et al., 2014; Khan et al., 2017).

Surgical arthroscopic partial meniscectomy is the most common treatment for a torn or injured meniscus in sporting populations, as there are minimal healing capabilities in the meniscus and recovery time following a meniscectomy is often shorter compared to meniscal repairs or transplantations (Englund et al., 2008). The loads on both the medial and lateral compartment of the knee are even greater during dynamic tasks when considering the high demand on the knee in sport-specific movements such as running, landing and changing of direction (De David et al., 2015). Medial meniscectomies have been researched more frequently, which may be due to them being more common and reoperation rates being higher (Paxton et al., 2011). The lateral meniscus, however, is of particular importance in young active people, particularly in athletes and sportspersons as it aids in cushioning the knee during dynamic movement due to its mobility. Previous studies have demonstrated less favourable outcomes after lateral meniscectomy compared with medial meniscectomy in terms of joint degeneration (Frabricant et al., 2007), time to return to pre-injury level and incidence of adverse events (Nawabi et al., 2014). However, the biomechanical mechanisms associated to these outcomes lack investigation following a lateral meniscectomy. Longo et al., (2019) analysed 57 individuals pre-and post-partial meniscectomy in both the medial and lateral meniscus and found that there was significant progression of knee OA in both groups of individuals following medial meniscectomy ranging from 17.2% pre-surgery to 65.95% post-surgery and in individuals following lateral meniscectomy ranging from 17.64% pre-surgery to 58.82% post-surgery. The fact that individuals following medial and lateral meniscectomy are at risk of developing knee joint OA clearly highlights that both need to be analysed in terms of the biomechanical outcomes to identify ways to slow OA progression in both compartments. Greater understanding following lateral meniscectomy in comparison to medial meniscectomy needs to be established, specifically how the menisci deals with knee loading during competitive sports where it is at greater risk of injury/re-injury (Mitchell et al., 2016). To date, there has only ever been one study that looked at the biomechanical outcomes post-lateral meniscectomy, and this was investigated during bilateral drop landing (Ford et al., 2011).

Individuals who have sustained a traumatic meniscal tear are usually young and active with tears occurring during sporting tasks (Beaufils et al., 2014). Traumatic tears frequently occur during an instance where the individual has an increased load occurring at the knee during a twisting motion (Weiss and Whatman., 2015). Therefore, it is important to look at multi-directional dynamic movements which would be replicated in a sporting environment. Individuals that participated in competitive sport prior to a meniscectomy place a high demand on their meniscus to manage the loads that occur across the joint following surgery and aim to return to full competitive sport as soon as possible (Eberbach et al., 2018). Zedde et al., (2014) suggested that returning to competitive activities such as basketball should be longer than three months post-surgery, however the return to sport criteria often allows individuals following meniscectomy to return at three months post-surgery. It is vital to understand knee loading following meniscectomy and whether compensatory mechanisms are used in the early stages on rehabilitation, which may have a detrimental long-term effect

Although tibiofemoral knee loading has been previously analysed following meniscectomy, this has generally been done during walking, with only a few studies looking at running and more dynamic tasks (Willy et al., 2016; Hall et al., 2017). Additionally, the running studies were seen not to be ecologically valid, and when looking at the young active population (Mitchell et al., 2016), it is important to identify the loads that occur in tasks such as landing and change of directions. Willy et al., (2016) examined treadmill running which, although the loads during treadmill running and over-ground running have been shown to be similar (Fellin et al., 2010), running on a treadmill cannot simulate in-game dynamic movements (Raja Azidin et al., 2015). Only one study has investigated over-ground running (Hall et al., 2017) and this was conducted barefoot at a relatively slow speed jogging pace of (2.45 m/s) compared to typical running speeds seen in competitive sports (5-7 m/s) (Ferro et al., 2014). Ford et al., (2011) and Hsu et al., (2016) were the only studies to examine drop landing and single leg hop movements in individuals following meniscectomy. Further research is needed to explore movement patterns and knee joint loading during more demanding sport-specific tasks post meniscectomy and return-to-sport abilities for the young active populations.

As many athletic individuals with a meniscal tear undergo partial meniscectomy intend to return to sports, knowledge of the changes in knee joint loading during such activities are important to identify the implications that may affect the ability to return to their competitive level of activity, however this is significantly under researched (Sherman et al., 2020). Following meniscectomy, reduced contact surface area within the joint and increased contact pressures can be seen, resulting in a reduced ability to transmit load (Badlani et al., 2013). Indirect measures of medial knee loading, such as the external knee adductor moments (EKAM) and knee adduction angular impulses (KAAI) and knee flexion moment (KFM) and muscle activation, have been associated with increased risk of developing patellofemoral and medial tibiofemoral OA (Hall et al., 2014; Mills et al., 2008; Hulet et al., 2015; Willy et al., 2017; Thorlund et al., 2017; Chang et al., 2014). Coordination of muscle activity also contributes to knee joint loading (Schmitt & Rudolph, 2008). The quadriceps and hamstrings contract simultaneously during the stance phase of walking and play an important role for knee joint loading as muscles support the joint due to them crossing over the knee joint and controlling knee joint movement (Winby et al., 2009). Despite information about contributing factors and underlying mechanisms of meniscus injuries and the progression to OA, there is still a lack of information in the current literature on specific movement patterns and the effect on knee joint loading during sport-specific movements.

Muscle strength recovery is considered important for young individuals after an arthroscopic surgery to regain the capacity to participate in sports or other activities (Batailler et al., 2018). Both pre- and post-operative knee extensor strength have been reported to predict better functional outcome of knee surgery post-meniscectomy (Ericsson et al., 2009). The reduction in muscular strength levels is clinically relevant for the return to sport criteria, as most individuals following meniscectomy have seen a 25% strength reduction in the affected leg compared to the contralateral leg (Hall et al., 2013). For individuals at a highly competitive level of sport a leg strength discrepancy is often capped at 10% or less between legs to be ready to return to their sports (Grindem et al., 2016). Explosive movements, such as running and jumping, require good muscle strength and control which is reduced in individuals following meniscectomy up to a year after surgery (Hsu et al., 2015). Muscle strength is closely linked with balance and joint stability, creating a clinical implication for day-to-day living (Baltich et al., 2015).

Co-contraction of the muscle, or altered timings of the muscle contractions, are also important as this can show compensatory techniques post-operation which can increase compressive forces in the knee (Selistre et al., 2017). Greater co-contraction of the medial muscles at the knee have demonstrated a faster progression of knee OA in individuals diagnosed with medial knee OA (Hodges et al., 2016). Therefore, it is important to understand whether individual's post-meniscectomy have greater co-contraction and whether this could be a risk factor to lead on to future knee OA progression. Changes in muscle activation could have major implications for individuals following meniscectomy as this could identify issues post-surgery. Therefore, strategies and modalities to help offload the knee and slow knee joint degeneration, allowing these athletic individuals to carry on with competitive sport are key.

Fear of movement is often linked to muscle weakness due to surgery and re-injury, which have been previously reported as having negative psychological effects to return-to-sport outcome and therefore, should be another important area for investigation following meniscectomy (Ageberg & Roos, 2016; Everhart et al., 2020; Hart et al., 2020). The psychological influences such as confidence in function (Chmielewski et al., 2008), pain catastrophizing (de Boer et al., 2012), Knee injury and Osteoarthritis Outcome Score (KOOS) (Collins et al., 2011), kinesiophobia (Kvist et al., 2005) are highly important when understanding re-injury and participation in dynamic sport following surgery (Brand and Nyland., 2009). Therefore, these aspects should be taken into consideration when looking at a meniscectomy population who wish to return to sport and partake in more dynamic movements, as individual's negative attitudes toward their movement can cause gait adaptations to occur and aid in compensatory movements to be established (Tichonova et al., 2016).

A variety of footwear interventions have been used in individuals with OA to reduce knee loading and pain (Butler et al., 2007; Chapman et al., 2013; Erhart et al., 2008). Recent, significant advances have occurred in the design and manufacturing of athletic footwear (Malisoux et al., 2017). Commercially available footwear, which is easily accessible for the general population to buy has greatly improved over the past decades, with many different types of footwear being available to accommodate for individual preferences (Kong and Bagdon., 2010; Hurst et al., 2017; Chughtai et al., 2018). Jones et al., (2015) found that in individuals with knee OA, lateral wedge insoles were effective in reducing the external knee adduction moment EKAM by shifting the ground reaction force (GRF) laterally, altering the knee angle into a valgus position. This shift of the GRF thereby decreases the moment arm which results in a reduced EKAM on the knee joint (Kakihana et al., 2005; Jones et al., 2014). An increased EKAM has previously been reported in individuals following a meniscectomy (Hall et al., 2014), therefore examining lateral wedge technology which could offload the medial knee compartment could be beneficial in minimising or delaying the progression of joint degeneration in this population. Mølgaard et al., (2015) analysed the use of a lateral wedge in individuals following medial meniscectomy and found that the lateral wedge did reduce EKAM, however not to the level of healthy controls. Different footwear interventions have not been examined in individuals following meniscectomy, however, this could be implemented as an offloading strategy of the knee by shifting the ground reaction force away from the affected compartment of the knee with the aim to help slow knee joint degeneration.

Cushioning insoles have been shown to help support the affected compartment of the knee, with a reduction in impact through shock absorption resulting in clinical improvements of tibiofemoral pain (Voloshin & Wosk, 1982). Paterson et al., (2014) stated that cushioning and stability footwear have been recommended for individuals who suffer from knee OA and pain. Following injury or surgery, stability is often reduced (Almekinders et al., 2004), however it seems that adding more stability or stiffness to footwear may not be the most beneficial for an active clinical population. It has been well established that stable supportive footwear styles increase knee loads significantly in knee OA (Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). Current evidence regarding footwear has mainly focussed on off-loading the knee in knee OA individuals (Shakoor et al., 2010; Bennell et al., 2009; Hinman et al., 2012; Paterson et al., 2018), however, it is unclear how footwear could affect knee joint loading following a meniscectomy where individuals are at high risk of developing knee OA. Furthermore, understanding the influence of footwear during sport-specific movements in individuals who have had a meniscectomy will inform recommendations for appropriate footwear for effective self-management

Understanding the biomechanical outcomes which have been linked to the risk factors of knee OA progression in post-meniscectomy individuals compared to healthy controls during functional and sport-specific tasks is vital. Combination of assessment tools are crucial to develop a holistic approach to understanding coping mechanisms post-meniscectomy. This type of study should facilitate more informed biomechanical outcomes, conveying measures that can be implemented to reduce the risks of OA in individuals following meniscectomy and in the hopes of improving and aiding their recovery.

Aims and objectives

The aim of this thesis was to examine the biomechanical changes during sport-specific tasks and the use of commercially available footwear as offloading strategies in individuals following meniscectomy. The thesis was formed around two studies; the BOOM and MENI-FOOT studies. The aim of the BOOM study was to analyse knee loading in individuals following meniscectomy, with three objectives. The first objective was to compare knee loading and offloading strategies between individuals following medial meniscectomy and individuals following lateral meniscectomy. The second objective was to analyse knee loading during functional and sport-specific tasks and the third objective was looking at outcomes that influence knee loading following meniscectomy. The aim of the MENI-FOOT study was to look at footwear as an offloading mechanism for the knee following meniscectomy, with three objectives. The first objective was to identify the difference in knee loading wearing a stability, cushioning and lateral wedge footwear in comparison to neutral footwear. The second objective was to look at knee loading in the three different types of footwear during dynamic tasks and the third objective was to analyse the comfort of these different types of footwear following meniscectomy.

Hypotheses

H_1: Individuals following both medial and lateral meniscectomy show differences in knee loading demonstrated by the EKAM, KFM and KAAI

- H_0: there is no significant difference in the EKAM, KFM and KAAI between individuals following medial meniscectomy and individuals following lateral meniscectomy.

H_2: Individuals following meniscectomy show greater EKAM, KFM and KAAI compared to healthy controls

- H_0: there is no significant difference in the EKAM, KFM and KAAI following meniscectomy

H_3: Individuals following meniscectomy show greater EKAM, KFM and KAAI during dynamic tasks (running, landing and change of direction) compared to healthy controls

- H_0: there is no significant difference in the EKAM, KFM and KAAI during dynamic tasks in individuals following meniscectomy compared to healthy controls

H_4: Individuals following meniscectomy show lower KOOS pain, physical activity and quality of life self-reported outcomes measures compared to healthy controls

- H_0: there is no significant difference in self-reported outcome measure between meniscectomy individuals and healthy controls

H_5: Individuals following meniscectomy demonstrate lower isometric quadriceps muscle strength compared to healthy controls

- H_0: there is no significant difference in isometric quadriceps muscle strength between individuals following meniscectomy and healthy controls

H_6: Individuals following meniscectomy have a greater co-contraction of the agonist/antagonist (extensor/flexor) (medial/lateral) muscles compared to healthy controls

- H_0: there is no significant difference in muscle co-contraction between individuals following meniscectomy and healthy controls

H_7: Stability, cushioning and lateral wedge footwear show a difference in EKAM and KFM compared to neutral footwear

- H_0: there is no significant change in the EKAM, KFM whilst wearing different commercially available footwear

H_8: Stability, cushioning and lateral footwear reduce the EKAM, KFM during dynamic tasks in individuals following meniscectomy

- H_0: there is no significant change in the EKAM, KFM whilst wearing different commercially available footwear during dynamic tasks in individuals following meniscectomy.

H_9: Stability, cushioning and lateral wedge footwear exhibit differences in comfort during dynamic tasks compared to neutral footwear in individuals following meniscectomy

- H_0: there is no significant difference in comfort whilst wearing different commercially available footwear during dynamic tasks in individuals following meniscectomy.

Chapter Structure

Literature Review	**Methodology & Repeatability study**	**BOOM study**	**Meni-Foot study**	**Final Discussion**
Full introduction of topic area and the gaps of research	Introduction to set up, experimental procedure and analysis	Biomechanical outcomes associated with OA progression in individuals following meniscectomy during athletic and functional tasks (BOOM)	The effect of commercially available Footwear interventions on biomechanical outcomes associated with knee loading in individuals following meniscectomy	Final discussion of both studies, limitations of study, future research, and conclusion
	Repeatability study to show intra-session and between -session reliability of researcher and tasks	Medial vs. Lateral meniscectomy Muscle strength, balance, co-activation of muscles and self-reported outcomes	Comparison of four different trainers in dynamic tasks and qualitative outcomes	
Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6

Chapter 2 - **Literature Review**

2.1 The Meniscus

2.1.1 What is the meniscus?

Throughout history, the knowledge of the human body has constantly evolved. The first recorded use of the word “Meniscus” was in 615 BC (Sappho., 615BC). Hippocrates first examined injuries to the bones and joints in approximately 400BC. Whilst, it was not until Vesalius in 1543AD that the meniscus structure and function was looked at in detail and showed the importance of the meniscus for total knee joint health (Vesalius., 1543). The meniscus are made up of two fibrocartilaginous C-shaped discs which can be found between the tibial plateaus and the femoral condyle (Murphy et al., 2019). The term "meniscus" is from the Ancient Greek word μηνίσκος (meniskos), meaning "crescent." (Diab., 1999). Each knee has a medial meniscus and a lateral meniscus which have slightly different structures and functions (Makris et al., 2011). The menisci of the knee joint are important functional units able to improve joint congruence and load distribution, thereby reducing the stress on the knee joint, a function that is considered primordial to protect the articular cartilage and prevent osteoarthritis (Messner and Gao, 1998).

2.1.2 Structure

The meniscus plays a key role in the health of the knee joint (Chang and Brophy, 2020). The knee is made up of medial and lateral fibrocartilaginous discs, located between the tibiofemoral joint. The medial meniscus is crescent shaped and occupies around 60% of the medial compartment of the knee (Vermesan and Prejbeanu., 2015). The menisci under the age of 10 years are both highly cellular and vascular, with a blood supply available throughout the whole menisci (Clark and Ogden, 1983), however, as adulthood is reached only the outer 10-30% of the medial meniscus and 10-25% of the lateral meniscus contain a good blood flow, which has important implications for healing (Danzig et al., 1983; Harner et al., 2000). Vascularization is strongly related to healing in the meniscus, however, is not solely dependent on blood flow, and may be affected by the reduced production of synovial fluid and mechanical pumping (Bray et al., 2001). The outer rim of the menisci is called the red zone as it is the only part of the meniscus that contains blood flow (Mordecai et al., 2014). The outer rim is thick, convex in properties and is attached to the joint, while the inner edge known as the white zone is concave, thin, does not have any blood supply available and has a free edge (Figure 2.1) (Fox et al., 2015). The rest of the meniscus receives nourishment through either endoligamentous vessels from the anterior and posterior horns which travel a short distance into the menisci (Danzig et al., 1983), or via synovial diffusion or mechanical motion (Meyers et al., 1988). A tear in the inner compartment of the meniscus is most likely to require surgical treatment due to no blood supply and therefore limited healing capabilities (McDermott et al., 2006). The healing capacity of each area is directly related to blood circulation, leaving the white region susceptible to permanent post-traumatic and degenerative lesions (Arnoczky and Warren., 1982).

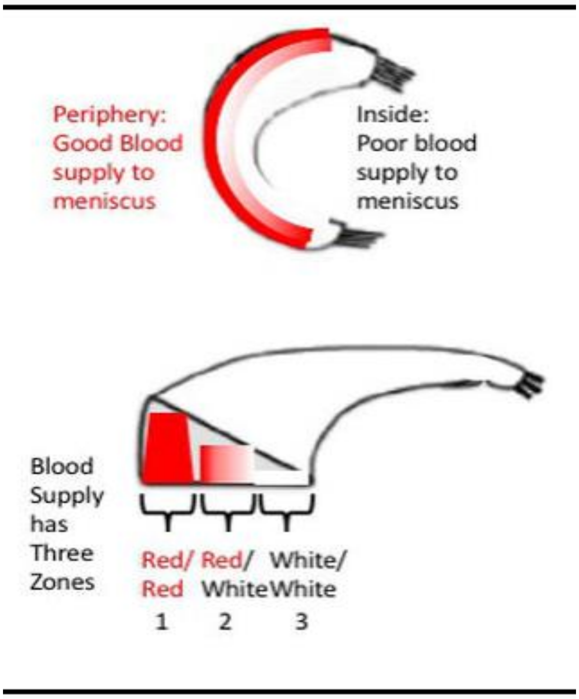


Figure 2.1: The bloody supply in a meniscus. Source: https://www.nwskelleymd.com/copy-of-ankle-instability

The meniscus is highly hydrated as it is made up of 72% water with the rest consisting of organic matter made up of mostly extracellular matrix (ECM) (28%). Collagen makes up around 75% of the ECM organic matter, with GAGs, DNA and glycoproteins (Ghadially et al., 1983). The amount of collagen in the meniscus varies depending on the area of the meniscus, with the red zone holding more collagen than the white zone (Fox et al., 2015). When ageing or damaged, the meniscus loses some of that tensile strength and increases in stiffness due to a reduced water composition (Tsujii et al., 2017). This reduces the capability of the meniscus to manage high loads and deal with twisting movements as seen in competitive sports which may be linked to joint degeneration (Rath and Richmond, 2000). Rai and McNulty (2017) highlighted that specific biomarkers change in the meniscus when an injury is sustained. These include inflammatory cytokines, chemokines, damage-associated molecular patterns, matricryptins, and elevated protein levels (adiponectin and resistin) similar to what is observed in knee joint degeneration (Rai et al., 2017). Imaging tools and biomarkers in the meniscus can be beneficial in tracking meniscus health and disease, including those related to biomechanical signaling and inflammatory paths such as the proteins (Cook et al., 2017; Brophy et al., 2017). Melrose et al., (2017) showed that alterations in the meniscus biology following an injury are generally noticed after the injury has occurred, whereas studying the knee joint mechanics can highlight the initial response to the structural and functional changes by reporting a change in load bearing of the knee (Zhang et al., 2019).

Three distinct mechanoreceptors can be found within the meniscus (Ruffini endings, Pacinian and Golgi tendon organs; Kennedy et al., 1982). The Ruffini mechanoreceptors mainly detects changes in joint deformation and pressure (Han et al., 2020). Pacinian mechanoreceptors detect changes in tension. Finally, the Golgi is associated with neuromuscular inhibition by hindering the knee joint from excessive flexion, extension, and extreme rotation of the knee (Assimakopolous et al., 1992). These mechanoreceptors detect changes in joint deformation and pressure, tension, speed, acceleration, direction of movement and determination of the position of the knee join in space, respectively (Zimny, 1988; Denti et al., 1994). Mechanoreceptors contribute towards functional stability and neuromuscular control and therefore it has been seen that damaged mechanoreceptors alter neuromuscular functions, as well as diminish somatosensory information (proprioception), which in turn can create instability in the knee (Lephart., 1994), which is present in individuals following meniscus injury (Salata et al., 2010). The menisci also have proprioceptive properties which are demonstrated by the presence of mechanoreceptors in the anterior and posterior horns of the menisci, which are essential for joint health and functional movement (Messner and Gao, 1998; Karahan et al., 2010). When the meniscus is damaged, neural changes at the receptors occur reducing the functional ability for the meniscus to deform and transmit loads (Fox et al., 2012).

The medial meniscus is fixed in place, attached with one anterior and one posterior insertion point to the tibia (Fox et al., 2015) (Figure 2.2). The lateral meniscus is generally more of a circular shape and is smaller and more mobile compared to the medial meniscus, enabling it to aid with cushioning during dynamic movements (Fox et al., 2015). As the meniscus is shaped like a wedge with a thin inner edge and a thick outer edge, the shear forces that constantly act on the meniscus between the tibiofemoral joint are distributed throughout the whole meniscus, creating circumferential stress (Makris et al., 2011). The meniscus helps dissipate the load in the knee by increasing joint surface area when it compresses (Koenig et al., 2009). As the medial meniscus cannot move, it is more likely than the lateral meniscus to suffer from a tear (Sari et al., 2018). However, when the lateral meniscus tears, it is generally a complex tear as it either tears straight through, tears at the root or causes a greater surface area tear (Fox et al., 2014). Similar to the medial meniscus, the lateral meniscus occupies between 60 and 80% of the lateral compartment and also has two separate insertion points to the tibial plateau (Fox et al., 2015). Due to this the loss of the lateral meniscus from a meniscal tear may result in increased cartilage contact stress as there is a lower cross-sectional area to help dissipate the load across the menisci and therefore there is a greater risk of joint degeneration (Seedhom and Hargreaves., 1979; Krych et al., 2020).

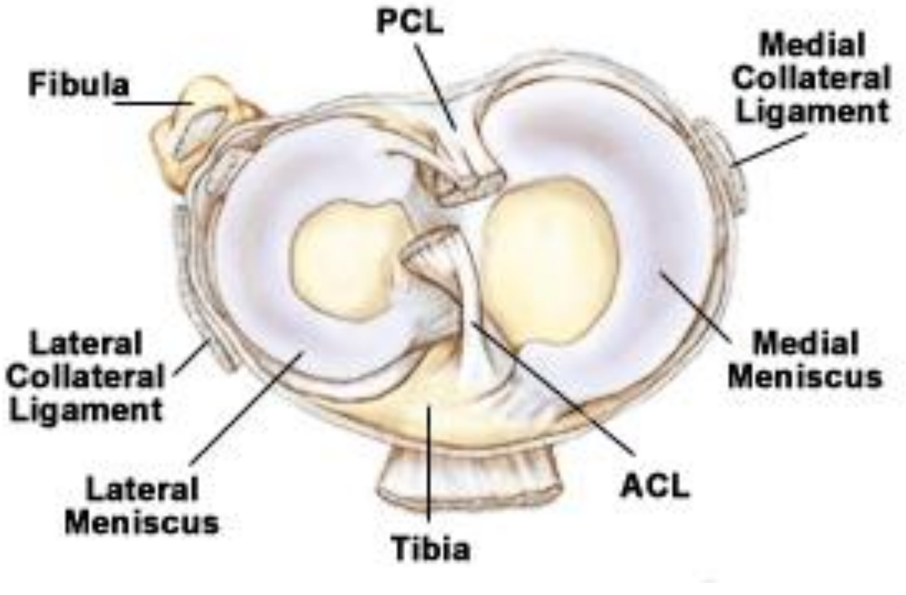


Figure 2.2: This figure shows the medial and lateral compartments of the meniscus, where it can be seen that the lateral meniscus is more circular and smaller. Source: http://www.physio-pedia.com/images/9/91/Lat.meniscus.gif

2.1.3 Function

It is now accepted that the menisci are not “functionless vestiges” (Fox 2012), as was thought in earlier centuries, but are in fact vital for the normal functioning and longevity of the knee joint health, as described in early research (Fairbank, 1948; Arnoczky et al., 1988; Roos et al., 1998, 2001; Rodkey, 2000; McDermott and Amis, 2006; Fox et al., 2015). The meniscus functions transmit load (Fairbank, 1948; ; Seedhom et al., 1979), act to absorb shock by increasing the contact area when compressed and therefore, reducing contact stresses in the knee (Voloshin and Wosk, 1983; Andrews et al., 2011), aid in knee joint stability (Müller, 1994; Wu et al., 2002), support joint nutrition (Makris et al, 2012, Travascio and Jackson, 2017) and joint lubrication (Lee et al., 2000; Bonnevie et al., 2014), and provide additional proprioceptive mechanisms (Al-Dadah et al., 2011; Karahan et al., 2010). It is now accepted that the primary function of the meniscus is to transmit shear and tensile loads across the tibiofemoral joint while decreasing the resultant stress placed on the articular cartilage (Messner and Gao, 1998). In extension, the lateral and medial meniscus deals with 40-60% of the load transmitted through the knee (Mansfield et al., 2019). Knee loading increases by up to 90% when the knee is in flexion, highlighting the importance of the meniscus (Dudhia et al., 2004), particularly in activities where high flexion movements occur. The medial knee compartment deals with 60% greater biomechanical knee loading compared to the lateral compartment during walking (Prodromos et al., 1985). Given the different loading contribution observed between the lateral and medial menisci, one would think that they should be approached independently.

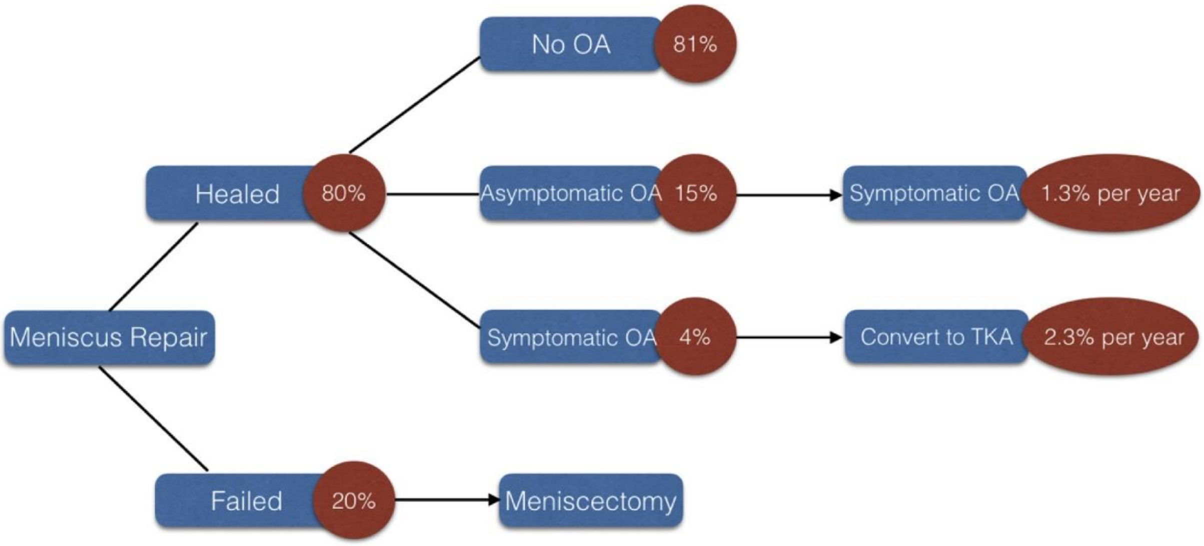
On impact, drag forces occur as fluid escapes the tissue of the meniscus, allowing shock absorption to occur (Voloshin and Wosk, 1983). The fixed attachment of the medial meniscus to the tibia contributes to anterior stability of the knee and is consequently more frequently torn. Lubrication in the meniscus is not well researched, however Fox et al., (2015) believed that when the knee is loaded, the meniscus compresses and circulates fluid into the articular cartilage, reducing friction and additionally providing nutrition to the joint (Mac, 1950; Arnoczky et al., 1988). Any of these processes can cause functional deficits or biomechanical adaptations when the meniscus is injured.

2.2 Meniscal injuries

2.2.1 Incidence and prevalence of meniscus injury

In 2013, meniscal injuries were responsible for an estimated 25,000 hospital admissions in the UK and each admission cost between £2,000-£4,000 per surgery (Snoeker et al., 2013). In the private hospitals around the UK the cost for a meniscectomy surgery, excluding rehabilitation and initial consultation has been shown to be between £2000-£5000 depending on the area (Private health UK, 2020). In 2016-2017, it was reported that 42,651 people in the UK National

Health Service (NHS) were admitted for meniscal surgery (Hospital Episode Statistics, NHS Digital, 2017). Post-operative treatment costs vary depending on private or national care services (£15-£60 per session), and resources are becoming more available online such as physio-guided exercise plans being available in private health (Litchfield and Buttress., 2019). Although in the short-term a meniscectomy compared to meniscal repair is more cost effective as there is often a greater re-operation rate following meniscal repair (Figure 2.3), it was shown in the US that in the long term a meniscal repair ($23,948) was less of an economic burden compared to a partial meniscectomy ($38,648) as it had a lower incidence of leading on to knee OA and follow up treatments (Rogers et al., 2019). Knee OA costs the UK health service on average £10.2 billion annually, which includes the cost of treatments, surgery, and impact on work (Woolf, 2018). Abram et al., (2018) found that the greatest incidence of meniscal injuries was between the ages of 20-39 and was more evident in males (10.4/100,000 athletic exposures) than females (4.3/100,000 athletic exposures), as in Abram et al., (2018) study, the males were found to perform in more higher impact sports compared to the females. Athletic exposures were defined as the susceptibility of injury during each practice or competition in an individual’s chosen sport (Mitchell et al., 2016). In comparison, knee injuries such as ACL injuries, also show a greater incidence in males (36.0/100,000 athletic exposures) compared to females (12.8/100,000 athletic exposures) (Abram et al., 2018). Mitchell et al. (2016) reported an average of 5.1 meniscal injuries per 100,000 athletic exposures (training or game) (during football, basketball, American football and hockey), highlighting the types of sport which all involve twisting movements with increased knee loads and therefore have a greater risk of injury to the meniscus.



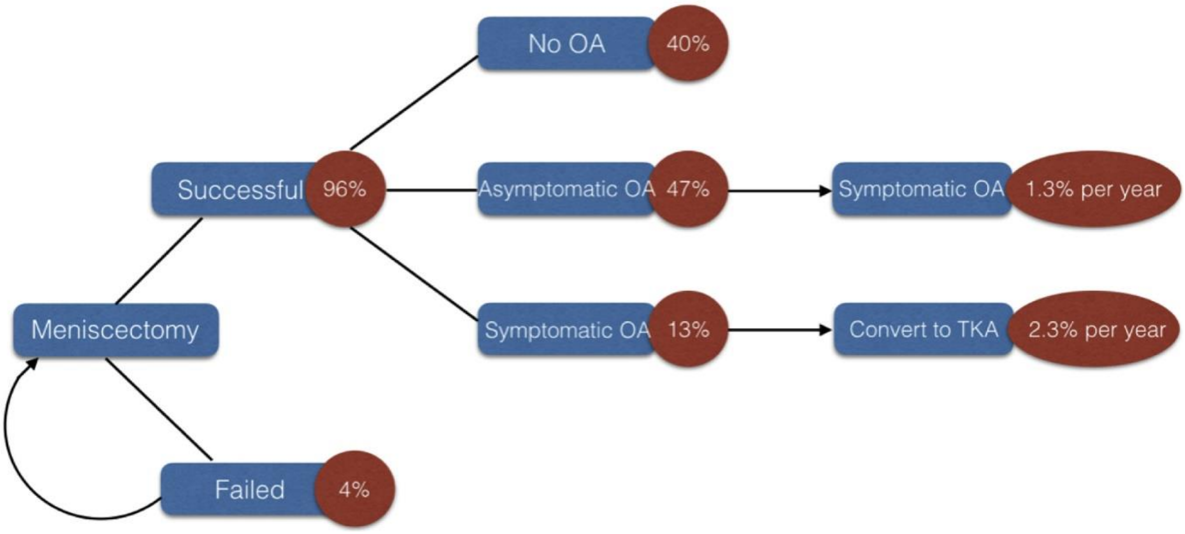


Figure 2.3: Illustration of Markov models comparing the percentage of incidence of isolated meniscal repair to partial meniscectomy and the risk of knee joint degeneration (Rogers et al., 2019)

2.2.2 Degenerative tear

Tears become more complex as we reach adulthood and older age as the meniscus undergoes significant degeneration during a lifetime (Pujol and Boisrenoult, 2009). With age the water content in the meniscus increases by around 15%, with the collagen and proteins (glycoaminoglycans) decreasing by around 5% reducing the stiffness of the meniscus and therefore the ability to deal with high compressive loads (Herwig et al., 1984). Tsujii et al., (2017) also highlighted the reduction of synovial fluid with age. Synovial fluid aids in the lubrication of the meniscus and therefore causes constant friction on the tissue, and in turn, breakdowns of the meniscus. Degenerative tears are more difficult to treat with surgery, however, this is generally the only option (Fox et al., 2015).

Degenerative meniscal tears can develop slowly when the meniscus loses resilience (Beaufils et al., 2017) which is more problematic due to the whole joint degenerating, causing portions of the meniscus to break off leaving frayed edges. Beaufils et al., (2017) found that following meniscectomy surgery, individuals continue to feel knee pain and discomfort due to the tissue having frayed and only the mechanical problems (locking) are removed. The increased pain following a degenerative tear is generally associated with the onset of knee osteoarthritis which would not be improved with surgery (Englund et al., 2003). Fairbank et al., (1945) described the narrowing of the joint space and the flattening femoral condyle with age, particularly once the meniscus was injured leading to osteoarthritis due to the reduction in cushioning (Thorlund et al., 2017).

2.2.3 Traumatic tear

Traumatic tears generally occur in younger, active individuals during a twisting/loading action on a planted/inverted foot (Browner et al., 2003) or jumping and landing movements (Mitchell et al., 2016) as seen in competitive sports. There are distinct types of traumatic tears (longitudinal, radial, horizontal and bucket handle) which are all located in different sections of the meniscus and have different treatment pathways (Figure 2.4). In the United States a traumatic meniscal tear showed an 8.7 per 1,000 incidence rates in the active duty military population due to infantry-related duties, occupations that require frequent squatting/kneeling, and sports such as rugby, football, basketball, skiing, and other high impact sports (Raj and Bubnis., 2019).

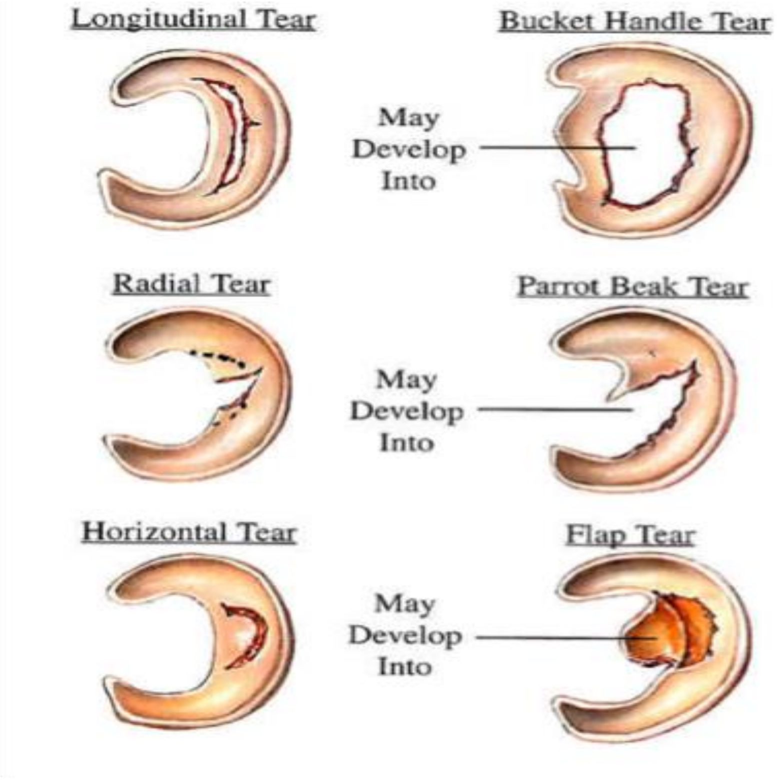


Figure 2.4: This image shows the several types of traumatic tears that occur in the meniscus. Source: http://www.limbreconstructions.com/meniscal-injuries.html

For example, tears on the inner edge of the meniscus will normally be treated with a partial meniscectomy, where they cut out the affected part of the meniscus as there are no healing capabilities in this area due to the limited blood flow in the inner compartment (McDermott, 2011). A longitudinal tear is more common on the medial meniscus compared to lateral owing to the fixed nature of the medial meniscus, whereas a radial tear has been seen more frequent on the lateral meniscus (Mordecai et al., 2014). The presence of tears in the red zone (good blood supply) of the meniscus leads to better long-term prognosis following repair compared to the white zones (Bochynska et al., 2016).

In general, the medial meniscus is ten times more likely to get a meniscal tear than the lateral meniscus as the medial meniscus is fixed in place and does not have any mobility characteristics (Ahlback, 1968; Campbell, Sanders and Morrison, 2001). Medial meniscal tears often in connection with ACL injuries and are therefore most commonly seen in ACL deficient knees (Raj and Bubnis, 2019). On the contrary, Yeh et al., (2012), identified 129 isolated meniscus tears in professional basketball players and highlighted the lateral meniscus tears were involved in 59.2% of all incidences and the medial meniscus were involved in 40.8% of all meniscus tears. Ridley et al., (2017) found that medial meniscal tears were only more common with increased age in individuals over 30 years (52.2%), whereas lateral meniscal tears were more common in the younger populations with individuals under 20 years (63%). The lateral meniscus tears were stated to be more common in the young individuals due to the lateral meniscus playing a greater role during knee loading and motion characteristics. Meniscal injuries can cause knee pain, swelling and locking, reducing the ability for an athlete to perform sporting task and finally leading athletes to cease participation in sports (Hall et al 2011).

2.3 Management of meniscal injuries

2.3.1 Diagnostic procedure

Joint line tenderness has been reported to be the gold standard test to identify a meniscal injury, due to its ability to highlight the rough location and severity of a meniscus tear (McKeon et al., 2009). This test is used if the pain is localised to either the medial or lateral aspect of the joint. Symptoms that can occur with joint tenderness are joint stiffness, swelling, redness, warmth, and joint pain (Stephen et al., 2010). McMurray's test, indicates a positive result for meniscal tears if a pop or snap can be heard at the joint line whilst flexing or twisting the knee, is then used. Ji et al., (2015) analysed the sensitivity of the McMurray test and found that it is 79.3% sensitive which mean that the test has a high ability to correctly identify those individuals with the disease and therefore, can be used for both a screening tool and post-operative outcome tool. Hing et al., (2009) looked at 25 studies which analysed the sensitivity of the McMurray test and showed that it varied from 16%–88%, and therefore a negative result should not be taken as law and further assessments are recommended. The Thessaly test is also used to look at the dynamic reproduction of knee joint loading and see if there is any catching or locking (Karachalios et al., 2005). For this test, the individuals have to stand on one leg with knee flexion both 5° and 20° whilst slightly twisting at the knee. Karachalios et al., (2005) looked at the diagnostic accuracy of the Thessaly test for detecting meniscus tears and found that at 20° there was a 94% accuracy for medial tears and a 96% accuracy in detection of lateral tears. Gossens et al (2014) were in agreement and found a positive detection value of 87% from 593 individuals, however, found that the sensitivity was only 62%. When comparing both the McMurray test and the Thessaly test it was found that McMurray test had a better specificity and sensitivity, however the Thessaly test has a higher detection accuracy at 20° (Venkata Ram Kishore et al., 2019). This shows that neither should be used on its own, but in combination for an initial assessment. Finally, the patient will undergo an MRI of the joint which has a crucial role in visual analysis of individuals with injuries to the knee and can help establish what kind of treatment is most adequate moving forward. Abram et al., (2019) developed a meniscal tear management guideline, that clearly states the process of meniscal tear identification and then what treatment options should be considered, highlighting that the most conservative and preservative treatments should be considered first unless not possible (Figure 2.5).

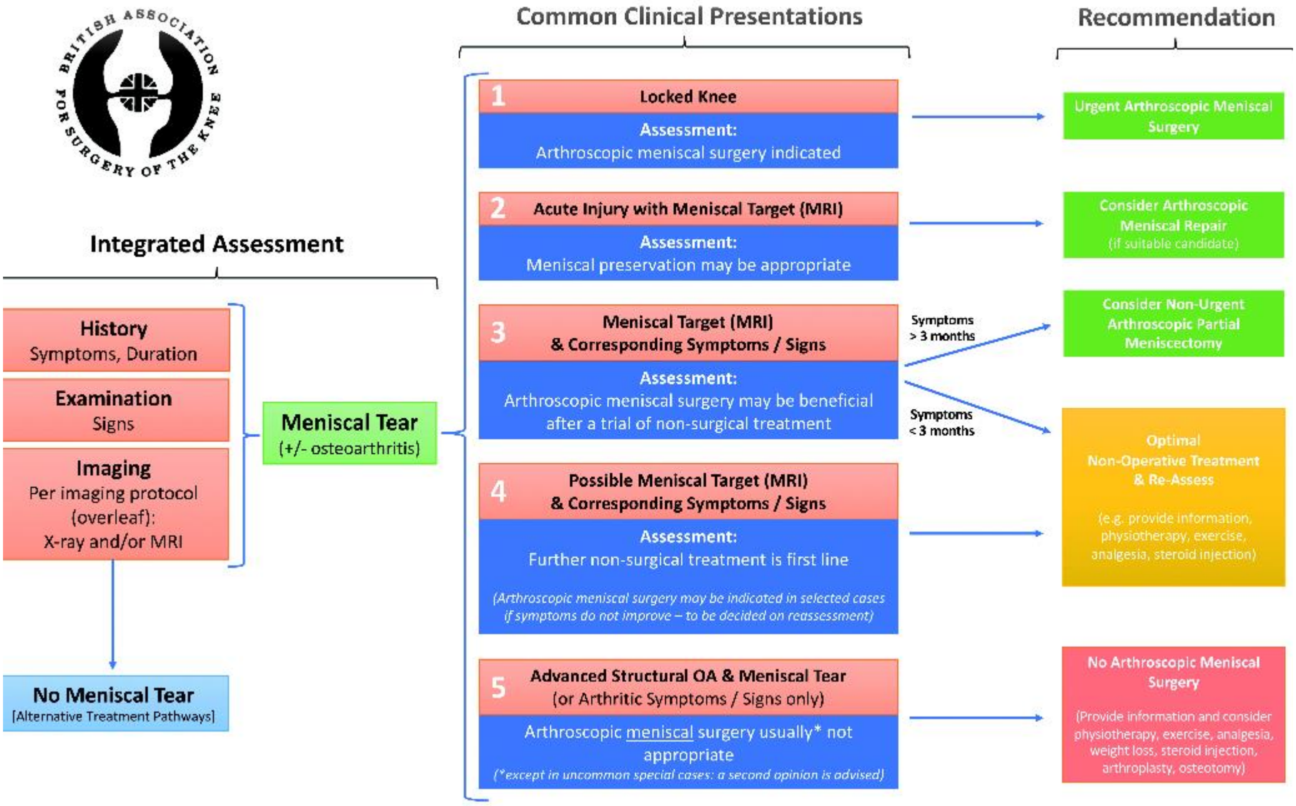


Figure 2.5: Abram meniscal management guideline (Abram et al., 2019)

2.3.2 Conservative treatment

The meniscus plays an important role in knee joint health and therefore preservation of the meniscus is essential to preventing joint degeneration (Zedde et al., 2014). Non-invasive treatment of meniscal injuries in the general population is viable for stable, incomplete, peripheral tears (less than 10 mm) and tears located at less than 3mm from the medial compartment of the joint (McCarty et al., 2002; Alessio-Mazzola et al., 2016). King et al., (1936) was the first to reveal that a peripheral meniscal tear has the potential to heal itself due to the available blood flow and therefore can recover without surgery. Small, degenerative meniscal tears are frequently treated conservatively by reduced loading and weight bearing on the joint through activity modification, while also treating with physiotherapy (El Ghazaly et al., 2015). Where non-surgical approaches are taken it is vital that a good level of strength is maintained in the affected leg in comparison to the contralateral leg. Any activities which require pivoting upon the leg or other sudden changes of direction should be avoided until dynamic tasks have been incorporated into the physiotherapy programme. If the tear is severe enough the patient will be asked to rest and take time out of competitive sports. In a sporting population, meniscal tears are generally complex or radial, meaning mechanical changes are present, reducing the capability for healing (Aune et al., 2014). Therefore, the conservative approach to treatment is less favourable due to the greater functional demands for the sport-specific movements and the injured person's need to rapidly return to compete at a competitive level (Zedde et al., 2014).

Conservative treatment for meniscal injuries can include a range of interventions. These include physiotherapy as mentioned above (El Ghazaly et al., 2015), medication against inflammation and pain (Machado et al., 2017), injection such as steroids or other lubricants (Turajane et al., 2019), knee bracing (Hunter, 2015), and orthotics or footwear (Wagner and Luna, 2018). Knee braces or orthoses vary in size, design and material and may contain mechanisms to limit joint movement (Coppola 2009). Unloader or off-loader knee braces have been used by individuals with knee OA to help relieve mechanical stress on the affected joint compartment and shift load from the symptomatic compartment to the non-affected compartment (Laroche et al., 2014). However, other knee brace mechanisms may improve the stability, proprioception, and warmth of the knee joint, which in turn improves quality of life (Hunter, 2015). These conservative treatments may help relieve some of the pain and discomfort symptoms, however, are unlikely to improve mechanical symptoms arising from a displaced or unstable meniscal fragment. Squyer et al., (2013) also found that wearing knee braces was too uncomfortable for some individuals because it altered gait and was considered too heavy to take part in any physical activity. The key problem for young active populations in wearing knee offloading braces, specifically during sport, may lead to discomfort and slippage due to construction of brace and therefore may cause further damage which is not advisable in the sporting population. Knee braces have not been analysed in individuals following meniscectomy and could be a future potential research area to focus on.

Siemieniuk et al., (1982) was one of the first studies that showed a conservative approach is preferred to a surgical approach following meniscal tears. This study highlights that the benefits of arthroscopy may not outweigh the burden and risk of joint degeneration which have also been reported in later studies (Khan et al., 2014; Kise et al., 2016 and van de Graaf et al., 2018). These studies showed that in middle aged individuals with non-obstructive meniscal tears, there were no greater benefits from having a meniscectomy compared to physiotherapy alone. Additionally, Sihvonen et al., (2013) looked at the difference between meniscectomy and sham surgery in individuals following a degenerative meniscal tear and found at 12 months follow up, individuals were not significantly different between the groups, showing that individuals with a degenerative tear may not benefit from having the surgery. Thorlund et al., (2015) undertook a systematic review which included nine studies and found that there was no benefit in individuals having a meniscectomy in individuals with degenerative meniscal tears. Although there was some improvement in pain in the early stages following meniscectomy, this did not continue to be the case after 24 months, which could be linked that the patients in only two of the nine studies did not have osteoarthritis which may have contributed to the pain. Due to the degenerative nature of the tear and OA being highly common, surgery may not be recommended for these individuals as the tissue may continue to degrade further.

Katz et al., (2013) found that 30% of the participants who were assigned to a physiotherapy group alone, rather than surgical intervention, underwent surgery within six months as the pain was not bearable and there were no signs of improvement of the WOMAC score, which measures physical function for knee osteoarthritis. El Ghazaly et al., (2015) agreed with these findings because the physiotherapy group did not report satisfactory outcomes as pain and mechanical locking did not subside with only physiotherapy following the injury and therefore, surgical intervention was undertaken. If the tear is large, in a low vascularised region, or if conservative management fails to alleviate the associated pain and joint dysfunction then surgery is the next step (Messner and Gao., 1998). In Van de Graaf et al., (2018) study, 159 individuals underwent a meniscectomy and 162 individuals had physiotherapy treatment, however 47 individuals in the physiotherapy group ended up needing a meniscectomy. The results showed a slight increase in function following meniscectomy, however there were no significant differences between groups and showed that in non-obstructive meniscal tears, physiotherapy is as effective and therefore should be the first option, however a meniscectomy may be needed in some cases. Equally, Kise et al., (2016) also analysed the comparison between a meniscectomy compared to physiotherapy in middle aged individuals following a degenerative meniscal tear and found that there were no significant differences in the outcomes between groups, however out of 70 individuals 13 ended up having a meniscectomy anyway highlighting the importance to start with a conservative approach unless surgical intervention is necessary.

2.3.3 Surgical approaches

In 1731, Heinrich Bass was one of the first physicians who combined knee injury, anatomy and surgical techniques when writing about a meniscal tear which was treated by a meniscectomy (Bass., 1731). Until 1883 when Thomas Annandale performed the first meniscal repair, treatment of the menisci was still conservative and by today's standards, primitive as they would either remove the whole menisci or leave it as it was which in the worst case may still happen, however, with the understanding of the importance of the meniscus, if the whole meniscus needs to be removed, where possible a meniscal transplant is now possible. Surgical options currently include either resection (partial meniscectomy), repair or replacement of the damaged meniscus (Howe et al., 2017). Meniscal resection (partial meniscectomy) is the most common treatment for meniscal tear, although the number of meniscal repairs is growing (Vidal 2012; Pujul and Beaufils, 2019). Historically, total resection (total meniscectomy, or removing) of the meniscus was widely used as the primary standard surgical treatment for meniscal injuries (Sutton, 1897). Annandale (1885) was the first person to operate on the meniscus and after years of research found that removing the meniscus entirely had degenerative adverse effects and therefore, the meniscus should be preserved as much as possible. A partial meniscectomy involves the removal of the damaged or frayed section of the meniscus and trimming the cartilage back to a stable rim (Katz et al., 2013). Recent research has stated meniscal repairs are being strongly advocated rather than meniscectomy to prevent future joint degeneration, showing an increase in meniscal repairs of 6.64%/year between 2009/2010 and 2016/2017 in England (Abram et al., 2018). In France between 2005 and 2017, the rate of meniscal repair showed a 320% increase, while meniscectomies showed a 21.4% decrease, with the largest meniscectomy reduction effort occurred in private hospitals compared the public hospitals (Jacquet et al., 2019). Abrams et al., (2020) reported that in the UK the rate of meniscal repairs doubled between the years of 1998 and 2017. Meniscectomies are still in some cases the only possible treatment, as without blood flow or healing capabilities, meniscal repair is not possible without the chance of the meniscus catching, locking, or reinjuring (Makris et al., 2011).

A meniscal repair is carried out either arthroscopically or by open surgery when the surgeon sutures the part of the meniscus that has been torn (Yoon 2014). In France, the rate of meniscal repair in stable knee increased from 2.5% to 12.05% between 2006 and 2012, at 14,781 operations in 2012 (Lutz et al., 2015). Until recently a meniscal repair was deemed possible only in the vascular peripheral zone of the meniscus where blood flow is present and therefore, has healing capabilities (Moulton et al., 2016). Recently, this has been reported to not be the case and meniscal repairs can extend into the avascular zone (Kalliakmanis et al., 2008; Howe et al., 2017). It has been found in the Karia et al., (2018) that meniscal repair may be more possible depending on the type of tear and location. Vertical tears are the most common to be repaired as they are often quite large in circumference and occur along the periphery of the meniscus where healing capabilities occur (Karia et al., 2018).

Radial tears are normally treated with a meniscectomy as they occur from the medial compartment on the meniscus where the white zone is and no blood flow occurs (Ode et al., 2012). Noyes and Barber-Westin (2002) found that using an inside-out vertical divergent suture technique for a meniscal repair had an 87% success rate in active individuals under the age of 20 years. Beaufils et al., (2009) stated that a meniscal repair was suitable for anything as far as 4 mm from the periphery as long as there is some partial blood flow, however contradictory to this belief, many believe that anything more than 2 mm from the periphery should not be treated as there is too low a healing capability (Xu and Zhao., 2015). Additionally, Paxton et al., (2011) found that there is a much greater reoperation rate with meniscal repairs compared to meniscectomies, which highlighted that meniscal repairs between 0-4 years post-operation had a 16.5% reoperation rate compared to 1.4% for meniscectomy. Following 10 years this increased to 20.7% compared to 3.9% of meniscectomy (Paxton et al., 2011). Paxton et al., (2011) also showed that between 4-10 years there was a greater reoperation rate following a medial meniscal repair (29.9%) compared to lateral meniscal repair (23%), however, it was found to be the opposite case following a medial meniscectomy (0.5%), with greater reoperation rates following lateral meniscectomy (1.4%). The key factors taken into consideration when deciding on surgical procedure are dependent upon the clinical evaluation done arthroscopically, related previous lesions and the exact type, location, and extent of the meniscal tear (Jensen et al., 1994)

Arthroscopy is normally necessary to take a detailed look at the meniscal tear and determine the most suitable treatment. Partial meniscectomy which is the most commonly used treatment (Lau et al., 2018), which is also done arthroscopically serves to remove as little functional meniscal tissue as possible. The aim is to remove all the fragments that might interfere with the joint and cause locking, while addressing the clinical symptoms that may have caused the tear (Beaufils et al., 2017). Following meniscectomy improved short-term outcomes such as reduced pain, increased mobility, and no more mechanical locking are evident along with a reduced recovery period, making it a preferential and highly suitable treatment for sporting populations (Xu and Zhao, 2015).

Meniscal replacement (transplantation) surgery has developed and progressed over the last century and has often been used for tears that cannot be repaired or where a significant amount of meniscal tissue has been lost (Pereira et al., 2019). Meniscal replacement is not yet used as a standardised treatment for meniscal tears, with the procedures and techniques continuing to evolve and be refined, as long-term results are yet to be established and quantified (McCormick, 2014). Meniscus regeneration is also a new clinical technique following extensive research and laboratory trials (Guo et al., 2018). Meniscus regeneration has evolved rapidly and significantly during the last decades and has grown to include cell-free scaffolds, gene therapy, and intra-articular delivery of progenitor cells (Scotti et al., 2013). Re-establishing the meniscus integrity after injury is now considered a necessary approach in knee surgery. Meniscus regeneration seems promising for young individuals, however, is still in the experimental phase (Li et al., 2018).

Over the years, joint degeneration has been documented in 89% of young athletes 5-20 years after arthroscopic partial meniscectomy in the knee joint (McDermott, 2006). To date there is no consensus to which treatment is necessary or most beneficial for young athletes with meniscus injuries. For instance, Nepple et al., (2012) found that in both the short- and long-term follow-up, meniscal repair has generally been associated with higher failure rates when compared to partial meniscectomy, which was in agreement with Pujol et al., (2011) who found a 5-43% chance of failure in meniscal repairs compared to meniscectomy. Stein et al., (2010) found that a repair approach when feasible seems to be superior to partial meniscectomy in terms of long-term clinical outcomes as it does not leave the cartilage exposed in the same way a meniscectomy does and creates a reduced likelihood of developing osteoarthritis. Howe et al., (2015) equally showed a superior IKDC, Lysholm and Tegner score following meniscal repair, highlighting a better quality of life compared to meniscectomy. However, the reoperation rate is greater following meniscal repair compared to meniscectomy and therefore, for a young active population who want fast, effective short-term results, the meniscectomy is still more commonly used (Lau et al., 2018).

In both the medial and the lateral meniscus, a meniscal repair shows greater contact pressure in the knee following meniscectomy. However, Lau et al., (2018) stated that resection of up to 50% of the meniscal depth may be acceptable without causing too much further damage (OA) when a repair is not feasible. To summarise, although meniscal repairs are more recommended as they leave the meniscus intact without increasing the contact loading in the knee as seen following meniscectomy, there are still many types of tears which do not allow for a meniscal repair to be performed and therefore, meniscectomy is the best option. In young active populations the short term-recovery from a meniscectomy is also often still the chosen method to deal with the meniscus tear. Regeneration will be highly beneficial in the future of meniscal tear treatment but is not yet being used in everyday treatments.

2.4 Long-term consequences following meniscectomy

As discussed above, the meniscus plays a large part in knee joint health, specifically in load transmission, shock absorption, and lubrication of the joint (Fox et al., 2015). Tears often result in long-term degeneration, joint swelling, joint line pain, and mechanical blocking, which have severe negative effects on daily life (Li et al., 2018). Persistent pain can be overwhelming, this can result in people altering the way they load their body as they compensate to avoid pain (Boyer, 2018). Locking and catching are two common symptoms caused by meniscal tears; they either causes the knee to lock up and stiffen, which restricts range of motion, or to catch on the meniscus fragments which causes compensatory mechanisms to be employed. Depending on the type of tear, locking may occur, causing the individual to lift his or her hip during walking instead of flexing at the knee to gain ground clearance (Anetzberger et al., 2014).

Fairbank et al., (1948) was one of the first authors to describe the load-bearing function of the meniscus and the degenerative changes that occur when injured, such as the narrowing of the joint space and reduced load bearing capabilities, which are important for the meniscus. The loads in the meniscus are well distributed when the meniscus is intact (Fox et al., 2015), however, its removal results in a significant reduction in tibiofemoral contact area and therefore, a significant increase in contact stress, increasing the load in the remaining meniscus which may lead to joint degeneration (Rodeo et al., 2019). Fairbank et al., 1948 showed that following meniscectomy, the contact stress in the lateral component can be seen to increase up to 300%. When standing, the meniscus absorbs most of the load, however, during walking or stair climbing, contact forces shift medially (Walker and Erkman, 1975; Gilbert et al., 2013). These loads applied to the meniscus are increased even more when the knee is flexed, and in particular when injured under increased load during stair climbing or activity (Fox et al., 2015). Bernholt et al., (2017) highlighted a significant increase in physical function (4.5%), reduction of pain (8%) and therefore improved quality of life when analysing patient-reported outcome measurements six weeks following meniscectomy compared to pre-surgery. Voloshin and Wosk (1983) found that without a meniscus there would be approximately 20% less shock absorption in the knee due to the biological changes. The meniscus also acts as a secondary anteroposterior stabiliser of the knee joint, aids in proprioception and contributes to the lubrication to reduce friction between the joint of the articular cartilage (McDermott et al., 2008; Chevrier et al., 2009; Englund et al., 2009). When the lateral meniscus is torn there is an increased pivot shift in the knee causing a shift in the location of the loads towards the affected compartment of the knee (Musahl et al., 2010). Individuals would benefit from a focus on rehabilitation following partial meniscectomy to restore proper knee mechanics (Lau et al., 2018)

Understanding all the functional changes that occur post-surgery is important, particularly in the young active population as no joints should become damaged over time due to the surgery. Many young active populations often are willing to incur the risk of joint degeneration or functional changes for a faster return to sport time (Gortz et al., 2012). Evidence regarding the negative long-term effects of meniscectomy surgeries needs to be explored further by looking at the joint loading capabilities and what procedures can help delay these changes specifically for an active young population that is most at risk of long-term damage affecting their expected normal physical functions and lives.

The meniscus is capable of detecting proprioceptive information, thus playing an important role in the sensory feedback mechanism of the knee which is necessary for both sporting and functional tasks, however the effect meniscal injury or surgery has on this is not well documented (Karahan et al., 2010, Fox et al., 2015). Mechanoreceptors contribute towards proprioception and neuromuscular control (see section 2.13). Following surgery damage to these mechanoreceptors alter neuromuscular functions, increase instability in the knee (Lee et al., 2020). Location of injury will affect proprioceptive ability, for instance, with Ruffini corpuscles (type I mechanoreceptors) located mainly in the posterior horn of a medial meniscus and generally responding to static joint position, and Pacinian corpuscles (type II mechanoreceptors) located mainly near blood vessels at the posterior horn of the lateral meniscus which rapidly adapts to changes in dynamic joint motion (Lee et al., 2018).

2.5 Comparison between medial and lateral meniscectomy

Medial meniscectomies are more commonly studied compared to lateral meniscectomies, which may be, in part, due to prevalence being higher (Paxton et al., 2011). However, lateral meniscectomies show greater functional deficits as the menisci stability properties are affected resulting in altered load transmission of the articular cartilage (Salata et al., 2010), which highlights that both medial and lateral meniscectomies need to be studied in detail. The lateral meniscus is of particular importance to absorb the high loads produced during dynamic movements in young, active people (Chatain et al., 2003). Ridley et al., (2017) found that after analysing 782 individuals following either medial or lateral meniscectomy, that medial meniscectomies generally occurred in individuals aged 30 or above. Furthermore, 63% of isolated lateral tears occurred at the age of 20 years and below, highlighting that young, active populations are susceptible to both medial and lateral meniscal tears which result in requiring a meniscectomy (Ridley et al., 2017). There are roughly 2.5 times greater loads on the medial tibiofemoral joint compared to the lateral tibiofemoral joint during walking (Schipplein and Andriacchi, 1991) due to the ground reaction force passing medially to the knee joint.

When considering knee loading, the medial and lateral properties of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004). A cadaver study looked at load distributions on the menisci, showing that the lateral meniscus deals with 70% of the load in the lateral compartment, whereas the medial meniscus deals only with 40% of the load on the medial compartment (Seedhom et al., 1979). There is also more significant displacement in the lateral meniscus compared to medial meniscus when under load shown by another cadaver study (Bylski-Austrow et al., 1994). Increases in knee loading post-medial meniscectomy compared to healthy controls have been found in several studies (Hall et al., 2014; Sturnieks et al., 2008; Thorlund et al., 2016). Despite the consideration that medial and lateral menisci properties of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004), there have been no previous biomechanical studies analysing the comparison between individuals following medial and lateral meniscectomy. The lateral meniscus has been seen to play a more vital part in dynamic movements compared to the medial meniscus (Fox et al., 2015), therefore looking at the individuals following medial and lateral meniscectomy in isolation was highly important, specifically in relation to knee joint loading during dynamic tasks. Shelbourne and Dickens (2000) analysed 49 individuals 12 years post-medial meniscectomy and found that there was a joint space reduction as high as 2 mm compared with the unaffected knee following the procedure, showing joint degeneration occurring following medial meniscectomy. Further research is needed to analyse gait outcome measures and to look at the activity levels of these individuals to understand knee joint loading in active individuals following lateral and medial meniscectomy.

2.6 Risk factors of knee joint degeneration

Knee osteoarthritis (OA) is a degenerative joint disease affecting approximately 30% of the population and is a leading cause of disability and pain worldwide (McDonough and Jette., 2010; Silverwood et al., 2014), with the medial compartment of the joint more commonly affected than the lateral (Asay et al., 2017). Loss of joint cartilage is considered the main cause of OA, despite the disorder including problems with synovial fluid, the meniscus, and sub-chondral bone (Hügle and Geurts, 2017). The most commonly affected population for joint degeneration is the elderly population, including those over 50 years of age (Sasaki et al., 2019). Knee OA can be painful and is associated with several risk factors including increased body mass, a history of knee injuries, knee alignment and age (Driban et al., 2014). Acute trauma to the joint, such as a meniscal injury and treatment, increases the risk of early onset OA, stating that 38% of individuals following medial meniscectomy and 24% of individuals following lateral meniscectomy developed OA at 4.5 years post-surgery (Carbone and Rodeo., 2016). Individuals with a history of knee injuries are three times more likely to develop knee joint degeneration and have been found to have structural changes as soon as five years post-injury, without factoring in biomechanical changes following surgery (Muthuri et al., 2011). The risk of developing knee osteoarthritis 10 years after meniscectomy is nearly 80% post-meniscectomy (Chatain et al., 2003). Englund et al., (2003) showed that following a partial meniscectomy an individual is six-fold more likely to develop OA.

Walking is the most common form of human locomotion, happening daily for the general population, when biomechanical loading on the knee joint during walking is shown to exceed 3-4 times body weight (BW) (Vannini et al., 2016). It has been widely hypothesised that higher knee joint loading is causally linked with accelerated knee joint degeneration (Felson et al., 2013). Henriksen et al., (2014) identified five prospective cohort studies focusing on three estimates of knee joint loading: the peak external knee adduction moment (EKAM), knee adduction angular impulse (KAAI) and overall tibiofemoral compression force through a systematic literature search. They identified that there was no evidence of a causal link between knee joint loading during walking and structural progression of knee OA (Henriksen et al., 2014). Healthy joints can usually be expected to withstand a lifetime of repetitive stress and loading while undertaking usual and non-exceptional activities without developing OA (Miller, 2017). Exceptional stress and mechanical demands which exceed articular cartilage tolerance play an important role in both the development and the progression of joint degeneration. Driban et al., (2017) showed that although knee loading in standard walking may not be enough to cause progression in knee OA, participation in sport such as football, wresting, weight-lighting where the knee loading is significantly increased, did indeed have a 3-7 times higher prevalence in knee OA.

Sports activities can generate higher or exceptional loads on the tibiofemoral joint with jogging showing a load of 9 times the BW at each step, (approximately 2-3 times walking loads), running up to 14 times the BW, and jumping up to 20 times the BW (Vannini et al., 2016). Knee OA incidence in current or former football players is reported between 16 and 80 %, being 5–12 times more frequent than in the general population (Kuijt et al., 2012). Furthermore, incidence among this population has been shown to occur on average 4–5 years earlier in life (Kuijt et al., 2012). Driban et al., (2014) stated that aside from repetitive overloading of the joint, pre-existing sport-related knee injuries involving ligaments, menisci and/or cartilage are associated with an accelerated progression of knee OA. Driban et al., (2017) followed this study up by stating that there is a higher incidence of OA in knees of former high-impact sports players than in those of the normal population, which may be correlated to either increased joint overloading or number of injuries in the joint.

Muscle co-contractions have also been shown to affect knee joint loading as it is associated with all the muscles crossing the knee activating to support externally applied moments (Starkey et al., 2020). Current evidence demonstrates that individuals with knee OA exhibit excessive muscular co-contraction (simultaneous activation of the quadriceps and hamstrings) during walking (Sharma et al., 2017). With increased co-contraction, increases in compressive loads at the knee joint can be seen (Brandon et al., 2014). Greater co-contraction of the medial muscles at the knee have demonstrated higher joint loading (Lloyd & Buchanan, 2001; Meyer et al., 2013; Schipplein & Andriacchi, 1991) and faster progression of knee OA in individuals diagnosed with medial knee OA (Hodges et al., 2016; Heiden, Lloyd, & Ackland, 2009; Wu et al., 1990; Zeni et al., 2010). Preece et al., (2016), found that a reduction in clinical pain in individuals with OA was associated with a reduction in medial co-contraction, and that this reduction could be used as an effective treatment target within knee OA. Hodges et al., (2016) agreed to this and showed that there was an increased medial co-contraction of the muscles in individuals following OA, however with an increased lateral muscle co-contraction the medial compartment can be offloaded, and joint degeneration slowed. Heiden et al., (2009) also found that there was no significance increase in external knee adduction moment (EKAM) shown as the surrogate for knee loading in their OA population, which may be related to the increased lateral co-contraction of the muscles. Therefore, examining co-contraction is essential.

Proprioceptive sense plays a role in daily life, for example protecting the knee joint from extreme compulsive and traumatic movements and against falls (Mani et al., 2020). Proprioception, although highly researched, still shows significantly mixed results, with some studies highlighting the importance to look at proprioceptive changes and how these can be associated with joint degeneration (Bayramoglu et al., 2007; Hassan et al., 2001; Baert et al., 2013) and other studies, highlighting that proprioception itself does not affect joint degeneration, as it is often associated with muscle weakness and age (Sharma et al., 1997; Hall et al., 2006; Mani et al., 2020). Individuals who are physically inactive due to pain as seen in individuals with OA, also show connective tissue that may become fibrotic and muscle fibres may shorten which, causes the Golgi tendon organs in the extrafusal muscle fibres to be inhibited (Proske et al., 1993). Van der Esh et al., (2014), analysed proprioception and muscle weakness in individuals with OA and its association to falls and found that proprioception itself was not the cause for the increased falls with OA, but, knee extensor and flexor muscle weakness was the main substantive cause of the increased incidence of falls.

Individuals with OA have commonly been reported to display muscle weakness around the knee and hip, mainly seen in the quadriceps with strength deficits of 20 to 45% compared with age and gender-matched controls (Palmieri-Smith et al., 2010; Alnahdi et al., 2012; Omori et al., 2013). Takagi et al., (2018) showed however that muscle weakness was not only present at early stages of OA, it had a high prevalence in knee OA also after a 6-year period. The quadriceps have an important protective function at the knee joint, working during the early stance phase of walking to cushion the knee joint and act to decelerate the limb prior to heel strike, thereby reducing impact loading (Brandt et al., 2008). Weaker quadriceps have been associated with an increased rate of knee joint loading (Alnahdi et al., 2016), and future tibiofemoral joint space narrowing, highlighting the importance of the analysis of muscle strength to support the joint (Segal et al., 2010). Takagi et al., (2018) stated that quadriceps muscle weakness was linked to an increased incidence of knee OA, however, it was not linked to its progression, and therefore identifying muscle weakness in the early stages of OA may be highly beneficial.

Biological and mechanobiological changes such as reduced collagen fibres, reduced shear stress, reduced stiffness of the tissue and increased moments in the knee joint are associated with increased risk of developing knee OA following a meniscectomy (Figure 2.6) (Andriacchi et al., 2014). This framework shows that following meniscectomy gait adaptation occur including increased knee joint loading, increased co-contraction in the muscles and changes in joint angles. With these changes individuals still try to return to sport sometimes as early as 3 months post-treatment which with the compromised cartilage may lead to the risk of joint degeneration as soon as 5 years post-meniscectomy due to the biological and mechanobiological changes as stated in Figure 2.6. Therefore, if the gait adaptations following meniscectomy were considered prior to returning to sport, the risk of knee joint degeneration may be slowed.

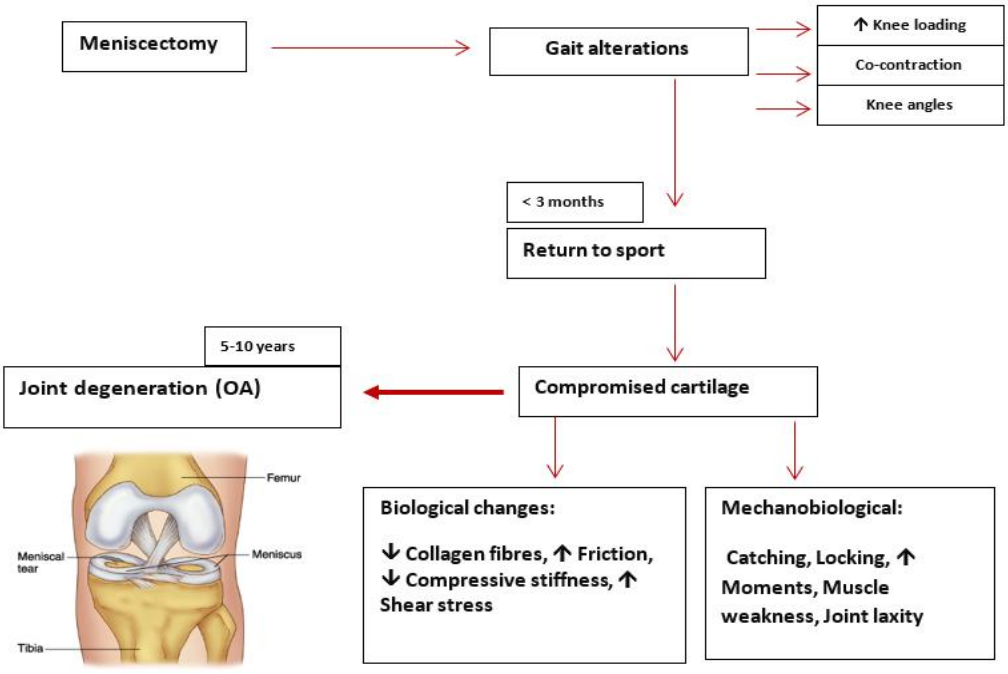


Figure 2.6: The framework of how a meniscal injury causes a continuous loop to occur which in turn creates joint degeneration and links meniscectomy to OA. (Andriacchi et al., 2014)

Obesity has also been shown to be a high indicator of OA development. A body mass index (BMI) that is too high (over 30 kg/m^2) causes an increase in the load being transferred to the knee joint (Felson et al., 2000; Yusuf et al., 2011). Felson et al., (2002) stated that 60-70% of weight-bearing load is transmitted through the medial compartment of the joint, creating a higher chance for medial OA in obese individuals. Research has shown that an increase in body weight by two units of BMI in obese individuals with knee OA may increase the risk of disease progression by 50 % (Felson et al., 1993). Following meniscectomy, it is essential to make sure that the body mass is not too high for the joint to cope with the loading, which with a young and active population is not generally a concern. Women had a slightly lower BMI at follow up in an Englund et al., (2004) study that also found that lateral meniscectomy was more common in women (38%) compared to men (16%).

Hinman et al., (2002) performed a comparison between individuals with knee OA with a healthy control group to assess static and dynamic standing balance. They found that individuals with knee OA demonstrated poor dynamic standing balance compared to the healthy control group. Balance has also been seen to be a predictor of knee OA progression OA (Hinman et al., 2002), which has also been seen in lower limb injuries (Bennell et al., 2003; Pilsky et al., 2006; Herrington et al., 2009). In addition, individuals with knee OA demonstrated greater trunk lean in anterior-posterior and lateral directions as a compensatory mechanism compared to the healthy group (Hinman et al., 2002). Trunk lean has been used in studies to evaluate static balance deficits using force platforms (Kollegger et al., 1992). Trunk lean has been found in individuals following meniscectomy (Hall et al., 2014), however, a full picture of compensatory mechanisms highlighting all the biomechanical outcomes which could be linked to OA progression in unison including muscle weakness, increased co-contraction, stiff gait and pain has not been developed.

2.7 Knee loading

As technology, research progress, diagnostic and surgical techniques improve, understanding of all biomechanical consequences following a meniscectomy and associated degenerative changes in the knee is highly important (Sari et al., 2018; Englund et al., 2006; Thorlund et al., 2017). During normal gait, several factors play a key role, such as stability through co-contraction, range of motion to allow full, healthy ambulation, joint alignments to maintain integrity, and ground reaction forces for even weight distribution (Bennell et al., 2008). The available literature describes in some detail the biomechanical effects when analysing knee loading post-meniscectomy surgery (Hall et al., 2014; Mills et al., 2008; Hulet et al., 2015; Willy et al., 2017; Thorlund et al., 2017). However, biomechanical research following meniscectomy still appears limited and is unable to fully describe the whole effect meniscectomy surgery has on knee joint health both the short-term and long-term (Lau et al., 2018). Following partial meniscectomy, there is a reduced tibiofemoral contact area in the knee, which diminishes the capacity to manage loads (Atmaca et al., 2013). Consequently, activities with elevated knee joint loading such as sporting tasks may be particularly harmful to tibiofemoral joint articular cartilage in an individual's post-meniscectomy (Willy et al., 2017). Therefore, understanding knee joint loading and changes in a compromised joint, specifically when loads are increased is vital.

Joint moments have been identified as one of the key surrogate indicators of joint loading including the external knee adduction moment (EKAM) and the knee flexion moments (KFM) (Richards et al., 2018). Joint moments essentially describe the muscular effort applied to rotate a body segment around a joint centre of rotation as a balance to externally applied forces (Flaxman, 2017). Joint moments are calculated as the product of the magnitude of the vertical ground reaction force vector (GRF) and the distance from the joint center of rotation where the force acts (Figure 2.7)(Lau et al., 2018). For example, increases in the EKAM are shown to increase medial tibiofemoral loading, whereas the KFM has been shown to increase anterior tibiofemoral loading, which is linked to disease severity and rate of OA progression (Sturnieks et al., 2008; Miyazaki., 2002; Barrios et al., 2012, Hurwitz et al., 2002; Asay et al., 2018). During walking there are two peaks in the moment curves, the first peak can be found in the early stance (0–50%) and the second peak in the late stance (51–100%) (Thorp et al., 2006). Studies have found the association between frontal knee alignments and EKAM magnitude (Barrios et al., 2009) where malalignment of the varus knee leads on to an increase in tibiofemoral EKAM in individuals following meniscectomy (Hall et al., 2014). Additionally, varus knee alignment has been found to be high in individuals with medial knee OA (Tanamas et al., 2009). Therefore, reducing the varus knee alignment leads to EKAM reduction and thereby might delay the progression of medial compartment OA of the knee joint (Miyazaki et al., 2002; Teichtahl et al., 2009). Individuals following meniscectomy have demonstrated greater EKAM as early as three months post-meniscectomy during barefoot walking at both a slow and fast speed and is still present between 10- 20 years post-meniscectomy (Hall et al., 2014). Additionally, an increased KFM was found in individuals following meniscectomy over a 2-year period (Hall et al., 2013), which has been linked to medial tibial cartilage and patellofemoral joint degeneration (Chehab et al., 2014; Teng et al., 2015).

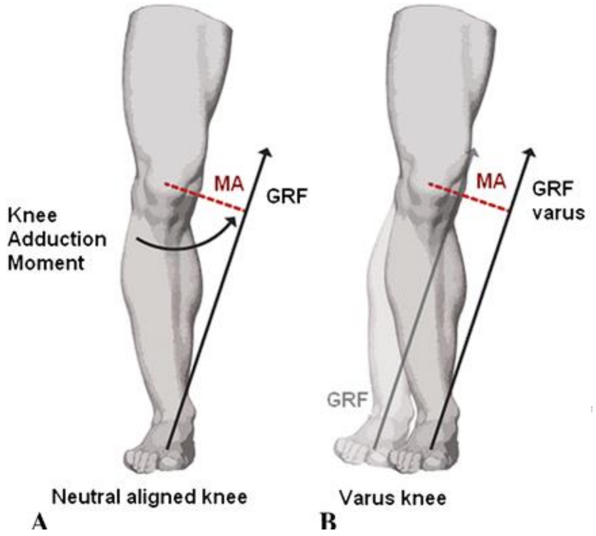


Figure 2.7: Ground reaction force vector location and moment in (a) healthy (b) medial meniscectomy (Duivenvoorden et al., 2015)

The knee adduction angular impulse (KAAI) has been considered as another important measure for medial knee loading (Bennell et al., 2011). The KAAI has been used in addition to the EKAM and KFM as a complimentary assessment to measure knee loading (Selistre et al., 2017). The first or second peak of the EKAM only analyse a single time point during the stance phase and do not represent the overall stance phase, whereas the KAAI analyses the magnitude of the EKAM and the duration of the medial knee loading during the whole stance phase (Thorp et al., 2006). This measure is calculated as the area under the EKAM curve (Figure 2.8). KAAI has been associated with degenerative disease progression (Bennell et al., 2011), as well as pain and disability (Kito et al., 2010) and therefore, would be applicable for individuals following meniscectomy. Thorp et al., (2006) stated the importance of analysing the KAAI and highlighted that it is more sensitive to detecting differences in mild OA rather than just severe OA when compared to the first and second peak of EKAM. For these reasons, the EKAM should be considered alongside the KFM and KAAI to better understand the behaviour of medial and lateral compartment loading. KFM is used to highlight knee loading at the patellofemoral joint (Sturnieks et al., 2011).

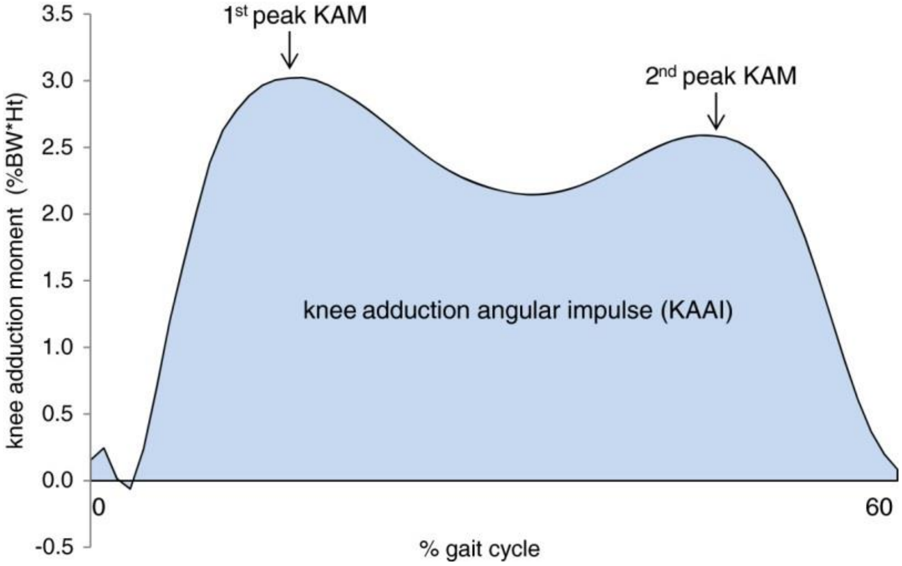


Figure 2.8: 1st and 2nd peaks of the external knee adduction moment and the knee adduction angular impulse under the curve (KAAI). (Levinger et al., 2013)

Thorp et al., (2006) was one of the first studies that looked at the KAAI for knee loading. They studied 117 individuals and found that both EKAM and KAAI increased with increased grade of OA. Individuals with a medial meniscectomy have greater magnitude of the external knee adduction moment waveform and longer stance phase than the matched healthy group, however no studies have looked at using statistical parametric mapping (SPM) (Thorlund et al., 2017; Zedde et al., 2014). The use of SPM allows for the comparison of entire movement cycles, which reduces the errors in the reporting of statistical inferences. Thorlund et al., (2014) reported an increase in KAAI compared to the contralateral limb at three months following meniscectomy, which was also found in the EKAM. In a follow-up study Thorlund et al., (2016) found that the KAAI was still increased at 12 months post-meniscectomy, highlighting that the short-term compensatory mechanisms may have harmful lasting effects which can lead on to OA.

A study conducted over five years investigated the effect of EKAM and KFM on cartilage changes in individuals with OA and found that both EKAM and KFM should be analysed to get both medial and lateral knee joint loading (Chehab et al., 2014). Walter et al. (2010) agreed with this as they found that reduction in the first peak of the EKAM did not guarantee the reduction in the medial knee contact force due to a reduction in the peak of the KFM. Hall et al., (2015) highlighted there was a reduction in KFM in the affected knee compared to the contralateral knee three months post-meniscectomy, however, at 12 months post-meniscectomy, the KFM had increased, however they did not have a control patient group to compare this to. Therefore, the intitial KFM reduction may just be a short-term effect to alleviate post-surgical pain and may be associated with weaker quadriceps muscles (Fisher et al., 2019). Chehab et al., (2014) stated that reducing the EKAM and increased the KFM may have large benefits in slowing knee joint degeneraton, which therefore highlights its importance in looking at both in individuals following mensicectomy. Boyer et al., (2012) highlighted that KFM was sensitive to pain and therefore caused adaptations in individuals with OA, reducing quadriceps muscle activation when walking (Miyazaki et al., 2002). Pain, reduced muscle strength and reduced muscle activation have been seen in individuals following meniscectomy (Ogawa et al., 2016; Ericsson et al., 2019; Sturnieks et al., 2011), however, only few studies have firstly looked at KFM in individuals following meniscectomy and none have looked at the link between KFM, muscle activation and pain.

There are a variety of different compensatory strategies to help offload the knee, such as increasing lateral trunk sway towards the affected stance limb during walking and running (Mündermann et al., 2005; Hunt et al., 2008), decreasing speed with shorter stride length (Andriacchi, 1994), and increasing foot progression (toe-out) angle during stance phase (Chang et al., 2007; Jenkyn et al., 2008) that have been observed in individuals with medial knee OA. Jamison et al., (2012) showed that an increased lateral trunk lean should act to pull the GRF and centre of pressure laterally, decreasing the moment arm on the medial compartment of the knee and therefore decreasing medial knee loads. Additionally, whilst manipulations in the trunk lean alters knee joint loads, it is also often used in competitive sport to deceive opponents and therefore, laboratory tasks should strive to mimic the in-game situation (Zebis et al., 2009). Fox et al., (2018) highlighted that proximal motion at the trunk during a change of direction appears to have a large effect in managing the loads experienced at the knee following ACL reconstruction. Lateral flexion of the trunk toward the intended change of direction were frequently linked to reduction in loads (i.e., external knee abduction moment) experienced at the knee during change of direction tasks (Mornieux et al., 2014, Jones et al., 2016). Lateral trunk lean has not yet been researched in individuals following meniscectomy, however, have been seen in combination with increased EKAM as a compensatory strategy in OA (Gerbrands et al., 2017) and therefore, it would be beneficial to see if these compensatory strategies are also being implemented after surgery. For example, Mündermann et al., (2008), analysed the impact of lateral trunk lean in healthy individuals and found that it can be used to lower the external knee adduction moment in healthy individuals by shifting the GRF away from the affected compartment of the knee. In addition, individuals with medial knee OA demonstrated reduced EKAM with greater lateral trunk lean as a compensatory strategy to help offload the knee (Gerbrands et al., 2017). The reduction of knee loading was due to a medial shift of the knee joint centre, shortened distance of the centre of pressure to knee joint centre, and shortened distance of the knee–ground reaction force lever arm during the stance phase (Tokuda et al., 2018).

Dempsey et al., (2007) however, found that there was an injury-performance conflict as using a lateral trunk lean over the push off leg has been shown to increase external knee valgus (abduction) moments (a surrogate measure of increased ACL injury risk), which may also put the meniscus at risk. The initial increase in knee loads by Dempsey et al., (2007) was thought to be due to the lack of familiarisation of the task with an added trunk lean, however Dempsey et al., (2009) undertook a follow up study, analysing the effects on knee loading with alterations to the change of direction technique and found that following a 6-week training program, knee loads were lowest when the trunk was more upright. During a change of direction task, in contrary to walking and running, it may not be beneficial to use trunk lean to offload the knee, rather to aim to reduce the knee moments to as little as possible and just shift the load and overcompensate as seen by the trunk lean during a change of direction. Fox et al., (2018) found that biomechanical strategies that are employed to reduce the risk of injury in an ACL population, are also biomechanical strategies that may have a negative impact on performance such as soft landings, however adding a lateral trunk lean does not seem to reduce performance but has had a positive effect in reducing knee loading. Kristianslund et al., (2014) stated that to reduce knee loading during dynamic tasks such as landing or change of direction you either have to reduce the GRF which may be achieved with a softer landing with increased knee flexion, or by reducing the moment arm by reducing the knee valgus angle.

Knee motion is an important outcome measure for individuals who have suffered an injury, and following surgery, as reduced range of motion is often linked to pain, swelling, stiffness, muscle weakness and fear avoidance (Lau et al., 2018). Dempsey et al., (2013) showed that reduced motion at the knee was linked to increased loading and reduced joint space leading to OA development. A primary focus area that should be considered when looking at the biomechanical outcomes following meniscectomy is knee motion, which is essential for many functional tasks in daily living.

Knee joint loading is also determined by the coordination of muscle activity (Horsak et al., 2015). The main limitation of using solely frontal and sagittal plane moments to interpret joint loading is that external joint moments do not account for the contribution of muscle forces to joint loading (Starkey et al., 2020). The quadriceps and hamstrings contract simultaneously during the stance phase of walking and play an important role for knee joint loading as muscles support the joint due to them crossing over the knee joint and controlling knee joint movement (Winby et al., 2009). Muscle activation supports frontal plane moments, altering knee joint stability and loading (Sturnieks et al., 2011).

The estimation of muscle co-contraction is a useful clinical tool to better understand how pathology can affect the muscle strategies during gait (Den Otter et al., 2006). Co-contraction is defined as the simultaneous activation of the agonist and antagonist muscle groups around a joint (Selistre et al., 2017). Greater muscle co-contraction between the quadriceps and hamstrings muscles have been found in individuals with knee instability to compensate for instability when compared to healthy individuals and the contralateral leg (Schmitt and Rudolph, 2008).

Methods used to examine the simultaneous actions of agonist and antagonist muscles can vary from mathematical models (Solomonow et al., 1986) to electromyography (EMG) measurements (Rudolph et al., 2000). These EMG measurements are often presented in a normalised form to represent muscles co-contraction, due to the complexity in estimating the muscle moment (Kellis, 1998). EMG activity and force do not have a linear relationship, particularly during dynamic activities (Buchanan et al., 2004). Additionally, it must be noted as a further drawback of normalised moment or EMG values, that differentiation between the force production capacity of the agonist and antagonist muscle group cannot be shown. Souissi et al., (2017) performed a study to compare co-contraction index (CCI) computed from muscle moments to different co-activation indexes derived from EMG data at the ankle and the knee joint during gait. The co-activation methods produced lower values than the CCI. The co-activation methods trend was to underestimate the simultaneous action of agonist and antagonist contraction. Because the EMG-driven model included the muscle mechanical properties (e.g., force-length-velocity relationship) and muscle moment-arm, the co-contraction based on major agonist and antagonist muscle moment provided a more accurate description of muscle action compared to co-activation index, however the difference was not significant, and both are commonly used as biomechanical outcomes.

Both quadriceps and hamstrings are biarticular i.e., cross the knee joint (Marchetti et al., 2016) and equal co-contraction of the quadriceps and hamstring muscles occur during linear movements such as walking, whereas in more dynamic movements medial muscles are activated to support externally applied abduction moments and lateral muscles for adduction moments (Zhang et al., 2001; Besier et al., 2003). Increased medial co-contractions also increase medial joint loading and therefore could aid in a fast progression of medial osteoarthritis (Lloyd and Buchanan, 2001). Muscle activity and co-contractions should be researched more in relation to meniscal injuries, particularly in the sporting population and for how muscle strength can be used to aid in slowing OA progression. Surface EMG can be used as a non-invasive method to supply clinically meaningful information about neuromuscular control deficits as it provides the information from the muscles and explores the activity of each muscle (Farina et al., 2014; Frigo and Crenna, 2009).

Knee muscle strength and co-contraction are also key aspects which are affected following injury and surgery. Muscle strength is essential to control movement, including movements such as change of direction and landing, which are involved in many sports (Rudolph and Snyder-Mackler., 2004). Previous studies have reported increased quadriceps weakness as a consequence of meniscectomy surgery (Becker et al., 2004; Ericsson et al., 2006). Becker et al., (2004) found that in 25 individuals after four years following a partial meniscectomy, quadriceps muscle strength was lower compared to healthy controls with lower voluntary muscle activity being measured by electrodes whilst performing an isometric leg extension. Ericsson et al., (2006) also stated that four years following meniscectomy muscle weakness was present and found that individuals with less weakness also showed less pain and a better quality of life, highlighting the importance of muscle strength even in the long term. The quadriceps muscles are primary contributors to dynamic knee joint stability and associated with increased risk of joint degeneration when the quadriceps are weakened and joint stability is reduced (Segal and Glass., 2011). Sturnieks et al., (2008) found increased EKAM in 102 individuals due to reduced knee extensor strength compared to controls at 11 weeks following a meniscectomy. Sturnieks et al., (2011) analysed both strength and muscle activation in 89 individuals following meniscectomy and found that between one- and three-months post-surgery, there were no significant differences in muscle strength, however there was a significant increase in knee flexor muscle activation during gait which may increase tibiofemoral knee loading as it increases the compressive forces in the knee. These results may have been due to the short time following surgery, however, have also been seen in individuals with knee OA (Mills et al., 2013).

Hubley-Kozey et al., (2008) found increases in lateral hamstring activation during walking gait in severe and moderate knee OA. Sturnieks et al., (2011) found an increase in hamstring activation in both early and late stance phase of walking following meniscectomy compared to healthy controls. Yet, quadriceps activity was only increased during mid-stance phase, which could show the duration of the activation to be longer rather than greater compared to healthy controls. Seeing as individuals following meniscectomy also have increased external knee adduction moments (Sturnieks et al., 2008) it can be assumed that they may also walk with increased laterally directed co-contraction of the quadriceps muscles to try and offload the medial compartment of the knee.

Stronger muscles protect the structure of the knee as the muscles work in tandem with the joint throughout movement, for example: when we flex the knee, the hamstrings contract; to extend the knee, the quadriceps come into play and help carry the weight and stress of the movement (Richards et al., 2018). Ericsson et al., (2009) found that hamstring strength was not significantly reduced following meniscectomy. However, the quadriceps strength was still 9% lower in the meniscectomy leg compared to the contralateral leg, but after a 4-month functional exercise program quadriceps strength was fully regained. Hall et al., (2014) found that there was around 14-16% difference in quadriceps strength in individuals following meniscectomy compared to healthy controls at 3-months post-meniscectomy, however at 2 years post-meniscectomy the muscle strength was regained to a similar level compared to healthy controls. Equally, Ganderup et al., (2017) highlighted that in middle-aged patients who had sustained a degenerative meniscal tear, they showed superior knee function evidenced by improved task performance following surgery, and although there was a reduction in knee extensor strength three months post-surgery, this was not evident at one-year post-surgery. None of these studies mention a pre-injury level of training or physical condition which may have an influence on the results. Slemenda et al. (1998) found that quadriceps muscle weakness increases the development of knee OA. Such muscle weakness reduces the ability to absorb forces during movement, resulting in greater loads on the knee joint itself (Selmenda et al., 1998). The risk of further joint degeneration occurs up to four times more often with the presence of muscle weakness which has been found to be linked with valgus malalignment in individuals, which can increase the speed and level of joint degeneration (Sharma et al., 2001).

To reiterate, gait adaptations have been reported by previous studies with knee flexion angles being reduced (Willy et al., 2016; Chang et al., 2015), external knee adduction moments increasing (Hall et al., 2015; Sturnieks et al., 2008; Thorlund et al., 2016) following meniscal surgery, resulting in knee OA progression. Higher knee varus angle shift with medial meniscectomies, which could be rectified with longer co-activation of the lateral muscles compared to the medial muscles (Hall et al., 2014), which could be explained by muscle weakness, specifically the quadriceps and fear avoidance strategies (Ericsson et al., 2009). The increased knee loading that occurs due to a meniscectomy is detrimental in return to sport criteria, due to the high loads that occur with increased intensity. Specific research analysing the dominant activities that would be seen at return-to-play have not yet been examined, including specific rehabilitation exercises to address quadriceps avoidance which would have future implications for rehabilitation protocols and competitive sports performance or re-injury. Muscle strength recovery is important for young individuals after an arthroscopic surgery to regain capacity to participate in sports (Ericsson et al., 2006; Pietrosimone et al., 2016).

2.8 Balance and stability

Baltich et al., (2015) showed that there was a link between altered joint loading following a knee injury and reduced balance, due to impaired proprioception, reduced muscular strength and increased co-contraction (Hubley-Kozey et al., 2008; Ingersoll et al., 2008; Al-Dadah et al., 2011; Magyar et al., 2012). Al-Dadah et al., (2011) looked at 29 individuals three months post-meniscectomy and compared them using a single leg dynamic stabiliometry (Biodex Balance SD System, multiaxial moveable platform) to both their contralateral leg and healthy control and found that there was a significant proprioceptive deficit compared to both groups. It was stated that the individuals following meniscectomy were otherwise clinically successful had proprioceptive deficits (Al-Dadah et al., 2011). Mallious et al., (2011) analysed the balance and functional capabilities up to two years following meniscectomy comparing the injured leg to the contralateral control leg. They found that there was a significant difference between the injured leg and contralateral leg with a reduction in both the balance and functional outcomes in the meniscectomy leg, highlighting reduced proprioception. Lee et al., (2018) looked at postural stability using anteroposterior and mediolateral stabilometry comparing medial with lateral meniscectomies and found that both legs (injured and contralateral) in the individuals following lateral meniscectomy had reduced neuromuscular control compared to the individuals following medial meniscectomy. This study was however, not compared to healthy controls, as many studies that look at the proprioception and therefore it is hard to indicate how different the medial proprioception is compared to the norm from this study. Karahan et al., (2009) looked at the comparison between individuals following meniscectomy and healthy controls and found that there was still a significant difference in proprioception 2 years following meniscectomy compared to the healthy controls.

Balance has been found to be a key evaluation technique of neuromuscular function (Mallious et al., 2011). The star excursion balance test (SEBT) is a simple, inexpensive test used to measure dynamic balance (Gribble et al., 2012) that has been incorporated in several clinical settings and laboratories. SEBT is performed by measuring a maximal reach distance whilst the individual stands on one leg and then reaches the other leg in different directions while remaining balanced throughout (Olmsted et al., 2002; Gribble et al., 2007). As the SEBT in all eight directions takes a long time, focusing the assessment on specific directions that are that performed by certain muscles is a potential method to reduce the duration (Olmsted et al., 2002; Herrington et al., 2009), as these specific muscles are significantly activated more than other muscles in certain directions (Early and Hertel, 2001). In knee OA, the anterior and medial directions will be proposed to test because quadriceps muscles are affected with knee OA and become weak (Slemenda et al., 1997; Chang et al., 2005). The directions most valid for looking at the sporting aspect of this study were anterior, posterolateral and posteromedial direction as seen in previous studies relating to ACL injury (Herrington et al., 2009). Proprioception deficits can cause more issues than just the knee giving way or feeling unstable, it can also cause psychological anxieties where individuals become more apprehensive of their movements trying to anticipate when the knee becomes unstable and hinder movement (Tichonova et al., 2016).

2.9 Self-reported outcome measures

The value of rehabilitation has been increasing over the last decades, as it was seen that it promotes faster recovery time with improved long-term outcomes (Bade et al., 2011). Jahan et al., (2018) developed a validated rehabilitation protocol following extensive research for individuals following a meniscectomy. The study was split into two phases. In phase one of rehabilitation protocol a literature review took place including several previously demonstrated protocols and a draft protocol was made. Seven clinicians were then asked to analyse the draft protocol and the final eight-week protocol was established. Phase two included testing the protocol over an 8-week course which was split into 3 phases in 38 young active individuals following meniscectomy. For the most effective outcomes individuals were asked to attend the sessions three times a week for two hours each session as soon as three days following meniscectomy. Massage therapy and hydrotherapy were then added on separate days. In week 1 of the 8-week process the focus was on healing and rest. In this program the individuals were asked to walk with crutches and only bear 50% of their weight. The exercises were focused on range of motion and slight contraction exercises. In phase two of the protocol (weeks 2-4) the training increased to low impact leg raises and balance tasks. And in phase three (week 5-8) the focus of the rehabilitation program then included strength, endurance, balance and looked at gait. At the end of the program the aim was to get the individuals following meniscectomy ready for a normal community-based training program. This detail for rehabilitation in the national health service is not available but it is well understood that the time as stated in Jahan et al., (2018) study cannot be invested in the national health service, which may be why outcomes following meniscectomy lead on to knee OA. Therefore, analysing the type, intensity, and amount of rehabilitation an individual receives following meniscectomy is highly important.

Recently, the self-perceived outcomes on movement and function related to rehabilitation and following musculoskeletal injury have been increasingly researched (Ardern et al., 2011). Therefore, it is important to know which psychological factors are related to the rehabilitation process which can contribute to a good recovery (Tichonova et al., 2013). The psychological influences such as self-efficacy (people beliefs in their own ability) (Hsieh et al., 2013), confidence in function (Chmielewski et al., 2008), pain catastrophizing (negative orientation towards pain) (de Boer et al., 2012) influence the ability for individuals to return to sport and causes further gait adaptations to occur. Knee injury and Osteoarthritis Outcome Score (KOOS) (Collins et al., 2011), kinesiophobia or re-injury (Kvist et al., 2005) also influence outcome measures following the injury or treatment (Brand and Nyland, 2009). The influence of pain and kinesiophobia on knee function can be explained by the fear-avoidance model, which has an important role in patient behaviour and has been seen to effect return to sport levels (Ardern et al., 2011). The fear-avoidance model often occurs in relation to the fear of pain or with athletes the fear of re-injury, which therefore causes maladaptive and restrictive compensatory mechanisms to occur to avoid anything that may cause the individuals pain or re-injury

(Fischerauer et al., 2018). KOOS has been utilised in several studies as it looks at the individual's perception of their own knee function in daily living, sport and recreation and analyses their perception of their quality of life following their injury (Collins et al., 2011). Therefore, these two aspects should be analysed and considered when looking at a meniscectomy population.

2.9.1. Kinesiophobia

A variety of impairments could lead to altered gait, including abnormal psychosocial factors (Hsieh et al., 2013). Kinesiophobia causes individuals to avoid behaviours that may potentially elicit pain or re-injury (Tichonova et al., 2016). The injury can create feelings of uncertainty and fear of how far the injury will affect future function (Österberg et al., 2013). This causes the individual's negative attitudes toward the body and participating in daily activities and sports, which can cause gait adaptations to occur and aid in compensatory movements to be established. The tampa scale of kinesiophobia (TSK) was used to establish if there was any fear of movement or fear or re-injury as seen in ACL individuals following surgery, which would thereby alter movement patterns, particularly when going back to being more active (Chmielewski et al., 2008). Özmen et al., (2017) found that there was a relationship among quadriceps muscle weakness, increased pain, and kinesiophobia in individuals with knee OA. Kinesiophobia has not been researched well in individuals following meniscectomy. Tichonova et al., (2016) found that kinesiophobia decreased in individuals following meniscectomy following a good rehabilitation program, however a high level of kinesiophobia was significantly correlated with more difficulties experienced in daily activities and poorer knee-related quality of life before and after rehabilitation.

2.9.2 Knee injury and Osteoarthritis Outcome Score

The Knee injury and Osteoarthritis Outcome Score (KOOS) has been used to see how an individual is feeling about his or her knee and to identify if there is a link about the individual's perception of their knee and the ability to undertake daily activities and the development of OA (Collins et al., 2016). The score is made up of five subscales including pain, symptoms, function during daily activities, sport and recreational function, and quality of life. Each subscale ranges from 0 to 100 points, with 0 representing extreme knee problems and 100 representing no knee problems (Roos et al., 1998). The score was created involving individuals following knee injury that can lead on to OA such as meniscus injury, anterior cruciate ligament injury, and chondral injury (Roos et al., 1998). The KOOS questionnaire has been shown to be valid, reliable, and repeatable when looking at meniscectomy (ROOS et al., 1998). The KOOS outcome scores should help give an indication of knee function due to an individual's self-reported perception of their pain, physical activity, and quality of life following meniscectomy.

Lutz et al., (2015) compared meniscal repairs to meniscectomy 10 years following surgery and found that the meniscal repair has higher scores for all outcomes, except quality of life which was linked to protecting the knee joint against degeneration. Thorlund et al., (2017) analysed both traumatic and degenerative tears at 12 weeks and 52 weeks follow up and found that sports/recreation and quality of life scored the lowest at 12 weeks, which improved slightly, however at 52 weeks still averaged around 50 out of 100. Willy et al., (2016) found that a lower KOOS quality of life score was associated with greater hip, knee support moments, and knee extension moments. Therefore, KOOS activity and quality of life should be analysed in alignment with kinematics and kinetics following meniscectomy.

2.10 Dynamic movement

A traumatic meniscal tear in the younger population is generally caused whilst participating in sports that include knee loading with a twisting action seen in sports such as football, basketball and other dynamic sports that includes landing or changing direction at a speed (Zedde et al., 2014). While many young, active individual's post-partial meniscectomy return to sports that require running (Baumgarten, 2007; Hurd and Synder-Mackler, 2007), there is a lack of research highlighting the association between long-term physical activity and structural OA progression in individuals following meniscectomy (Hall et al., 2017; Willy et al., 2017). Hall et al., (2017) is one of the only papers that analysed running, which analysed 78 patients following meniscectomy at 3 months post-op and 2 years post-op barefoot over-ground jogging (2.46 ± 0.39 m/s) and found that at three months post meniscectomy, the KFM was significantly lower in individuals following meniscectomy than in the control group and the EKAM was much greater. Two years post-meniscectomy, however, the KFM was similar to that seen in the control group, but EKAM remained much greater than the control group. Willy et al., (2017), also found that compensatory factors could be seen when running at a self-selected speed after a meniscectomy operation. For instance, to offload the knee which showed a 14.5%

reduced knee extensor moment, there was an increased load on the hip on average 37 months post-meniscectomy.

While partial meniscectomy has a high likelihood to develop OA, little is still known regarding knee loading during running (Willy et al., 2016) or other typical sports movements including one study looking at single leg hop (Hsu et al., 2016) and one study looking at landing (Ford et al., 2011). Hsu et al., (2016) analysed individuals following meniscectomy performing a single leg hop at both post-rehabilitation and 1-year post-surgery in relation to return to sport. They found that there was a large association between reduced peak knee flexion angle, reduced knee extension moment and peak torque. Ford et al., (2011) looked at landing mechanisms 3-months following lateral meniscectomy compared to healthy controls to analyse return to sport implication. They found identically to Hsu et al., (2016) that knee extension moments were reduced at 3 months post-surgery compared to healthy controls which was associated with the reduced quadriceps muscle strength, highlighting that quadriceps strength is one of the greatest issues following meniscectomy, particularly in relation to return to sport. The aforementioned studies, however, only focus on linear movements, whereas active individuals will need to partake in multidirectional movements. For example, Kiesel et al., (2014) examined the movement patterns related to injury in football players, these do not solely involve landing or running movements but also changes of direction as seen in the game, highlighting the importance of looking at these movements in further studies.

2.11 Return to physical activity

As discussed previously, meniscal injuries may be hard to treat effectively to ensure full recovery without compromising knee function. This is particularly important for young, active individuals, as sports-related injuries account for more than one third of all meniscus lesions (Li et al., 2018). Meniscal injuries are amongst the most common knee injuries in the sporting populations preceded by movements including twisting at the knee on a planted foot or jumping and landing movements (Mitchell et al., 2016). The preservation of the meniscus is well understood, and therefore a meniscal repair is favoured for the general population (Paxton et al., 2011; Xu and Zhao, 2015). This is more controversial in an active competitive population as individuals aim to return-to-sport as soon as possible and with a meniscal repair recovery time is longer compared to following meniscectomy (Eberbach et al., 2018).

In a professional environment, taking substantial time to return to sport can lead to added pressure and cost implications for the athlete, resulting in a premature, and potentially damaging, return to sport outcomes (Lee et al., 2019). Early return to sport following ACL reconstruction has been shown to place an athlete at higher risk of re-injury (Cheney et al., 2020). This is quite relatable as ACL injury is associated with meniscal tears and are both traumatic knee injuries. Laboute et al., (2010) found that individuals following ACL reconstruction who returned to competitive sports within the first 7 months of surgery were three times more likely to sustain a re-injury. In addition, Grindem et al. (2016) found that the knee re-injury rate in ACL reconstruction individuals could be reduced by up to 51% for each month return to sport was delayed for up to 9 months post-surgery. Greater compensatory mechanisms have also been seen such as trunk lean in early return to sport individuals which may cause further issues down the line if they become learnt habits and can cause re-injury (Capin et al., 2016). Previous studies which analysed return to sport following meniscal surgery stating that on average between 30-60% of individuals manage to return to their competitive sport at the same level as before (Chalmers et al., 2013; Eberbach et al., 2018; Roos et al., 2000). Brophy et al., (2009) found that the career length was shortened substantially in American football athletes following a meniscectomy in a two-year follow up study that found 54.4% of individuals either needing a follow up surgery or developing OA and therefore were not able to compete at the same level as before. Yet, meniscectomies are still the preferred method of treatment in the young active population as short-term results are generally excellent with low complications plus, less reoperation rates (Aune et al., 2014).

Return to competitive sport guidelines have been found to vary in length and intensity depending on the level of sport at which the individual competes (Kim et al., 2013). Several studies stated that the mean timeframe of the individuals to go back to competitive sports was between 3-10 months, however it took some almost three years to get back to a semi-professional level due to pain, muscle strength and patient reported outcomes varying for each subject (Zedde et al., 2014; Logerstedt et al., 2014; Samitier et al., 2015). Capin et al., (2016) looked at delaying return to sport following ACL reconstruction and how they affect reinjury. Delayed return to sport even in the absence of any clinical or biomechanical alterations in gait may be necessary in preventing second ACL injuries for occurring in young women (Capin et al., (2016). Ekhtiari et al., (2018) stated that out of 244 individuals who had undergone a meniscectomy, 80.4% of them returned to their preoperative level playing their sport as soon as 4.3 months post-rehabilitation. This was due to the individuals having a very good and comprehensive level of physiotherapy as they were training at a high level, highlighting that rehabilitation plays a large role in return to sport.

At three months post-surgery, private surgeons generally ask the individual to come back to see their physiotherapist for a return to play screening which includes a functional movement screen, a drop landing, gauging range of motion, isokinetic strength tests and sport-specific tasks to give the individuals or club the all clear to play at a high level or compete (McDermott, 2011). For the national health system, this in-depth screening process is not always available, and the physiotherapist will discharge a patient straight after the operation allowing them to self-assess as to their readiness to participate again in sports (Lowe et al., 2007). Kim et al., (2013) found that the return to activity timescale is dependent on the age of the individual, the type of tear, and the undergone surgery. Three months post-surgery may not be enough, considering how many high impact movements are involved in many sports (Eitzen et al., 2009). Nawabi et al., (2014) agreed with this study and highlighted that return to play is also site- and location-specific, following their comparison of lateral and medial meniscectomy. Their study showed that it took nearly three times longer for lateral individuals following meniscectomy to return to their competitive sports, and that due to pain and swelling they faced significant adverse effects and could not return to the same level of performance as before. Hsu et al., (2016) found that the individuals who sustained a meniscal tear wanted to go back to their competitive sport post-surgery, however, only 44% managed to play at their pre-injury level 3 years post-meniscectomy, due to knee pain and onset of osteoarthritis (OA). Management of the injury also plays a key role as to when the individual should be able to return to sport. Non-invasive interventions such as footwear could alter biomechanics to lower EKAM and reduce the progression of OA, thus playing a key role in treatment strategies. However, a full understanding of the lower limb biomechanics in these individuals must be grasped. During physical activity, the footwear an individual wears plays a major role in re-injury risk and pain management, as more cushioning has been seen to help alleviate joint pain in individuals with OA (Chang et al., 2007). Therefore, to identify an adequate way to manage knee loads following meniscectomy with the knowledge that they would want to return to sports, further studies should look at different footwear conditions following meniscectomy as they are low-cost and effective to aid in management of symptoms as well as prevention or slowing of knee joint degeneration.

2.12 Footwear

For effective self-management for pain using footwear has been found to be an effective strategy, however, there is little evidence to inform what the appropriate footwear is for individuals after surgery (Shakoor et al., 2010). The design of footwear may substantially affect the loading patterns of the entire lower body, and these biomechanical effects may have important implications for conditions in which mechanical factors are important such as post-surgery or OA.

Trainers/running shoes and other footwear have evolved dramatically over the past few decades (Subotnick, 2017). Whilst there are many different types of shoes on the market, primary categories are minimalist shoes, cushioned trainers with a soft increased pitch, and stability shoes which aid in motion control. Understanding the loads and compressive forces that go through the knee is essential when choosing your footwear, particularly following injury, or surgery (Wang et al., 2018). Footwear has been seen to alter foot knee pathology in individuals with knee OA and is a comfortable and cost-effective way to reduce symptomatic pain and possibly slow OA progression (Bennell et al., 2009). There were no significant differences between using valgus brace and lateral wedge footwear treatments to medial knee OA; however, compared with knee braces treatment, the footwear treatment was more acceptable among individuals with medial knee OA due to comfort and ease (Fu et al., 2015). Schmitz and Noehren (2014) found that the most effective way to reduce the first peak of the EKAM was to reduce the knee adduction angle followed by the GRF, which should be done by retraining the gait or using footwear interventions.

2.12.1 Footwear and osteoarthritis

Depending on what surgery the patient has undergone, part of the cartilage may be exposed and loading, shock absorption and lubrication may be altered (Fox et al., 2012). Therefore, it can be assumed that more cushioning, support or wedges should be implemented to try and offload the affected part of the knee to help either reduce load, reduce movement or shift the loads (Levinger et al., 2013). Different footwear interventions have been used in individuals with OA to reduce knee loading and pain (Erhart et al., 2008; Chapman et al., 2013). The UK’s National Institute of Clinical Excellence (NICE) guidelines recommended either cushioning or lateral wedge footwear and insoles to be a part of the conservative management of knee OA

(National Institute for Health and Care Excellence, 2014). The biomechanical treatments of footwear and insoles are both cheap and effective (Wang et al., 2018).

It has been stated that the use of modern self-chosen walking shoes resulted in a 14% increase in dynamic loading of the knee compared to barefoot walking in individuals with OA, however other studies show that a lateral wedge or more cushioning has a greater advantage for individuals with knee OA (Voloshin, Wosk, & Brull, 1981; Jones et al., 2015). The greater demand placed on the knee during these sporting movements highlights the need for footwear interventions for active individuals particularly following surgery (Saxby et al., 2016). Individuals following meniscectomy generally are not advised to change their footwear as this is not regulatory, and therefore may go back to wearing the same shoes/trainers they were wearing before the treatment. It is unclear whether footwear design can affect knee loading and therefore OA risk in meniscectomy patient and therefore further investigation is needed.

In individuals with medial knee OA, it has been widely stated that lateral wedge footwear (Shaw et al., 2018) or shoes with midsoles that are stiffer laterally than medially where the knee load is redistributed away from the medial tibiofemoral compartment towards the lateral tibiofemoral compartment and can be beneficial for individuals with medial knee OA (Bennell et al., 2013; Jones et al., 2015). Likewise, footwear with midsoles that are stiffer medially compared to laterally, such as those with medial arch support seen in stability shoes (Shakoor et al., 2010), shift load toward the medial compartment which may allow a reduction in lateral tibiofemoral knee loading, however this has not been widely researched (Patterson et al., 2020). Patterson et al., (2020) found that in a healthy population, footwear with medial arch support shifted the GRF medially (Schmalz et al., 2006), reducing loading on the lateral tibiofemoral compartment and therefore may be feasible for offloading individuals following lateral meniscectomy. Looking at footwear for both medial and lateral individuals following meniscectomy therefore was of interest including a lateral wedge and increased medial arch support and cushioning footwear.

2.12.2 Cushioning footwear

Footwear with a soft cushioned heel, particularly those with an increased pitch (raised heel in relation to the forefoot), have been used to aid in firstly reducing knee loading during impact tasks and secondly to aid in propulsion during running to enhance running economy with an added spring from the increased soft pitch on the heel (Day and Hahn., 2019). Mercer et al.,

(2018) also looked at running economy with cushioning footwear, however found the opposite results and showed cushioning footwear did not influence running economy when compared to a control footwear, however their number of individuals used in the study was quite low (10) and therefore, further research needs to be done. Burns and Tam (2020) reported that the Nike Vaporfly 4% which had increased midsole cushioning managed to improve running economy by 4%, however this was reported to be due to the additional carbon plate in the footwear which was intended to reduce energy loss during toe bend. Running, is an exceedingly popular exercise worldwide, however, every year up to 50% of runners worldwide encounter injuries, which typically occurs due to repeated loading of the knee joint (Tschopp and Brunner, 2017). To reduce the risk of running-related injuries, running shoe manufactures have added cushioning to shoe soles aimed at reducing knee joint loading however, studies show no evidence of reduced running injury rates with increasing amounts of cushioning (Kulmala et al., 2018). In fact, some studies have even shown that there is an increase in knee loading when wearing footwear with increased cushioning compared to a harder sole (Chan et al., 2018; Baltich et al., 2015; Pollard et al., 2018). The increased in knee loading when applying increased cushioning was unexpected when taking into consideration early research looking at in vitro data (Aerts et al., 1993) and the attenuation theory which is often used for running (Kim et al., 1994), that showed increased sole cushioning should reduce knee loading.

The attenuation model takes into account the spring like mechanism of the leg during running, where the leg is compressed in the initial stance at impact and gradually decelerates, and then recoil in late stance to reaccelerate the body (Kim et al., 1994). This allows for efficient force production to occur during every stride through the stretch-shortening cycle of the muscles, which propels the body (centre of mass (COM)) forward and is also in the attenuation theory called the spring-mass system (Kim et al., 1994). This theory is important when analysing footwear stiffness, as it has previously been shown that when changing surface stiffness, leg stiffness itself is altered to maintain the COM movement (Kerdok et al., 2002). For example, as a runner transitions from a hard surface to a softer surface, the leg has been found to become stiffer to maintain the preferred spring-mass mechanics, which can also be associated to increased cushioning footwear (Kulmala et al., 2018). Gill et al., (2020) analysed the spring-mass model in individuals and looked at its association with foot-strike index. Gill et al., (2020) found that the spring-mass model could not be used for all individuals as only 34-46% of the individuals ran with a force-length linearity, therefore this model is not appropriate for all running styles, but it can be used as a baseline concept when thinking of running mechanics.

Several conflicting studies show that cushioning footwear can either reduce knee loading or increase knee loading (Chambon et al., 2014; Kulmala et al., 2018; Day and Hahn, 2019; Meardon et al., 2018). Meardon et al., (2018), similarly found that with increased footwear cushioning of around 10-20%, high loads at mainly the ankle but also the knee and hip could be seen during running. Wei et al., (2018) also demonstrated that cushioned shoes resulted in lower knee loading and tibial shock on the lower extremities, which could be beneficial to reduce knee loading following meniscectomy compared with the inferior cushioned footwear during landing. As only landing was analysed, it could be assumed that these findings displayed significant reduction in knee loading as it was in a controlled vertical motion and therefore, foot motion could be more controlled.

In comparison, when examining running and multidirectional loading such as seen during a change of direction, results showed increased knee loading when wearing cushioning shoes (Lindenberg et al., 2011). The increased knee loading is due to the additional imbalance caused by the increased soft heel, which the body needs to compensate for. Wei et al., (2018) found that the imbalance (increased foot motion) seen with an increased soft heel creates increased muscle activation around the ankle to stabilise the foot and therefore greater ankle stiffness. Kulmala et al., (2018) found that when wearing cushioning footwear compared to control footwear, leg stiffness increased which in turn increased impact loading on the knee to keep COM maintained with the increased compression of the cushioning. Jellema et al., (2019) also stated in their literature review that shoe sole hardness affects the sensitivity of the foot, allowing greater awareness and control to occur with sole hardness and therefore, with greater cushioning in the sole, increased instability is caused, which can be related to a compromised joint. The instability was demonstrated in this study by the increased variability in ankle inversion/eversion in the cushioning footwear compared to the neutral footwear.

2.12.3 Lateral wedge footwear

Lateral wedges have demonstrated reduced medial knee loading during walking in both affected and contralateral limbs in individuals with medial OA (Jones et al., 2013). It was Tomatsuri et al. (1975) who firstly proposed to use lateral wedges to treat medial knee OA.

Interventions such as the lateral wedge have been used in individuals with OA to reduce mechanical load on the medial compartment and lessen compensatory strategies such a lateral trunk lean (Esfandiari et al., 2013). For walking and running it has often been stated that a lateral wedge insole (LWI) can be used to offload the medial compartment of the knee (Voloshin, Wosk, & Brull, 1981; Jones et al., 2015). The maximum effect of the LWI occurs during early stance at heel strike (first peak of the EKAM) because of the structure of the LWI where the inclination of the insole was superior at the heel and gradually decreased to 0˚ at the forefoot (Shanib et al., 2016). The most common inclination angle of LWI was 5° because higher inclination of LWI would cause increasing and considerable discomfort in individuals with medial knee OA and therefore reduce compliance (Arnold et al., 2016; Butler et al., 2007).

Previous studies have highlighted that a lateral wedge of at least 5° produces reductions in the EKAM ranging, between 4% to 12% (Hinman et al., 2008; Bennell et al., 2011; Fantini Pagani et al., 2012). The mechanism of EKAM reduction caused by a lateral wedge due to ankle eversion occurring, laterally shifted centre of pressure and therefore reduced the GRF vector at the knee (Kakihana et al., 2005). Similarly, medial wedge insoles could reduce lateral knee loading for individuals with lateral knee OA by shifting the centre of pressure (COP) medially, however these have not been researched in detail as medial knee OA is more common (Rodrigues et al., 2008).

Jones et al., (2015) highlighted that lateral-wedge insoles in individuals with OA to be an important intervention to reduce the EKAM by shifting the ground reaction force laterally, altering the angle of the knee, thereby moving the moment arm which results in a reduced the EKAM on the knee joint as also seen in individuals following meniscectomy (Figure 2.9) (Kakihana et al., 2005; Jones et al., 2014). Hinman et al., (2012) found great variability in results, identifying that whilst wearing a lateral wedge knee loads have been seen to range from reductions in knee loading by to 25% to increases in knee loading of more than 20%, highlighting a responder, non-responder situation as stated by Jones et al., (2014). Hatfield et al., (2016) stated that difference in results could be due to differences in foot posture and subtalar joint mechanics and found that implementing a lateral wedge with a medial arch support better help reduce medial knee loading in individuals with OA with all foot types. Starbuck et al., (2017) found that during running whilst wearing lateral wedge footwear knee loading did not differ, which was stated to be associated with different foot strike patterns, therefore affecting the ability for the lateral wedge footwear to affect knee loading.

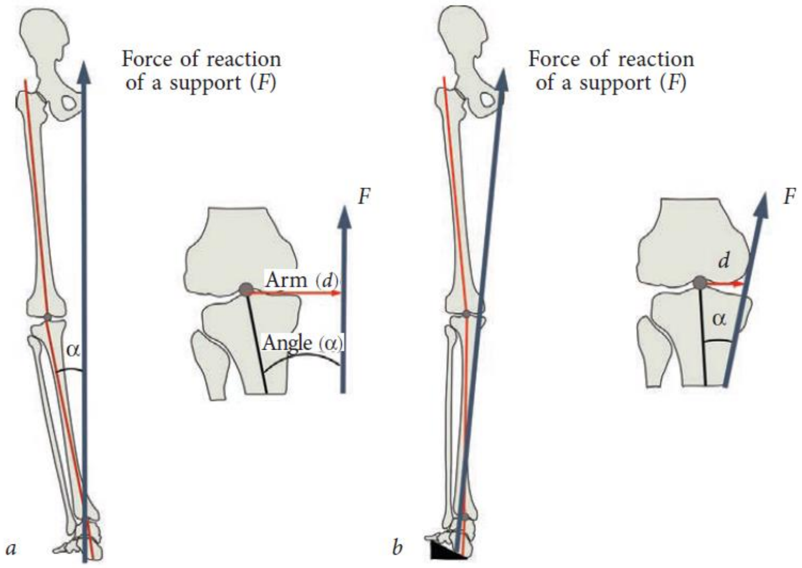


Figure 2.9: The shift of the GRF laterally wearing a lateral insole. Source: http://journals.eco-vector.com/files/journals/1/articles/6157/supp/6157-5635-1-SP.png

The typical lateral wedge insole has no medial arch support which means that most lateral wedge insoles have no limit to how far they laterally shift the COP, however with a medial arch support, this is more controlled by reducing the magnitude of the COP excursion (Hinman et al., 2009). Hatfield et al., (2016) found that lateral wedge footwear with medial arch support had the same EKAM reduction (8%), but individuals with OA indicated that the comfort with the medial arch was significant and therefore they would be more likely to wear them. Hunt et al. (2017) compared the lateral wedge insole with medial arch support in individuals with medial knee OA and found that pain and function were improved over prolonged wearing. Similarly, Jones et al. (2015) highlighted that both the typical lateral wedge (5.21%) and medial supported lateral wedge (6.29%) reduced the medial knee loading, but the medial supported lateral wedge insoles had a reduction in pain in individuals with OA whereas the lateral wedge did not affect pain.

ASICS in Australia have developed shoes with the mechanism of a lateral wedge insole with medial arch support as an integrated system, this created the Melbourne OA shoe (Kean et al., 2013, Van Ginckel et al., 2017, Bennell et al., 2013, Hinman et al., 2014). The Melbourne OA shoe has been found to reduce medial knee loading during walking when compared with control shoe for individuals with medial knee OA (Kean et al., 2013, Bennell et al., 2013). Hinman et al. (2016) found after six months of wearing the Melbourne OA shoe compared to a conventional walking shoe, pain and function improved on average 50% in both Melbourne OA shoes and conventional shoe groups, but no additional improvement such as quality of life or activity level) was found in the Melbourne OA shoe group. With more extensive knowledge this could be a simple and beneficial way to help manage both gait alteration post-meniscectomy and pain related to the injury and/or surgery at low cost. Given the potential long-term health implications of joint injury understanding offloading strategies to aid in slowing further re-injury or joint degeneration is highly important.

2.12.4 Stability footwear

High-supportive footwear generally classed as stability footwear typically possess medial, midfoot, and longitudinal stiffness and support (medial arch support) and, similarly, to cushioning shoes, have an increased pitch, which likely influences sagittal plane knee moments (Sayer et al., 2019). Stability footwear has been found to increase knee loads significantly by shifting the GRF anteriorly with reduced dorsiflexion and increased knee flexion moments in individuals with OA (Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). Following injury or surgery, stability is often reduced (Almekinders et al., 2004), however, it seems that adding more stability or stiffness to shoes may not be the most beneficial intervention for an active clinical population (Fisher et al., 2007). It has been well established that stable, supportive footwear increase knee loads significantly more in OA individuals compared to flat flexible shoe styles (Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). Chambon et al., (2014) found that increased midsole support had similar results to cushioning footwear where an increased knee flexion moment can be seen, however, this could potentially be solely due to a greater footwear pitch also being seen in stability footwear. Shakoor et al., (2010) found that footwear with midsoles that are stiffer medially compared to laterally, such as those with medial arch support seen in stability footwear, shift load toward the medial compartment in individuals with OA. Patterson et al., (2020) found that in a healthy population, footwear with medial arch support shifted the GRF medially, reducing loading on the lateral tibiofemoral compartment and therefore may be feasible for offloading individuals following lateral meniscectomy.

As well as cushioning footwear, high-supportive footwear generally classed as stability footwear, often have an increased pitch at the heel compared to low-supportive counterparts. The high-supportive stability footwear has also been found to result in increased KFM (Sayer et al., 2018). Stability shoes are designed for runners and have a mix of cushioning and motion control which includes more rigid elevated aspects in the shoe for instance the medial arch which prevents the foot from collapsing inwards (Barton et al., 2009). High-supportive shoes often have an increased tread at the heel compared to their low-supportive counterparts (Sayer et al., 2018). Following injury or surgery, stability in the knee is often reduced (Almekinders et al., 2004), however it seems that adding more stability or stiffness to footwear may not be the most beneficial for an active population with a compromised knee joint such as seen following meniscectomy.

Stable supportive footwear has typically been recommended by clinicians for people with knee OA to help stabilise the knee (Paterson et al., 2014). The effects of footwear and stability shoes on individuals following meniscectomy has not yet been looked at. Footwear with an increased pitch (raised heel in relation to the forefoot), specifically with a soft cushioned heel, have been used to aid in firstly reducing knee loading during impact tasks and secondly to aid in propulsion during running to enhance running economy with an added bounce from the increased soft pitch on the heel (Day and Hahn, 2019).

To summarise, non-invasive interventions such as footwear and insoles have been found previously to reduce knee loading during running (Lewinson et al., 2013). More recently, Starbuck et al., (2017) found that during running, whilst wearing lateral wedge footwear frontal plane knee loading was not reduced, highlighting that further research needs to be done on footwear to reduce knee loading during running. Individuals in young active populations sustain a sporting meniscal injury are likely to return to sport following treatment (Eberbach et al., 2018). Therefore, choosing the ideal trainer for the specific sports post-surgery could make a great difference when considering joint degeneration progression and could be used as a management tool. Reducing knee loads via non-surgical biomechanical treatment strategies is thus an appropriate treatment aim for people following meniscal surgery. Footwear is a promising avenue for self-management, therefore further research needs to be done to evaluate biomechanical outcomes from commonly commercially available trainers to understand how individuals following meniscectomy respond, which can then lead to a more systematic approach to understanding and identifying guidelines.

Stiffness of the footwear, particularly during running, has a large influence on fore-foot foot motion and therefore can influence running performance and injury risks (Stefanyshyn and Wannop, 2016). Hinman et al., (2013) found that increased medial stiffness caused an increase in medial knee loading in healthy individuals during walking which may in turn be even worse for clinical populations, and therefore not be recommended following meniscectomy specifically in a young active population. Clinical OA guidelines recommend appropriate footwear for knee OA self-management, with some guidelines specifying shoes with supportive and cushioning features (National Clinical Guideline Centre., 2014; Fernandes et al., 2013). Currently it is unclear whether characteristics of cushioning, medial arch support or minimal properties have favourable or negative effects on knee loading in individuals following meniscectomy as this has not previously been researched.

2.13 Gaps in the literature

Radiographic evidence has been reported following meniscectomy, however the biomechanical effects have not been well documented, and therefore understanding knee joint loading in individuals following meniscectomy will provide a clearer picture to determine whether gait adaptations occur in early stages of rehabilitation and if alteration strategies can be implemented. In reviewing the literature, the external knee adduction moment, knee flexion moment and knee adduction angular impulse have been used as surrogate measures of knee loading and have been seen to clearly identify increased knee loading following meniscectomy (Bennell et al., 2011). Knee flexion moment needs to be analysed to understand the frontal and saggital plane knee joint loading (Asay et al., 2018). Despite the consideration that medial and lateral menisci properties of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004), there have been no previous biomechanical studies analysing the comparison between individuals following medial and lateral meniscectomy. The lateral meniscus has been seen to play a more vital part in dynamic movements (Fox et al., 2015), therefore looking at the individuals following medial and lateral meniscectomy in isolation was highly important, specifically in relation to knee joint loading during dynamic tasks.

Evidence is limited when analysing post-meniscectomy outcomes during sporting tasks such as running, change of direction, and landing. Most studies focus on knee loading during walking and do not examine knee loading during sport-specific movements (Englund et al., 2003; Sturnieks et al., 2008; Thorlund et al., 2016). Assessing knee loading during sport-specific movements would reflect the types of movements sporting individuals would be required to perform when returning to sport. It is therefore not known if a change in the activity level changes the outcomes post-meniscectomy and whether a return to activity framework could be identified better with the understanding of the effect of high loads on a meniscectomy.

A full picture of all the biomechanical and functional outcomes which are both linked to OA progression and other joint diseases should be drawn, including muscle activation, 3D movement analysis, strength measures, and psychological factors in individuals following meniscectomy.

Conservative treatments, including footwear, are designed to reduce medial knee loading which could improve clinical and biomechanical outcomes. Evidence has shown that the external knee adduction moment is reduced significantly when using lateral-wedge insoles (Jones et al., 2012; Jones et al., 2013). Whilst cushioning and stability footwear still shows mixed outcomes when looking at knee loading and whether the increased pitch of soft sole can aid in supporting the knee during walking or increase knee loading during dynamic tasks (Paterson et al., 2014; Lindenberg et al., 201; Kulmala et al., 2018). Footwear has been well researched in individuals with OA, however there is little consensus in the studies, and it is unclear which footwear modalities could reduce knee loading, specifically following meniscectomy. Footwear has also not been looked at in a post-meniscectomy population even though this could be a beneficial tool to help offload the knee and slow OA progression.

In conclusion, to the author's knowledge, only a few studies have investigated the effect of high impact loads as seen in competitive sports in individuals following meniscectomy including two studies looking at non-ecologically valid running for sporting individuals (Willy et al., 2016, Hall et al., 2014) one study looking at landing (Ford et al., 2011) and one study looking at a single leg hop (Hsu et al., 2016). To the author's knowledge, there has not been a study analysing the combination of balance, which is important with neuromuscular stability in the joint and muscle activation (to help support the joint) in following meniscectomy. Footwear and other alternative coping strategies, which may help offload the knee and in turn slow OA progression, have also not been covered for individuals following meniscectomy. Using a full approach including kinematics, kinetics, muscle activation, muscle strength, muscle co-contraction, self-reported outcomes, balance and footwear could show major implication for individuals following meniscectomy and give strategies and modalities to help slow if not offset degeneration in the joint, allowing these athletic individuals to return to competitive sport. This will be the first study to provide a holistic approach to understanding biomechanical, clinical, and self-reported outcomes in a sporting population post-meniscectomy.

Chapter 3 - **Overall Methodology**

3.1. Chapter Overview

The results from the literature review showed a varied methodology for studies associated with the biomechanical outcomes following a meniscectomy, where 18 studies investigated the biomechanical effects following meniscectomy, however, these were generally looking at walking tasks only (Jiang et al., 2019). These studies all varied in measurement techniques, equipment used, and type of individuals measured. Two studies that have investigated running, as a task, in individuals following meniscectomy, are not perceived as ecologically valid protocols as they were performed on treadmills or performed barefoot (Willy et al., 2017; Hall et al., 2017). Three studies have investigated sport-specific tasks including landing and jumping which align with the tasks in this thesis (Ford et al., 2011; Hsu et al., 2016; Willy and Davis, 2018). When conceptually looking at the individual following a meniscectomy it is necessary to ensure strength, muscle activation and biomechanical loading are within normal limits as these could be risk factors for future knee disorders (Sturnieks et al., 2008; Baltich et al., 2015; Ericsson et al., 2009). To the author's knowledge, no studies have examined all these aspects in combination following a meniscectomy and how these are all perceived to be a risk factor for knee OA. In this chapter, a repeatable methodology was established which was confirmed by the repeatability study in chapter 3.8.

3.2 Research Environment

Data collection took place at the Manchester Institute of Health and Performance (MIHP). To ensure data quality, a between-session repeatability assessment was undertaken (section 3.09)

A marker placement repeatability (chapter 3.09) was conducted which showed that all the values for the SEM were under 2° for the kinematics data highlighting a high repeatability between sessions. The SEM dictates the amount of variability in a test which is caused by measurement error which indicated that if the measurement outcome is not greater than the measurement error, although significant, the data may not show clinically meaningful results.

3.2.1 Three-dimensional (3D) capture of data

Three-dimensional (3D) kinematic motion data was collected using 28 Qualisys infra-red Oqus cameras at the MIHP (QTM Oqus300, Qualisys AB, Sweden) with a sampling rate of 250Hz (Figure 3.1). These were positioned around the running track and adjusted. The cameras were centred around four force platforms at the MIHP which were embedded into the floor, which had a sampling rate of 1500Hz. To collect the data positional markers are recorded by at least two cameras and redefined with their new 3D location in the global coordinate system (LAB system), which enables the storage of positional information that can be used to analyse the kinematics (Perry & Burnfield, 2010). Infra-red light reflects off of the retro-reflective markers back to the camera, which produces a point in each image to provide the 2D position of each marker. These 2D markers (bright spots) are then reconstructed to generate a 3D location in the global coordinate system (LAB system), which then allows trajectories to be formed from the markers (Kirtley et al., 2006). Each marker must be seen by at least 2 cameras for each frame at any point during the trial to provide a 3D location to be determined within the LAB coordinate system, which allows storage of the positional information that is used to analyse the kinematics (Perry and Burnfield, 2010). To allow the conversion of the given 2-dimensional (2D) image of the cameras into a 3-dimensional (3D) workspace, a spatial calibration is needed (section 3.2.2).

Figure 3.1: Running track at the MIHP showing 10 of the 28 cameras (top)

3.2.2 Force platform data

The ground reaction force which is used to calculate the kinetic outputs was measured with floor embedded force platforms (AMTI, Washington, USA) (Figure 3.2). The measurement of the ground reaction force was synchronised with the kinematic data to calculate the kinetic data such as moments. Before each trial, the force platforms were zeroed to remove noise and make sure the force that is applied is solely the force from the individuals, therefore any force that exceeds the body mass of the individual is an extra force that is applied to the body.

Figure 3.2: 60m running track with embedded force platforms (in the white box) and timing gates. White X indicates centre of the collection area and where L-frame is placed

3.2.3 Calibration

To collect accurate and reliable data, and to allow the conversion of the given 2-dimensional image of the cameras into a 3-dimensional workspace, a calibration is needed. The system is first calibrated statically by placing an L-frame (equipped with four markers along with the metal frame) (Figure 3.3), in the centre of the collection area on the second force platform from the bottom (marked with white X) (Figure 3.2). The static calibration identifies the orientation and position of each camera in relation to the other cameras and the global coordinates of the gait laboratory. The fixed markers of the L-frame were used to define the X and Y axis of the laboratory coordinate system. The positive X axis points forwards and the positive Y axis points to the left when facing forwards, which were aligned along the two sides of the force platform. When the X and Y have been identified, the positive Z axis can be established (upwards). The coordinate system was coincident with the force platforms by making sure the

L-frame is aligned with the edges of the force platform to synchronise the force and camera orientation and set the same origin for both which was ensured by using the clips on the L-frame, so that the origin of the force platforms could be identified accurately as the origin on the coordinate system to establish the correct X, Y orientation.

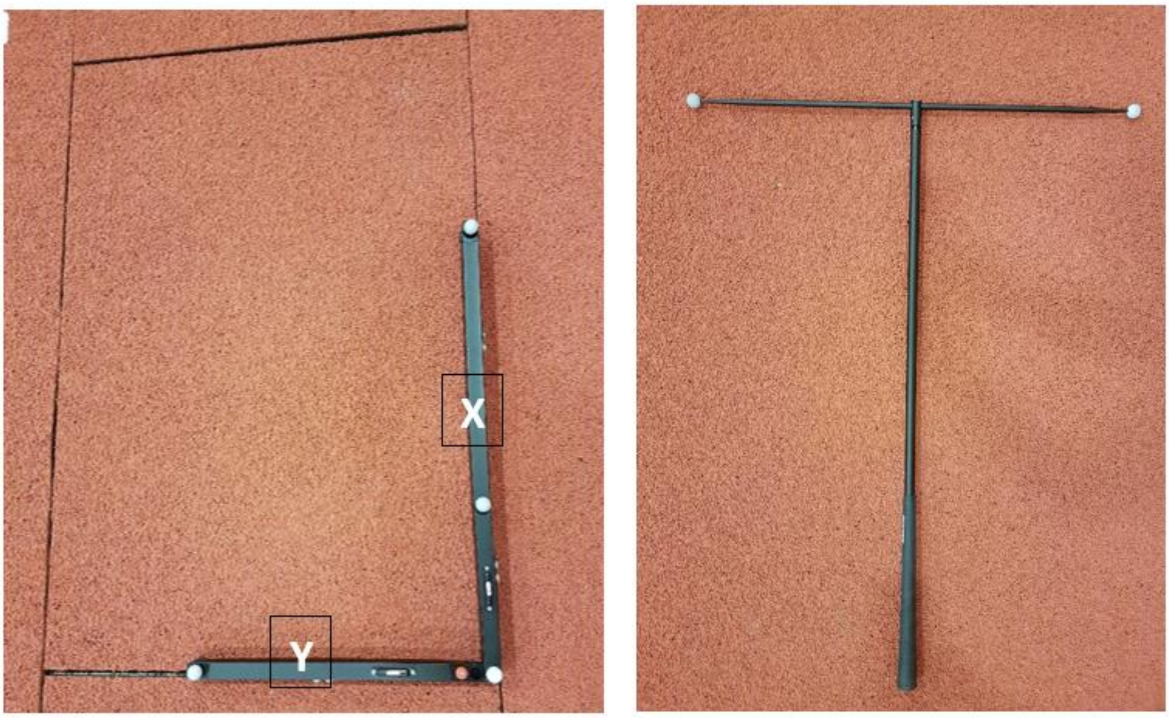
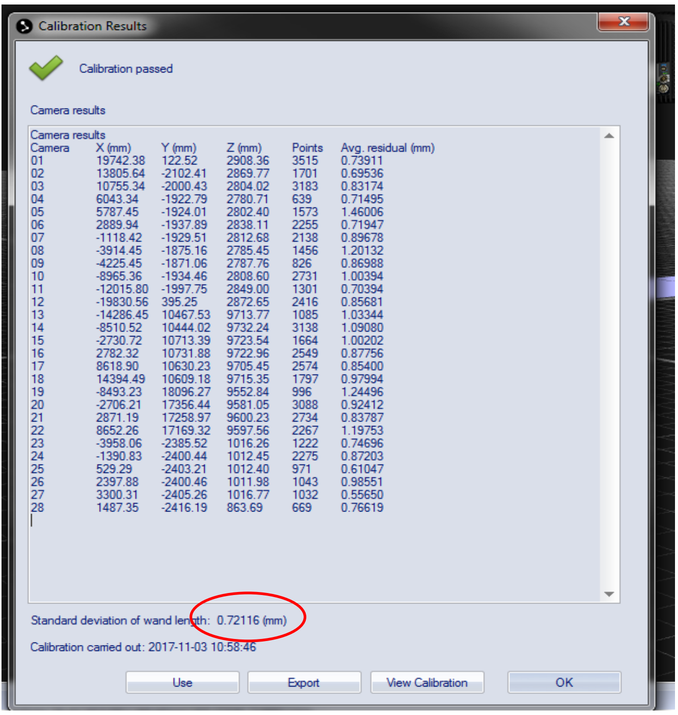


Figure 3.3: The calibration L-frame and T-shaped wand

Secondly, a dynamic calibration was performed to ensure that all motions within the measurement volume can be identified and captured. This was done with a T-shaped calibration wand (equipped with 2 markers at each end) (Figure 3.3), which was used to set the capture volume. The wand was randomly moved during the calibration in as many directions as possible around the test space ensuring that the volume between the floor and the highest point (roughly 2 m) were covered. The T-shaped wand was 601.6 mm in length and the calibration was set up for 120 s ensuring that all cameras could see the wand for a minimum of 500 frames.

The error of the calibration should be as low as possible, as the higher the residuals, the higher the inaccuracies involved in the results of the measurements. During the calibration, the standard deviation of the average residuals of the 3D marker points are analysed for every camera, whether each camera can see the calibration markers and then the average standard deviation for all cameras is calculated (Figure 3.4). This is known as a quality check for the measured position of the markers (Qualysis., 2006). The calibration established the global coordinate system where the x, y, z coordinates of each marker at each sample point of time could be saved. Whereby x is the anterior/posterior, z the vertical and y the left/ right (medial/ lateral) axis



```
Calibration passed

Camera results

Camera results
Camera      X (mm)      Y (mm)      Z (mm)     Points   Avg. residual (mm)
01          19742.38    122.52      2908.36    3515     0.73911
02          13805.64    -2102.41    2869.77    1701     0.69536
03          10755.34    -2000.43    2804.02    3183     0.83174
04          6043.34     -1922.79    2780.71    639      0.71495
05          5787.45     -1924.01    2802.40    1573     1.46006
06          2889.94     -1937.89    2838.11    2255     0.71947
07          -1118.42    -1929.51    2812.68    2138     0.89678
08          -3914.45    -1875.16    2785.45    1456     1.20132
09          -4225.45    -1871.06    2787.76    826      0.86988
10          -8965.36    -1934.46    2808.60    2731     1.00394
11          -12015.80   -1997.75    2849.00    1301     0.70394
12          -19830.56   395.25      2872.65    2416     0.85681
13          -14286.45   10467.53    9713.77    1085     1.03344
14          -8510.52    10444.02    9732.24    3138     1.09080
15          -2730.72    10713.39    9723.54    1664     1.00202
16          2782.32     10731.88    9722.96    2549     0.87756
17          8618.90     10630.23    9705.45    2574     0.85400
18          14394.49    10609.18    9715.35    1797     0.97994
19          -8493.23    18096.27    9552.84    996      1.24496
20          -2706.21    17356.44    9581.05    3088     0.92412
21          2871.19     17258.97    9600.23    2734     0.83787
22          8652.26     17169.32    9597.56    2267     1.19753
23          -3958.06    -2385.52    1016.26    1222     0.74696
24          -1390.83    -2400.44    1012.45    2275     0.87203
25          529.29      -2403.21    1012.40    971      0.61047
26          2397.88     -2400.46    1011.98    1043     0.98551
27          3300.31     -2405.26    1016.77    1032     0.55650
28          1487.35     -2416.19    863.69     669      0.76619

Standard deviation of wand length:  0.72116 (mm)

Calibration carried out: 2017-11-03 10:58:46
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Figure 3.4: The standard deviation of measurement (circled in red) of all the cameras

3.2.4 3D Marker construction

Once the reflective marker has been identified the camera software QTM$^{©}$ software (v 2019.1) will look for the same marker in the next time frame. If a marker is found it will be joined to the former marker to form a trajectory. To ensure a smooth trajectory of each marker, uses a 3D tracking function with a buffer of 4-10 frames to predict the next location of the trajectory's marker. In this thesis the maximum frame gap, which specifies the number of frames allowing the joining of two trajectories, was set to 10 frames (42 ms). The calibration algorithms extract the camera position and orientation for each camera by evaluating the camera's view of the calibration wand during the calibration (QTM Manual). Although the system is highly accurate, the calibration algorithm may have (1) prediction error or the (2) maximum residual may be off centre which need to be accounted for.

1) Prediction error: To predict the location of the marker in the next frame a prediction area is calculated where the marker placement can be calculated from the previous

location if a marker has dropped out (Figure 3.5). The QTM guidelines (2011) stated that a prediction error of 30 mm would be most consistent to predict the location of the markers, which was also used in the current. If the prediction error value is set too high, the likelihood increases that jumpy motions within single trajectories are seen. Equally, the greater the deviation, the higher the chance for a cross-over swapping between two trajectories. If this parameter is set too small, division of trajectories can occur, which might result in many more trajectories than markers.

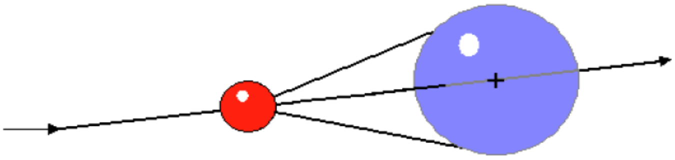


Figure 3.5: Prediction error (red ball = marker, arrow = prediction and blue ball = deviation) (QTM, 2011)

2) Maximum residual: The maximum residual function has been implemented together with the prediction error to ensure the continuation of the trajectory and sets the limit to the distance from the final location of the 3D point. If the value is too large, it can slow down the calculation and can cause a merger of 3D points (QTM, 2011). The default value of the maximum residual is 10 mm, however, due to the good visibility, it has been set in this thesis to 6 mm. The correct location in 3D space and force platform was ensured by using a CalTester which is a quality assurance tool for validating the laboratory by verifying the spatial synchronisation of the motion capture system and forces.

3.2.5 Retro-reflective marker set up and definitions of segments

For the 3-dimensional (3D) motion analysis collection, 44 retro-reflective markers were used which each had a diameter of 14 mm and were attached both on the lower limb and trunk using double sided hypoallergenic tape (Figure 3.6). The reflective marker itself is very light to reduce the skin movement artefact. All markers were placed by the principal researcher on the subject by palpating the anatomical landmarks (incisura jugularis (IJ), Spinous process of Thoracic Vertebrae 2 (T2), Spinous process of Thoracic Vertebrae 10 (T10), ASIS, PSIS, Illiac Crest, medial and lateral femoral epicondyles placed above the femoral condyle on the joint line, medial and lateral malleolus and the 1st, 2nd, and 5th metatarsophalangeal joint (Met)).

Figure 3.6: Marker Placement

At least three reflective makers are necessary on a segment (limb) to define the position and orientation in the 3D space. Cappozzo, Catani, Leardini, Benedetti, & Croce, (1996) investigated the number of markers needed to define one segment and showed that four markers represented the most advisable solution. To track a segment three markers should be identified by the cameras (Cappozzo et al., 1996), however, four were used in this thesis for all segments in case one marker could not be seen (trunk, pelvis, thigh, shank, and foot) adding some redundancy to the collection. As the markers are placed on the skin and not directly on the bone, the position of the marker is estimated and associated with the underlying bone, which causes instrumental errors due to the position error in the reconstructed coordinate system relative to the global frame and skin artefacts caused by the movement of the skin relative to the bone (Cappozzo et al, 1995). Movement artefacts can take place due to the skin and fatty soft tissues moving over the underlying bone, which can cause significant errors within the study (Cappazzo et al., 1996), therefore marker placement and marker set up are important. There are several different marker set ups for 3D motion capture with the most common being Helen Hayes, Plug-in gait and six-degree-of-freedom (Collins et al., 2009, Capozzo et al., 1995). The most commonly used marker set for clinical application is a variation of the Helen Hayes based marker set (Collins et al., 2009). The Helen Hayes was developed for low resolution systems to have few markers which are placed on the bony landmarks and constraining joint motion to three rotational degrees-of-freedom. The standard plug-in gait also uses fewer markers, and for instance in the foot model calculates the whole foot movement rather than splitting it up into segments which causes greater error (Paterson et al., 2017).

These constraints introduce errors to joint angle calculations, including the sharing of markers between segments can also increase error and decrease the independent segment calculations. The six-degree-of-freedom marker set such as the CAST marker set allows rotational and translational axes (vertical, medial/lateral and anterior/posterior) to be calculated as well and reducing the unnecessary error by tracking the individual segments with the application of clusters (Cereatti et al., 2007). To overcome these challenges Cappozzo, Catani, Croce, & Leardini, (1995) developed the calibration anatomical systems technique (CAST) which is a six-degree-of-freedom marker set which provides six variables for each segment to describe its position and orientation. The CAST set up provides information about the origin of *x,y,z* and the rotation about the principal axes for each joint segment (sagittal, frontal and transversal). The CAST marker set up has been shown to be valid and repeatable method, which attempts to minimise skin-movement artefacts by attaching markers to the centre of segments rather than single markers close to the joints and thus has been applied in this thesis (Collins, Ghoussayni, Ewins, & Kent, 2009; Schmitz et al., 2016; Żuk & Pezowicz, 2015).

3.2.6 Surface Electromyography (EMG)

Electromyographic (EMG) data were collected using the Delsys EMG system with wireless surface electrodes (Delsys, 16 Channel Trigno EMG System, Boston, MA). The Trigno control panel was used to synchronise the electrodes to the hub which was synchronised with the Qualisys software. The sampling frequency was set to 2000 Hz for the surface EMG, as it has been stated that the sampling frequency should be set to at least double that of the frequency that is being measured (Millette, 2013). This was then synchronised with the Qualisys system through the trigger. To ensure high accuracy of the EMG signal, the preparation of the skin and placement was in accordance with the SENIAM guidelines (Konrad., 2005). Based on SENIAM recommendations, bony landmarks were located and the distance between landmarks taken to identify and mark with a pen on the muscle belly. The placement did, however, vary between individuals as each participant is slightly different and therefore after the guidelines were followed, a submaximal isometric contraction determined whether the correct location had been marked in the first instance. To prepare the skin for the electrodes, any hair was shaven to allow full skin contact. The shaven area was then rubbed with an abrasive gel and then wiped with alcohol to allow no dirt or dead skin cells to get in the way. The wireless electrodes were then placed on the skin using double-sided hypoallergenic tape, in the direction of the muscle fibres (Nishihara & Isho, 2012).

The EMG electrodes were placed on the upper. On the thigh the electrodes were placed on the vastus medialis (VM) and lateralis (VL), biceps femoris (BF) and semitendinosus (ST) (Figure 3.7). The vastus medialis electrode placement was placed at 80% on the line between ASIS and the joint space in front of the anterior border of the medial epicondyle. The vastus lateralis was placed at 2/3 on the line from the ASIS to the lateral epicondyle. The biceps femoris was placed at 50% on the line between the ischial tuberosity and the lateral epicondyle. The semitendinosus was placed at 50% on the line between the ischial tuberosity and the medial epicondyle. These muscles have been chosen because they play the main role in movement and stability of the knee. To avoid additional artefacts, the electrodes were fixed in place with bandages.

Figure 3.7: The EMG electrode placement on the thigh

The magnitude of the EMG signal can be influenced by many factors such as muscle length, skin contact, movement artefact, cross-talk of muscles (De Luca, 1997). To control for outside factors from the data, the EMG signal was normalised to a reference contraction allowing for comparisons between different muscles (French et al., 2015). The SENIAM guidelines recommend normalising the EMG signal by using a maximal voluntary contraction (MVC) as the reference contraction (Merletti, 1999; Burden, 2010), which expresses the task EMG as a percentage of the maximal activation capacity of the muscle (Burden, 2010). Alternatively, to the MVC normalisation, dynamic normalisation methods exist such as the mean or peak normalisation. The dynamic normalisation method expresses the task EMG as a percentage of the mean or peak of the same EMG signal (Burden, 2010; Burden, Trew, & Baltzopoulos, 2003). Although to date, the MVC normalisation method is the most commonly applied normalisation method, no consensus has been reached about which method is the most appropriate normalisation method. Several studies investigated different normalisation methods and showed a higher intra-subject variability and reduced sensitivity of the MVC normalisation method compared with dynamic normalisation methods (Albertus-Kajee et al., 2011; Balshaw & Hunter, 2012; Burden & Bartlett, 1999; Burden et al., 2003; Chapman, Vicenzino, Blanch, Knox, & Hodges, 2010; French et al., 2015). In contrary, the MVC normalisation method demonstrated high repeatability (Bolgla & Uhl, 2007) and high sensitivity compared to dynamic normalisation methods (Benoit, Lamontagne, Cerulli, & Liti, 2003). Burden (2010) literature review revealed that the mean and peak normalisation techniques reduced the inter-subject variability more than any other normalisation technique (Burden, 2010). Therefore, in this thesis the maximal voluntary contraction (MVC) normalisation approach was used with a hand-held isometric contraction method as the isokinetic dynamometer was in a different room meaning separate software and set up would have had to be put in place (Figure 3.8).

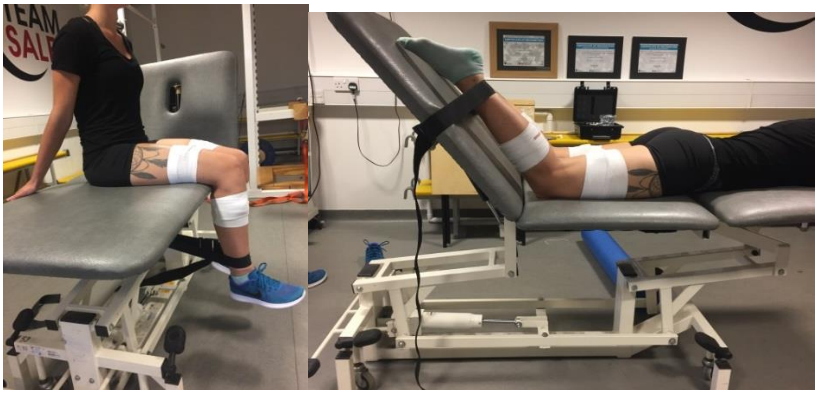


Figure 3.8: Normalisation strategies using handheld dynamometry to collect MVC for each muscle. Left = Quadriceps, Right = Hamstrings

For all MVC participants were asked to contract maximally against a resistance for three seconds. This maximal contraction was repeated three times with a five second rest between contractions to allow for muscle fatigue recovery, allow for a 3:5 work to rest ratio. The quadriceps MVC was measured first which involved the individuals sitting on the plinth with their leg at the ankle strapped to the fixed leg of the plinth at 90° whilst holding on to the back of the plinth as this was the angle where the leg was able to comfortably produce the most force without the strap slipping up the leg. They were then asked to push (kick out) against the strap as hard as possible for three seconds. This was then repeated for the hamstring muscles, where the individuals were asked to lay on the plinth face down, the back of the plinth was raised, the leg was strapped to the raised back at 30° knee flexion and the individual was then asked to pull their leg towards their head as hard as possible without lifting their hips as this was established to be the range where the hamstrings produce most force (Beyer et al., 2019).

3.3 Data collection procedures

The static and dynamic tasks involved, balance, several dynamic movement tasks and strength measurements. There was no randomisation of the tasks as the order of the tasks did not affect the results of the thesis, therefore the more dynamic tasks which were more likely to fatigue the individuals were done last for each participant. The participants were always asked to start with filling out the questionnaires, then the strength measurement, balance task, drop landing, walking, running, and change of direction to finish. There was as much rest between each task as was needed for each individual.

3.3.1 Questionnaires

3.3.1.1 Tampa Scale of Kinesiophobia

A variety of impairments could lead to altered gait, including abnormal psychosocial factors (Becker et al., 2004; Sturnieks et al., 2011; Adern et al., 2011). Kinesiophobia is defined as "an irrational and debilitating fear of physical movement and activity resulting from a feeling of vulnerability to painful injury or re-injury" (Kori and Todd, 1990). Kinesiophobia causes individuals to avoid behaviours that may potentially elicit pain or re-injury (Tichonova et al., 2016). The injury can create feelings of uncertainty and fear of how far the injury will affect future function (Österberg et al., 2013). This causes the individual's negative attitudes toward the body and participating in daily activities and sports which can cause gait adaptations to occur and aid in compensatory movements to be established (Chmielewski et al., 2008). Worse knee confidence is also described in people with knee OA and associated with higher pain and greater knee instability (Skou et al., 2013). Knee OA is highly prevalent after meniscectomy (Becker et al., 2004; Sturnieks et al., 2011), and factors such as knee confidence and kinesiophobia play a key role in those recovering from injury (Chmielewski et al., 2008). The Tampa scale of Kinesiophobia (Miller et al., 1991) was used to establish if there was any fear of movement or fear or re-injury. The Tampa Scale for Kinesiophobia is a 17-item scale with scores ranging from 17 to 68 points, which uses a 4-point Likert scale, measuring the fear of movement or re-injury. The greater the value on the scale, the greater the kinesiophobia level was.

3.3.1.2 Knee injury and Osteoarthritis Outcome Score

The Knee injury and Osteoarthritis outcome score (KOOS) has been used to see how an individual is feeling about their knee and to identify if there is a link about the individual's perception of their knee and the ability to undertake daily activities and the development of OA (Roos et al., 2003; Collins et al., 2016).KOOS score identifies if the individuals have pain, show symptoms and whether their quality of life has decreased which all may lead to compensatory strategies following surgery. Scores range from 0 to 100 with a score of 0 indicating the worst possible knee symptoms and 100 indicating no knee symptoms. To calculate each section 100 - $\frac{Mean\ score\ (P1-P7)\times 100}{4}$ is used with the correct question numbers depending on the number of questions in each subsection.

3.3.1.3 Physical activity survey

The physical activity survey looked at the level of physical activity the individuals were pre-injury, pre-surgery and post-surgery (Appendix 2.2). The physical activity questionnaire analyses the type of sport they were participating in, how many times a week and at what level. The three stages of the physical activity questionnaire were analysed to look at the changes in physical activity due to the meniscectomy and their return to activity level. The physical activity questionnaire was chosen to provide an in-depth assessment of type of sport and level of participation/ competition before and after injury and after surgery. The Tegner scale (Tegner, 1929) which is normally used assess the current activity levels and does not reflect all sports that are done.

3.3.1.4 Rehabilitation questionnaire

This questionnaire was given to individuals post meniscectomy to highlight time since surgery, time of rehabilitation, type of rehabilitation and intensity of rehabilitation (Appendix 2.3). The rehabilitation questionnaire gave of the standard of rehabilitation, including the most standard rehabilitation exercises following knee surgery and whether individuals were tasked to do these. This was to give an idea as to how good and thorough their rehabilitation was.

3.3.2 Isometric strength assessment

Following the questionnaires, the participants were asked to perform a maximum isometric strength measurement in a sitting position on an isokinetic dynamometer (Biodex System 3

PRO, Biodex Medical System, New York, NY, USA) with a sampling frequency of 120 Hz. Each participant was secured to the testing chair with a chest and pelvic belt (Figure 3.9). The participants were strapped and measured up to a chair to allow them to sit comfortably and safely to avoid any injuries. The knee joint centre was aligned directly with the pin of the lever arm of the dynamometer.

Figure 3.9: Biodex isokinetic dynamometer during isometric strength testing

The participants were asked to perform a maximal force (85 degrees hip flexion) with a knee flexion angle of 60˚ which was found to be the range where knee flexors produced their maximum capacity (Murray et al., 1980). The extension arm on the isokinetic dynamometer was attached 1 cm proximal to the malleoli of the ankle to the dominant shank in line with previous recommendations (Brown & Weir, 2001). Prior to the test, a warm-up session of four submaximal isometric quadriceps contractions were performed to habituate the participants to the test equipment and to ensure that the participants were warmed up. The familiarisation and warm up sessions were performed in accordance with previous recommendations (Brown & Weir, 2001). Following the familiarisation trials, participants were asked to perform maximal isometric contraction of the quadriceps. This involved a maximal contraction, pushing upwards against the lever arm at a 60° knee bend for five seconds. This was repeated five times with a break of 20 s between each test.

Concentric and eccentric strength of the quadriceps was also measured in the repeatability study. To set up the dynamometer prior to starting the trials, participants were asked to move their leg through the full available range of motion (ROM) from 90 degrees knee flexion to maximum knee extension pushing as hard as they can. To familiarise the participants to the movements, they were asked to perform five submaximal incremental repetitions of knee extension and flexion prior to the performance of maximal efforts. Following the familiarisation, the individuals were asked to start the trial which, involved the participants to push their leg upwards (concentric) with as much force as they can against the lever arm and then continuing to push upwards (eccentric) with as much force as they can still pushing against the lever arm at the speed of 60 deg/s. Each maximum torque measurement was performed three times with a break of 60s between the tests. The isokinetic protocol was not used in the main study as increased error could be seen in the isokinetic concentric/eccentric strength assessment in the repeatability study and therefore only the isometric toque was measured. The individuals also found the isokinetic task was much more difficult as they could not produce maximum muscle contractions at full knee extension and often needed help with releasing the lever arm in extension. Therefore, this protocol was also deemed unfeasible for individuals following a meniscectomy.

3.3.3 Y-Balance test

The Y balance test is part of the star excursion balance test (SEBT), which is an assessment to investigate dynamic postural control (Hertel, Miller, & Denegar, 2010; Kinzey & Armstrong, 1998). The reaching direction was reduced to three directions (the anterior, posterior-medial, posterior-lateral) (Figure 3.10) as these have been shown to be reliable and efficient in measuring dynamic postural control in individuals with knee injuries whilst challenging the muscles around the knee identifying neuromuscular control (Coughlin et al., 2012; Chimera & Warren, 2016). Participants were asked to maintain a single-leg stance on the participants assessed leg whilst reaching forwards with the opposite leg as far as possible along the chosen line with the most distal part of their foot. Participants were given as many practice trials as necessary until the individual was comfortable with the task (Chung-Hoon and Tracy, 2015). The individual was asked to keep their upper body upright and make sure the heel from the stance leg remained on the ground and keep their arms out to the side to help with balance. Participants were asked to complete three successful trials for both legs. If participants lost balance and put their foot down, they were just asked to stop the trial and repeat. The participants completed the test with their dominant leg for the healthy controls and the non-injured leg for the individuals following meniscectomy first and then repeated with their non-dominant for healthy controls and injured leg in the individuals following meniscectomy. The Y-balance task was performed on the force platforms using 3D motion capture as centre of pressure (COP) was considered as a variable which was why the task was performed on the force platform to see whether there was a shift in the COP in relation to the foot which was taken from the 3D motion capture. Measuring the reach distance with the 3D motion capture system was chosen over the standard Y-balance rig as foot contact was necessary on the force platforms to measure the COP which would have been affected by the lever arms of the Y-balance rig.

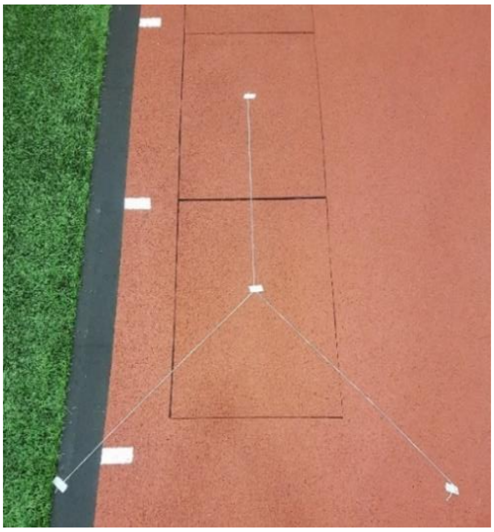


Figure 3.10: Y-balance task on the force platform

3.3.4 Drop landing

For the drop landing, the participant was asked to step off a 30 cm box and land with the same leg in a bent position onto a mark placed 10 cm away from the box. A 30 cm box was used where the intention was to examine a more sports specific landing. The 30 cm box was chosen as previous literature has stated that anything under 30cm does not represent sporting tasks (Zhang et al., 2000) and with increased height, there is a greater chance of injury (Yeow et al., 2010; Ali et al., 2014). The 30cm box was chosen in the current thesis to allow the task to be sport specific without causing any further risk of injury. The individuals were asked to land with a bent leg to cushioning the landing and prevent any sudden pain to occur on the affected knee in the individuals following meniscectomy. The participants were required to hold the position for three seconds without putting the elevated leg down. A three second hold was chosen to look at the individual’s stability and capability to perform the task adequately, as if individuals fell over straight after landing, it showed a lack of capability and the individuals should have been able to perform this task adequately with the idea of returning to sport following meniscectomy. The participant was not cued as to what to do with the upper body as the movement should be as natural as possible and most individuals chose to hold their arms out to the side for additional balance. Participants were given time to familiarise and ensure they were comfortable with the tasks. The uninjured leg was tasked to go first for individuals following meniscectomy, and the dominant leg was tasked to go first for the healthy controls. Participants were asked to complete three successful trials for both legs. If they lost balance and put their foot down before the three seconds, they were just asked to stop the trial and repeat.

3.3.5 Walking

Participants were asked to walk at a self-selected speed on the running track. Although gait changes can be seen with altered walking speed including increased stride length and knee moments (Ardestani et al., 2016), which is why self-selected speed was chosen as the results in this thesis were meant to be individualised and specific to what the participants natural walking speed, to see whether there was a reduced walking speed following meniscectomy compared to the healthy controls. Han et al., (2018) found that after a total knee replacement walking speed was still reduced compared to healthy controls which was linked to lower knee moments. For example, when you consider limb length as a small person may struggle to walk the same speed as a very tall person, therefore self-selected speed was chosen for the individuals. The participants were asked to walk through two timing-gates (Witty timer, Microgate, Bolzano, Italy) which were placed 6 m apart over a 30 m running track. Five successful trials were collected at their self-selected speed ±5%; each trial included left and right foot contacts. A successful trial required a full foot contact in the stance phase for each leg, without an overlap of the foot between force plate and the track. Unsuccessful trials were determined when less than three markers per segment were visible, speed changes were seen during the trials, or a partial/double contact with the force platforms occurred.

3.3.6 Running

Similarly, as for the walking trials, the participants were asked to run at a self-selected speed along a 60 m running track (with embedded force plates). Initially, five runs at their self-selected speed were collected to identify their average self-selected speed and the desired speed within ±5%. Five successful trials were then collected, with both left and right full foot contacts for the stance phase. A successful trial included a full contact phase on a force platform for each leg, without an overlap of the foot between force plate and the track. Rest was given between each trial or as much as is necessary. Unsuccessful trials were ones whereby less than three markers per segment were visible, speed changes were seen during the trials, or a partial/double contact with the force platforms occurred

3.3.7 Ninety degree change of direction

The timing gaits were moved to include a third set allowing the approach time and exit time to be recorded. These were set at 6 m and 4 m (Figure 3.11).

Figure 3.11: 90 degrees change of direction approach and exit distance

The participants were asked to perform several practice runs, to determine the correct starting point to gain force platform foot contact and to fully understand the task. The participants were asked to perform one maximal effort of the change of direction task running as fast as possible or comfortable to the last force platform, then run through a series of cones (placed at 90 degrees) (Figure 3.12). For the trials, the participants were asked to approach the force platform at 80% of maximum running speed and perform the change of direction movement on the force platform, then run through the final cones placed 90 degrees to the side. The running speed was chosen to be the most valid in terms of dynamic competitive sports such as football where individuals would run up to an opponent and change direction at speed. This is also the speed where most injuries are likely to occur. The participants were tasked to change direction through cones at 90°. Ninety degrees was chosen as most studies look at 45, 90, 135 and 180 degrees, however 90 was chosen as the most common angle individuals change direction whilst still being a challenge for the individuals and without causing too much of a 'twist' on the knee joint (Rouissi et al., 2017). Participants were asked to perform five successful trials on both the right and left leg. A trial was successful when a full foot contact was produced with a clear run up before and push through after. An unsuccessful change of direction included when individuals missed the force platform completely, miss-stepped on the force platform creating a hop and ran too slow.

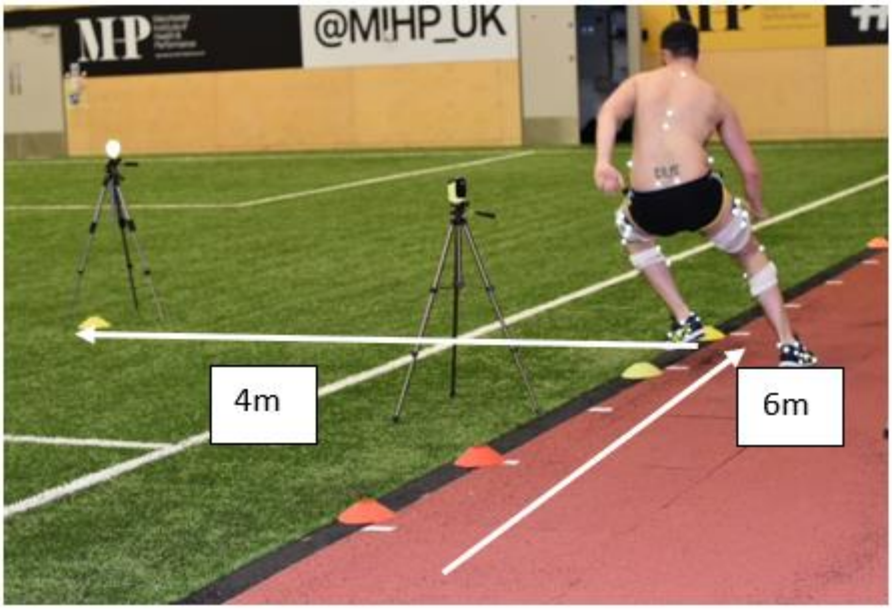


Figure 3.12: 90 degrees change of direction at 80% speed

3.4 Data processing

The following data processing was undertaken once the individual had completed all the tasks.

3.4.1 Kinematics and kinetics

All retroreflective markers were labelled using Qualisys 2.19 Track Manager software (QTM^{TM}), where the markers were identified, checked for irregularities, labelled and digitised.

Each trial was cut to include one step either side of the force platform. All successful trials were then exported to a C3D file which was processed in Visual 3D (V3D) software v6 (C-motion, inc., USA). To delete any unwanted noise in the kinetic and kinematic data, a Butterworth low pass filter with a cut-off frequency of 12 Hz was used as this was seen to be the most adequate frequency for both kinematics and kinetics during both static and dynamic tasks to be able to identify actual events without noise from the data and not lose too much data by over smoothing. It has been shown that using different cut-off frequencies for different studies could have a significant effect on the data, specifically the joint moments, and therefore, Kristanslund et al., (2012) recommended that the kinematic and kinetic data should be processed with the same filter.

In V3D, a six degrees of freedom model was adopted, which is made up of the collection of rigid segments that translates to the subject’s body segment. Therefore, the height and mass of each participant were recorded and entered to obtain subject-specific segmental inertia parameters to enable accurate and individual analysis for the moments and forces. The position and orientation of each segment were created by defining the proximal and distal joint locations and radius of each segment which allowed each skeletal segment to be created (Figure 3.13). The anatomical markers were identified for each segment, the tracking markers were then highlighted, and the x-y plane of the segment coordinate system was defined to allow accurate tracking of the segments. The joint centres were then calculated which was used to join the segments together and calculate the angles between these segments.

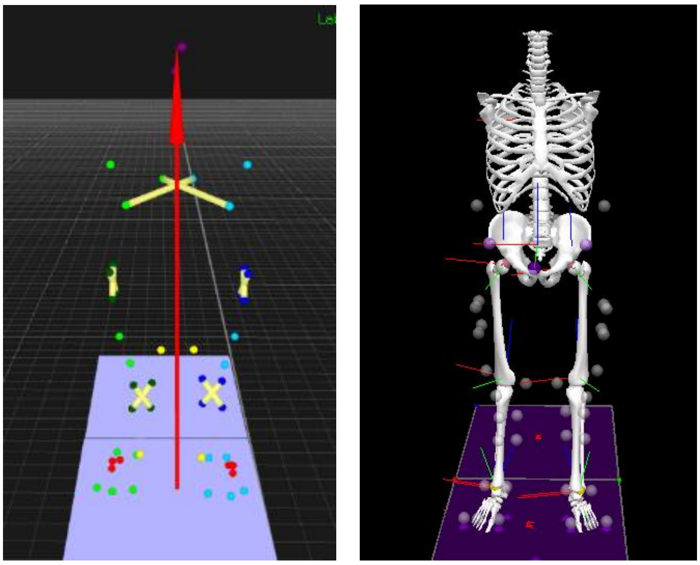
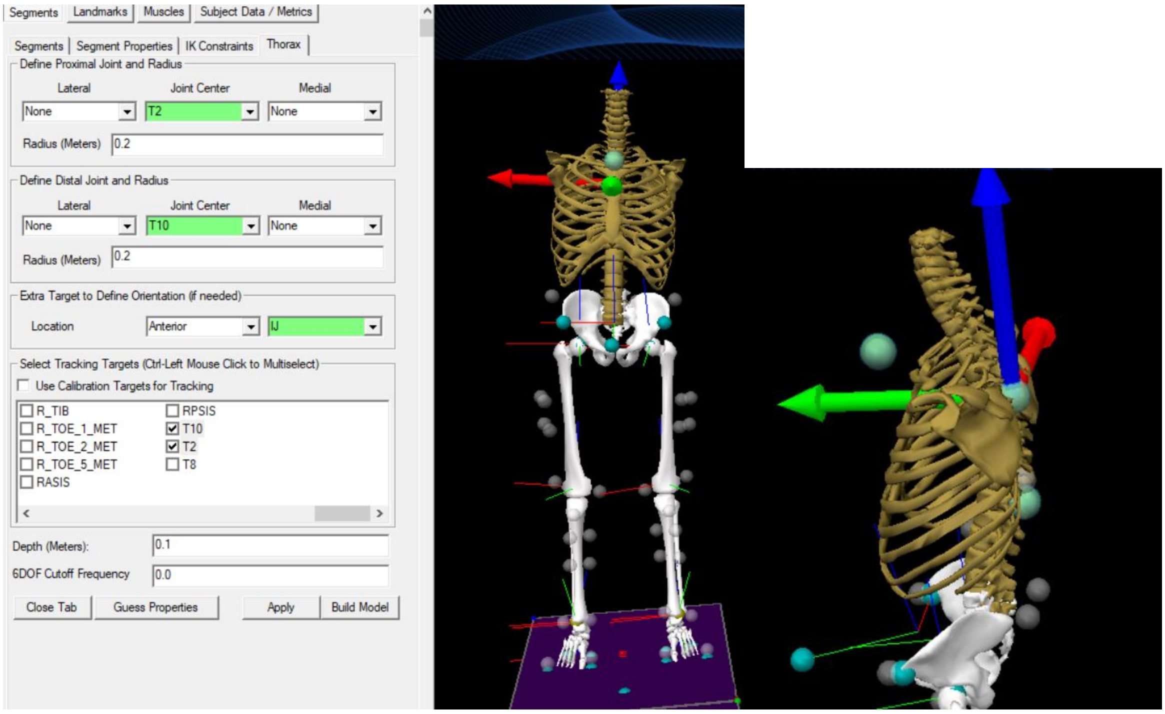


Figure 3.13: QTM raw static model (left) and Visual3D full segment model (right)

3.4.2 Definition of the segments

3.4.2.1 Trunk segment

To define the trunk segment, markers were positioned on the incisura jugularis (IJ), the spinous process of the Thoracic Spine (T2, T10 vertebrae) allowing a 3D model to be created as the markers are placed anterior and posterior of the body (Armand et al., 2014). In the 3D analysis, which in this case was Visual3D v6 (C-Motion Inc., Washington, USA), which is a premier biomechanics analysis tool for measuring movement and force data. The thorax segment was created by using the IJ as the orientation with an anterior orientation with the T2 as the proximal point and the T10 as the distal point. To create the thorax the depth was also set to 0.1 (Figure 3.14) with the tracking markers being marked as the IJ, T2 and T10.



Define Proximal Joint and Radius

Lateral	Joint Center	Medial
None	T2	None

Radius (Meters) 0.2

Define Distal Joint and Radius

Lateral	Joint Center	Medial
None	T10	None

Radius (Meters) 0.2

Extra Target to Define Orientation (if needed)

Location Anterior IJ

Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)

☐ Use Calibration Targets for Tracking

☐ R_TIB
☐ R_TOE_1_MET
☐ R_TOE_2_MET
☐ R_TOE_5_MET
☐ RASIS
☐ RPSIS
☑ T10
☑ T2
☐ T8

Depth (Meters): 0.1

6DOF Cutoff Frequency 0.0

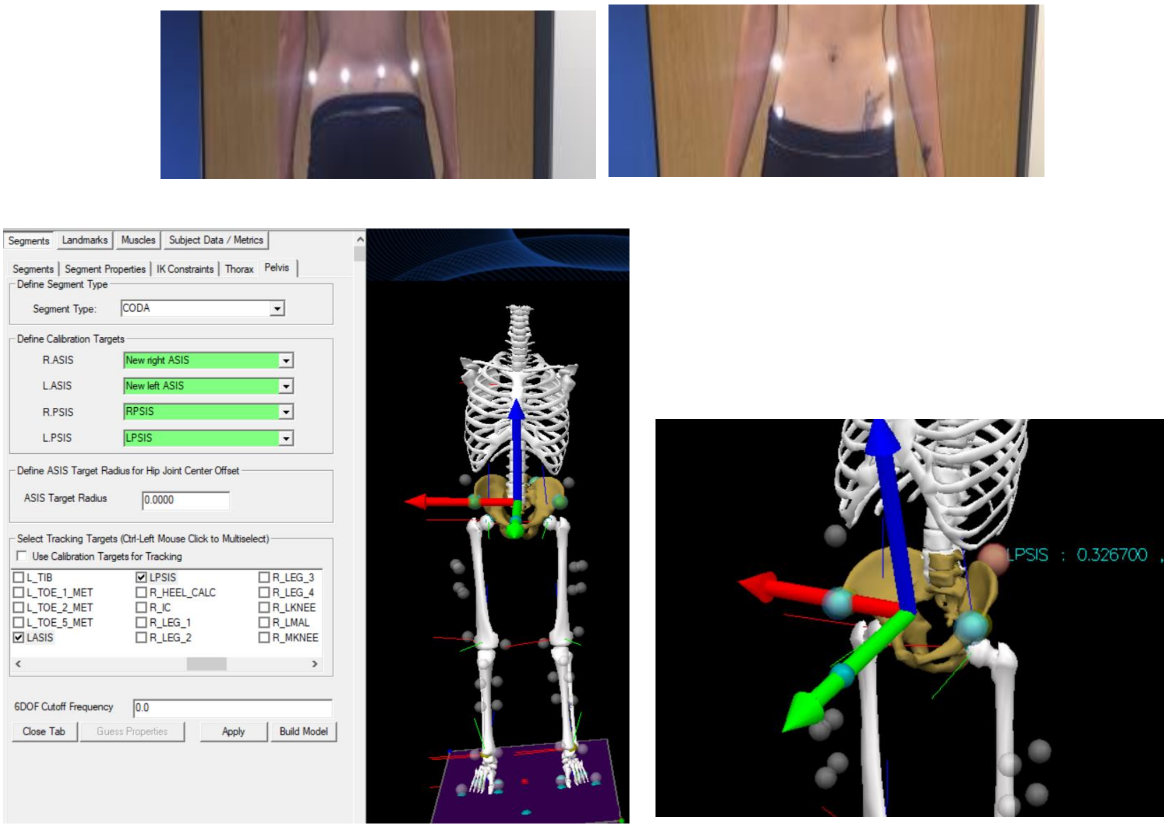
Figure 3.14: This shows marker placement and model on Visual 3D for the trunk

3.4.2.2 Pelvis segment

The pelvis segment was defined by positioning the markers on the predefined anatomical landmarks of the anterior-superior and posterior-superior iliac spin (ASIS & PSIS) (Figure 3.15). Additionally, a marker was placed on each side of the iliac crest in the case one of the markers, generally the ASIS could not be tracked. Within Visual 3D the standard CODA pelvis was used with the ASIS and PSIS as the calibration and tracking markers with the hip joint centre being calculated through the following calculation:

- 0.36*ASIS_Distance, -0.19*ASIS_Distance, -0.3*ASIS_Distance (ASIS_Distance is the distance between the ASIS of both sides)

This estimation is based on the established prediction method of Bell et al. (1990) which has been recommended for the use in motion analysis due to the small and unbiased errors (Leardini et al., 1999).



Define Segment Type

Segment Type: CODA

Define Calibration Targets

R.ASIS: New right ASIS

L.ASIS: New left ASIS

R.PSIS: RPSIS

L.PSIS: LPSIS

Define ASIS Target Radius for Hip Joint Center Offset

ASIS Target Radius: 0.0000

Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)

☐ Use Calibration Targets for Tracking

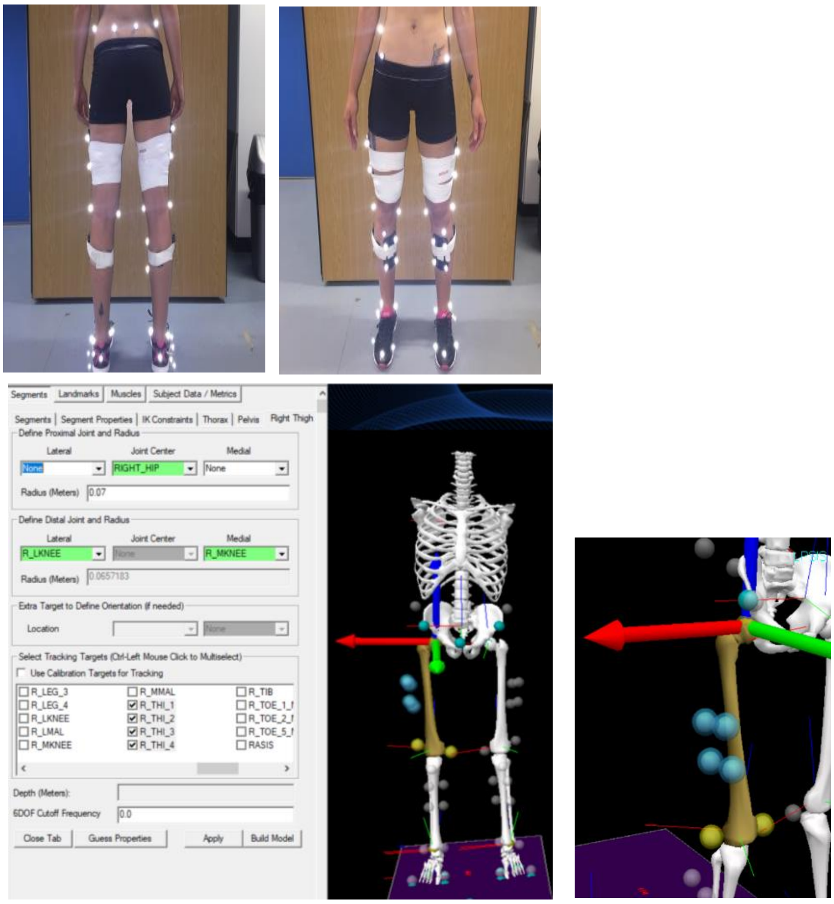
☐ L_TIB
☐ L_TOE_1_MET
☐ L_TOE_2_MET
☐ L_TOE_5_MET
☑ LASIS
☑ LPSIS
☐ R_HEEL_CALC
☐ R_IC
☐ R_LEG_1
☐ R_LEG_2
☐ R_LEG_3
☐ R_LEG_4
☐ R_LKNEE
☐ R_LMAL
☐ R_MKNEE

6DOF Cutoff Frequency: 0.0

Figure 3.15: This shows marker placement and model on Visual 3D for the pelvis

3.4.2.3 Thigh segment

For the thigh, the calibration markers were placed on the lateral and medial sides of the segments. The thigh was defined by the HIP which was created by the pelvis segment and the femoral epicondyles on each leg (R_LKNEE, R_MKNEE). These locations were identified by palpating the segment and following the joint line until the joint centre has been identified between the femur and the tibia. To ensure that the markers were placed on the true knee axis, the participants were asked to squat, and the marker placement was visually checked on the computer after the static calibration has taken place. The tracking markers for the thigh were attached with clusters which each had 4 markers mounted on a rigid plastic plate which was strapped to the side of the segment. Extra elastic bandages were wrapped around the clusters to minimise movement. The position of the clusters were marked with a pen around each corner, to ensure that there was no movement of the cluster during the trials and if movement did occur then the markers were repositioned, straps tightened and a new static collected (Figure 3.16).



Define Proximal Joint and Radius
Lateral: None
Joint Center: RIGHT_HIP
Medial: None
Radius (Meters): 0.07

Define Distal Joint and Radius
Lateral: R_LKNEE
Joint Center: None
Medial: R_MKNEE
Radius (Meters): 0.0657183

Extra Target to Define Orientation (if needed)
Location: None

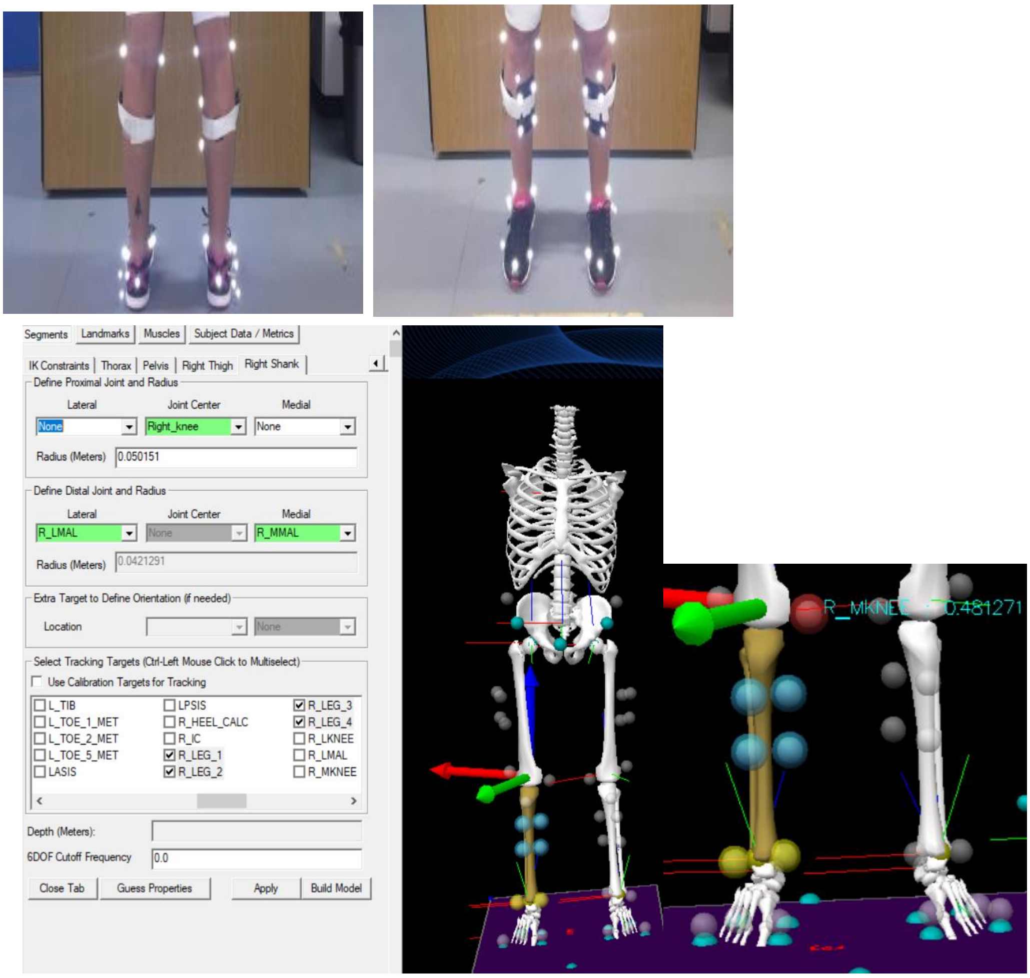
Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)
☐ Use Calibration Targets for Tracking
☐ R_LEG_3
☐ R_LEG_4
☐ R_LKNEE
☐ R_LMAL
☐ R_MKNEE
☐ R_MMAL
☑ R_THI_1
☑ R_THI_2
☑ R_THI_3
☑ R_THI_4
☐ R_TIB
☐ R_TOE_1_
☐ R_TOE_2_
☐ R_TOE_5_
☐ RASIS

Depth (Meters):
6DOF Cutoff Frequency: 0.0

Figure 3.16: This shows thigh marker placement and model on Visual 3D for the thigh

3.4.2.4 Shank segment

For the shank, the calibration markers were placed on the lateral and medial bony landmarks of thee knee and ankle. The shank is defined by the knee segment and the malleolus (R_LMAL, R_MMAL). These locations were identified by palpating the segment and following the joint line until the joint centre has been identified on the bony landmarks. The tracking markers for the shank were attached with clusters which each had 4 markers mounted on rigid plastic plate which was strapped to the side of the segment. Extra elastic bandages were wrapped around the clusters to avoid as little movement as possible, particularly when applying extra load (Figure 3.17). The position of the clusters were marked with pen around each corner, to ensure that there is no movement of the cluster during the trials and if movement does occur then the markers are repositioned, straps tightened and a new static standing condition collected.



Define Proximal Joint and Radius
Lateral: None
Joint Center: Right_knee
Medial: None
Radius (Meters): 0.050151

Define Distal Joint and Radius
Lateral: R_LMAL
Joint Center: None
Medial: R_MMAL
Radius (Meters): 0.0421291

Extra Target to Define Orientation (if needed)
Location: None

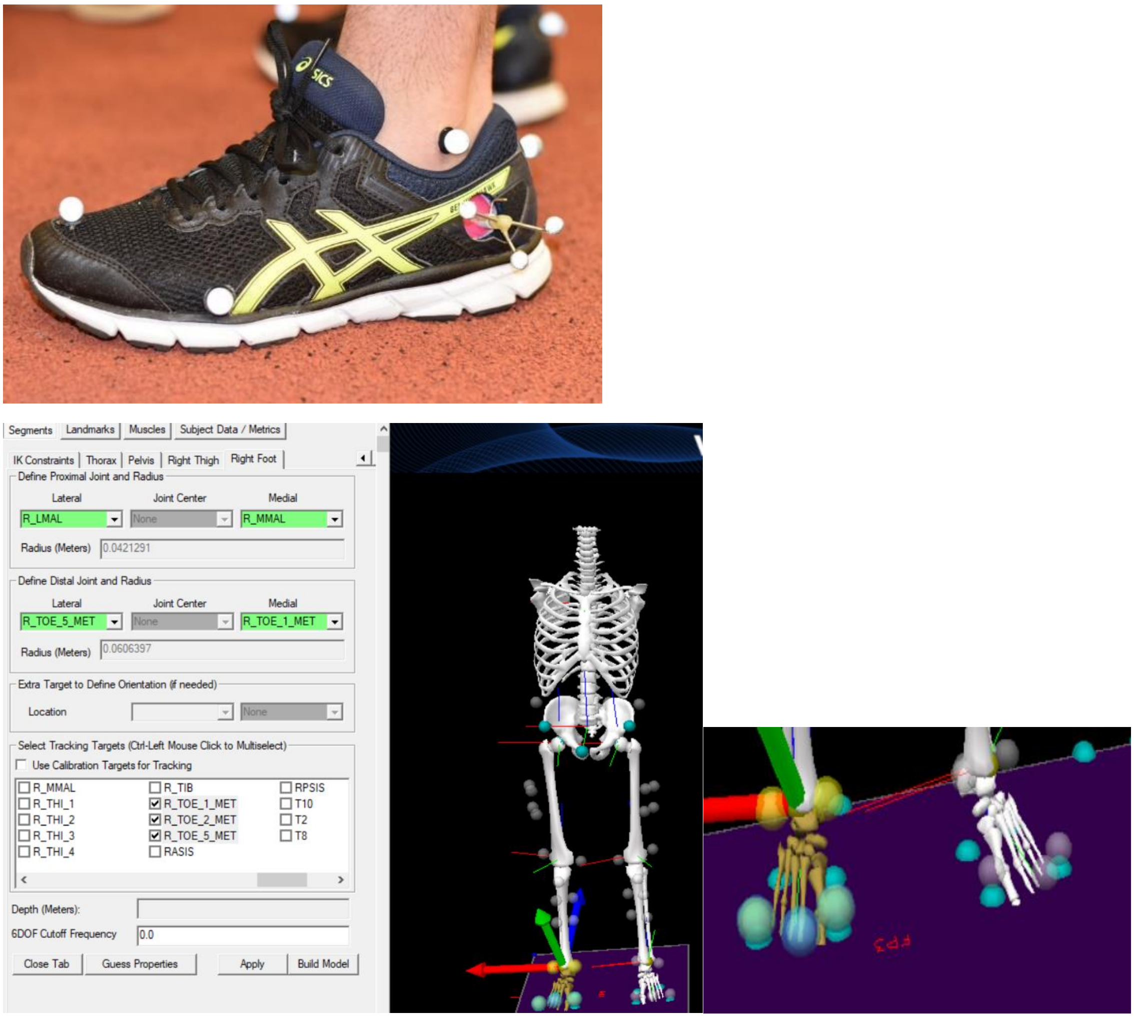
Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)
☐ Use Calibration Targets for Tracking
☐ L_TIB
☐ L_TOE_1_MET
☐ L_TOE_2_MET
☐ L_TOE_5_MET
☐ LASIS
☐ LPSIS
☐ R_HEEL_CALC
☐ R_IC
☑ R_LEG_1
☑ R_LEG_2
☑ R_LEG_3
☑ R_LEG_4
☐ R_LKNEE
☐ R_LMAL
☐ R_MKNEE

Depth (Meters):
6DOF Cutoff Frequency: 0.0

Figure 3.17: This shows marker placement and model on Visual 3D for the shank

3.4.2.5 Foot segment

The foot was tracked with both markers on the shoe and markers on the foot. Previous literature data was only collected barefoot as this is simplest and most accurately tracks the foot segment, however typically, activities of daily living and physical activity are performed while wearing shoes (Bishop et al., 2013). It has been shown that solely tracking the motion of shoe-mounted markers does not indicate the movement of the foot inside the shoe (Stacoff et al., 2001). Due to this, it is essential to consider the segments of the shoe with the added complexity of the foot, rather than just the shoe or foot in isolation. This would allow the foot to remain the major factor determining the kinematics, however, the shoe changes the basic assumptions of the segments (Bishop et al., 2013). Four markers were attached to the test shoes with a wand cluster attached to the calcaneus of the foot. These were either taped or glued to the shoe to allow as little movement as possible. On each shoe one marker was placed on the heel (calcaneus), one marker on the proximal head of the 1st and 5th metatarsal bone and one marker was placed distally on the metatarsal head of the 2nd metatarsal (Figure 3.18). The markers were kept on the shoe to keep as much of the structural integrity as possible, so the individuals could move as comfortable as they would in their day-to-day trainers. A calcaneus cluster was also attached to the skin of the foot through a hole in the shoe to help track the exact movement of the rearfoot, however, this was not used in the end as the markers came loose from many individuals due to sweat. The segment was created with the 1st and 5th metatarsophalangeal joint of the metatarsal (R_TOE_5_MET, R_TOE_1_MET) and the malleolus markers (R_LMAL, R_MMAL) with the cluster as the tracking markers. A virtual foot was put in place to be aligned with the shank to set the ankle joint angle to zero. The virtual foot was created instead of relating the joint angle to the static trial as during the motion trials the orientation of the segments constantly change which may vary from the orientation of the static segment and therefore the analysis of the motion trials would not be accurate.



Define Proximal Joint and Radius

Lateral	Joint Center	Medial
R_LMAL	None	R_MMAL

Radius (Meters) 0.0421291

Define Distal Joint and Radius

Lateral	Joint Center	Medial
R_TOE_5_MET	None	R_TOE_1_MET

Radius (Meters) 0.0606397

Extra Target to Define Orientation (if needed)

Location None

Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)

☐ Use Calibration Targets for Tracking

☐ R_MMAL	☐ R_TIB	☐ RPSIS
☐ R_THI_1	☑ R_TOE_1_MET	☐ T10
☐ R_THI_2	☑ R_TOE_2_MET	☐ T2
☐ R_THI_3	☑ R_TOE_5_MET	☐ T8
☐ R_THI_4	☐ RASIS	

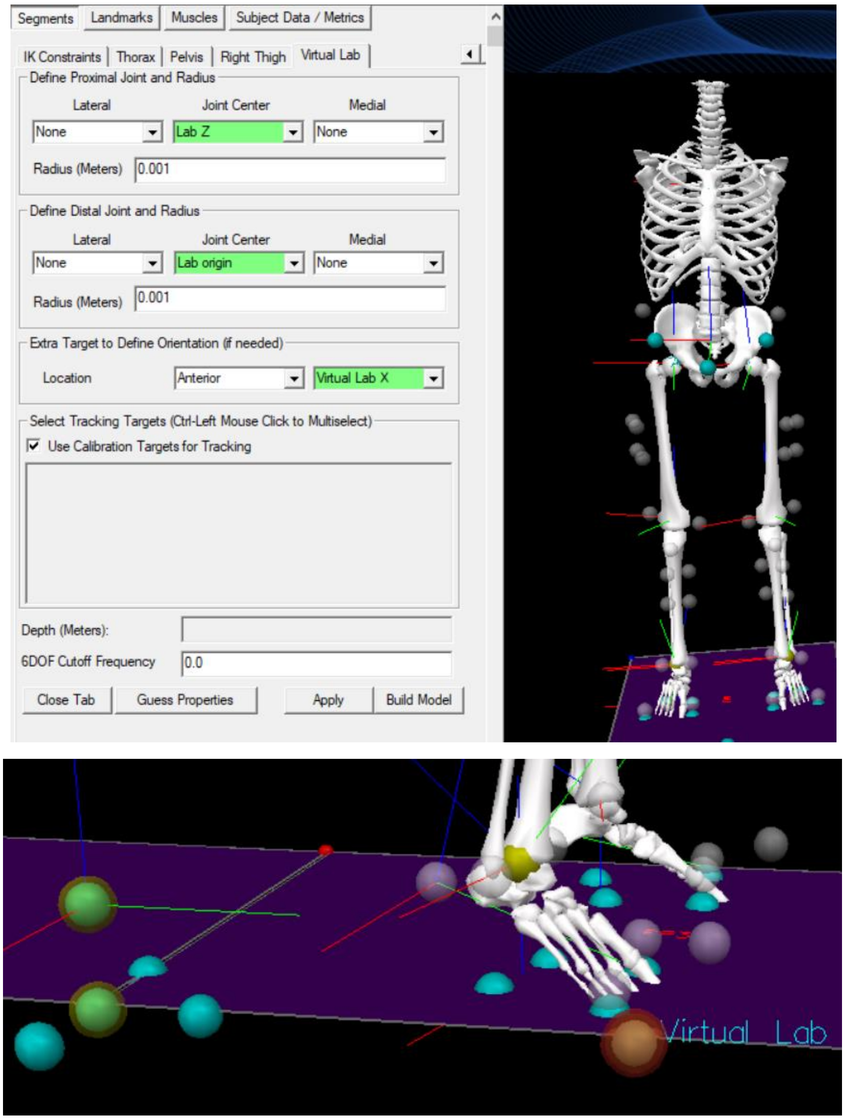
Depth (Meters):

6DOF Cutoff Frequency 0.0

Figure 3.18: This shows marker placement and model on Visual 3D for the foot

3.4.2.6 Virtual lab

With the lab coordinate axis having a positive and negative direction, there was a need to create a Virtual Lab which allowed data to be collected in both directions rather than just in the direction of the origin. The virtual lab was created by using landmarks such as the Lab Z direction (which had an offset of Z axis by 0.1) as the proximal joint centre and the Lab origin as the distal lab centre with a Radius of 0.001 (Figure 3.19). The Pelvis Lateral Projected landmark was created from the lab origin, lab orientation and pelvis and then used in the Virtual Lab segment as the Extra Target to define Orientation. The virtual lab coordinate system ensured that the data would remain consistent whether the individual went up or down the laboratory.



Define Proximal Joint and Radius
Lateral: None
Joint Center: Lab Z
Medial: None
Radius (Meters) 0.001

Define Distal Joint and Radius
Lateral: None
Joint Center: Lab origin
Medial: None
Radius (Meters) 0.001

Extra Target to Define Orientation (if needed)
Location: Anterior, Virtual Lab X

Select Tracking Targets (Ctrl-Left Mouse Click to Multiselect)
☑ Use Calibration Targets for Tracking

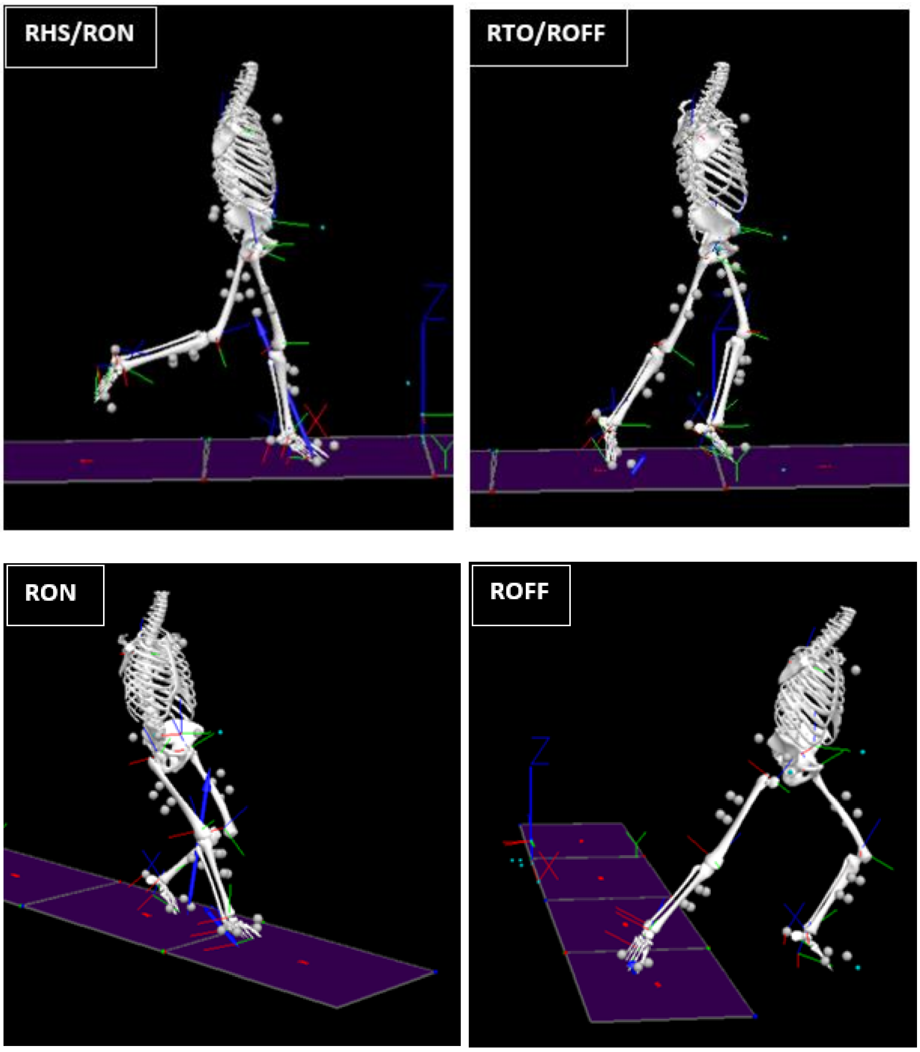
Depth (Meters):
6DOF Cutoff Frequency 0.0

Figure 3.19: This shows model on Visual 3D for the Virtual lab

3.4.3 Definition of timing events

To identify different tasks and create the ability to analyse these tasks with different calculations, tags were created. Automatic gait events were then created to identify the start and finish points of the analysis (Figure 3.20). Right and left heel strike (RHS/LHS) and right/left toe off (RTO/LTO) were the events created on V3D to identify the correct moment where foot contact starts and stops within the stance phase. Foot contact was defined at the first instance the foot touches the ground, whether it is heel strike or mid-foot strike or fore-foot strike. Over the force platform, foot contact occurs at the instance where the first force is produced under the foot. Toe off occurs at the last instance the foot is still in contact with the ground and on the force platform, this occurs at the last point force is produced under the foot.

During walking and running the kinematics were calculated taking into account the whole gait cycle included swing phase, which therefore was calculated from heel strike to next stride heel strike, for example from RHS to RHS. For the kinetics foot contact on the force platform was used for the analysis, which was identified with the events right/left on (RON/LON) and right/left off (ROFF/LOFF). The foot contact was based on the threshold of the vertical force. As soon as force was applied on to the force platform, foot contact was established and at toe/off the last frame was used where vertical force was being produced (Figure 3.20). The foot contact during the change of direction task for the kinematics and kinetics data calculations were established from the events where the foot first hit the last force platform (CUT_ON_R/CUT_ON_L) to when the foot was leaving the last force platform (CUT_OFF_R/CUT_OFF_L). For the drop landing the kinematics were calculated from the moment the individual had contact with the force platform (RHS/LHS) and for the kinetics (RON/LON) until maximum knee flexion was reached in the trial (Right_max_knee_flex, Left_max_knee_flex).



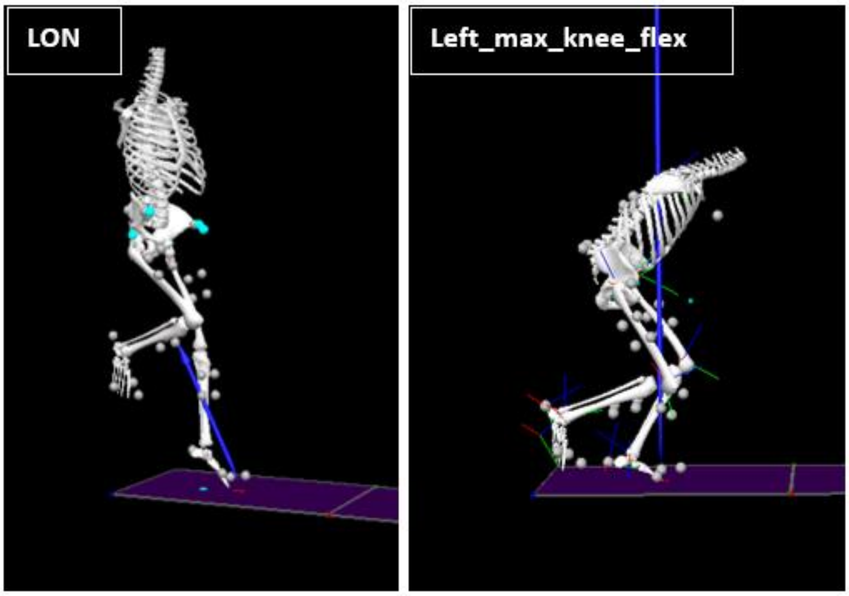


Figure 3.20: Events during running, 90-degree change of direction and drop landing

For walking and running data was analysed during the stance phase which was further divided into early and late stance. The data was time normalised to 101 points throughout the whole gait cycle for walking and running. The first peak and second peaks during walking and running were analysed for the kinematics and kinetics to highlight the loading phase as well as the whole propulsion phase (Figure 3.21). During walking the stance phase is stated to be the first 60-65% of the gait cycle. When calculating the angles the first and second peaks were calculated taking this into account, meaning that the loading phase is the 0-40% and the propulsion phase is the last 40-60% of gait. For the moments as these are taking into account the GRF and force platform contact, these stance phase is split 50-50% for impact loading and propulsion (Kirtley et al., 2006). There is a difference between kinematics and kinetics as in the kinematics swing phase is included during the later part of the gait cycle which is not being analysed, however the moments were only calculated through stance phase. During running the stance phase is the first 40% (Figure 3.21). To calculate the angles for running, the 0-20% were still used at the loading phase and the 20-40% were used as the propulsion phase.

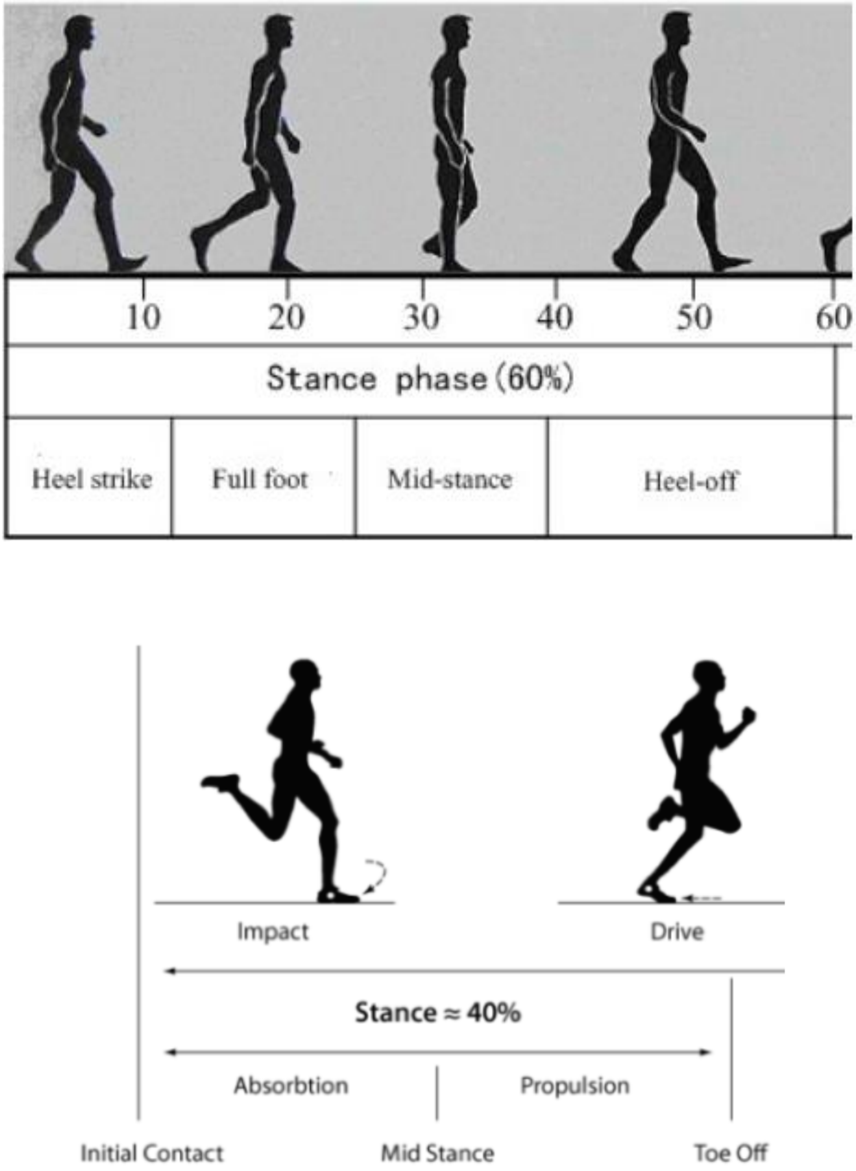


Figure 3.21: The stance phases during walking and running, identifying early stance (loading) and late stance (propulsion): Source https://www.kintec.net/wp-content/uploads/2016/02/runninggait-1024x375.png

The compute model based data on function Visual 3D was used to create angles, moments, powers, forces and centre of pressure. For the joint angles, the segment was chosen starting at the top of the body for example pelvis for the pelvic angle used the pelvis as the segment and virtual lab as the reference segment in the compute model based data function in Visual 3D. Then the hip used the thigh as the segment and the pelvis as the reference segment. The knee used the shank as the segment and the right thigh as the reference and the ankle used the virtual foot as the segment and the shank as the reference.

Inverse dynamics were used to calculate the ankle, knee and hip external moments using the proximal segment for the calculation. These are calculated as the product of the magnitude of the vertical ground reaction force vector (GRF) and the distance from the joint center of rotation to the through which that force acts (Lau et al., 2018). The moments were calculated with the force and motion data along with the inertial properties of the limb and the angular and linear velocities of the segments where the origin of the knee joint centre was defined as the midpoint between medial and lateral landmarks of the segments. The joint moments and force data were normalised to body mass to ensure that the observed differences are related to the physical characteristics and task rather than the body mass (Andriacchi, Natarajan, & Hurwitz, 2005). Analysis methodologies, mainly look at peaks in the curves or quantified differences at each time point of the movement cycles, however this practice has been shown to result in type I error. Statistical parametric mapping (SPM) allows for the comparison of entire movement cycles, reducing the likelihood of errors in the reporting of statistical inferences. SPM requires an identical number of cases and controls to perform the analysis, and therefore, could not be used in the current thesis. Additionally, looking at the peaks could be easily compared to previous research rather than SPM.

After all the correct calculations have taken place, an automated pipeline was created to export the data to an ASCII file where the values were checked in Microsoft Excel where the individual subject and sample curves were plotted. For this the Pipeline Parameters were set to choose the location where to save the data, the Active File was chosen to be the task and then all the angles, moments, KAAI, powers and force data were exported to the right location.

3.5 EMG processing

The following data processing was undertaken once the individual had completed all the tasks.

All Delsys EMG wireless electrodes were attached to the quadriceps and hamstrings and were collected simultaneously with a trigger through Qualisys 2.19 Track Manager software (QTM^{TM}), where the electrodes were identified and then the signal was checked for irregularities. Each trial was cut to include one step either side of the force platform. All successful trials were then exported to a C3D file which was processed in Visual 3D (V3D) software v6 (C-motion, inc., USA) and Excel.

Electromyography is inevitably affected by noise of the surroundings and other tissue movement; therefore it needs to be filtered to the point that the data is clear enough, without reducing any of the results (Aschero et al., 2010).To delete any unwanted noise generally a Butterworth Bandpass filter needs to be applied, however the system used in this study (Delsys) does this automatically whilst collecting data with the ACDC.

Following the bandpass filtering the EMG signal should be assumed to be clear with reduced levels of noise. The data was then full wave rectified and smoothed (low-pass, 4th order, zero-phase-lag Butterworth filter with a 15-Hz cut off frequency), producing a waveform which is easily analysable (Ervilha et al., 2012; Delsys, 2016). Normalising the EMG signal was done, following the SEMIAN guidelines by using an MVC as a reference contraction.

3.6 Primary outcome measures

3.6.1 Kinetics

3.6.1.1 EKAM

The peak EKAM was defined as the maximum peak adduction moment during the either the early stance (1st peak) or late stance (2nd peak) (Figure 3.22). During walking there are two peaks in the EKAM, the 1st peak can be found in the early stance which was determined as the loading phase (0–50%) and the 2nd peak in the late stance which was determined as the propulsion phase (50–100%) (Thorp et al., 2006).

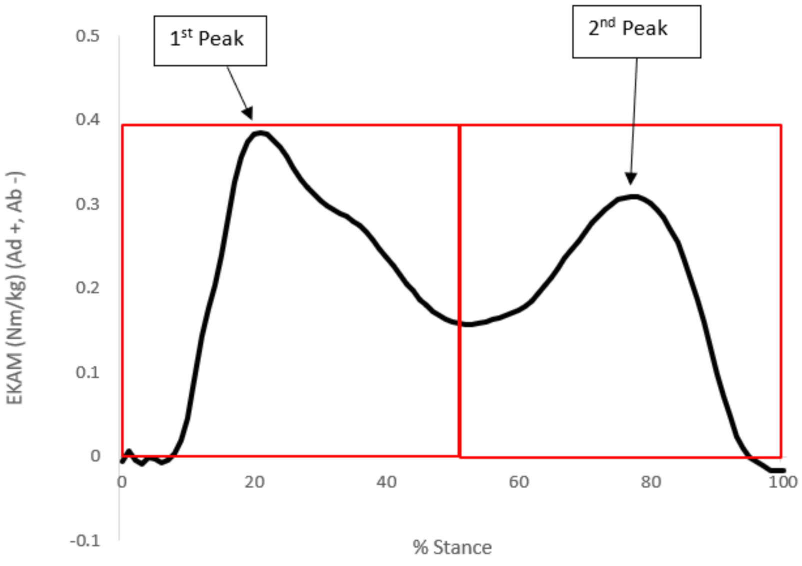


Figure 3.22: An example EKAM curve during walking indicating the early (1st peak) and late (2nd peak) stance phases

To calculate the moments for running, the 1st and 2nd peak were split between initial contact and loading throughout the stance. The initial impact loading took place between 0-20% of stance and the loading throughout stance was calculated as the peak between 20-100% of the stance phase (Figure 3.23).

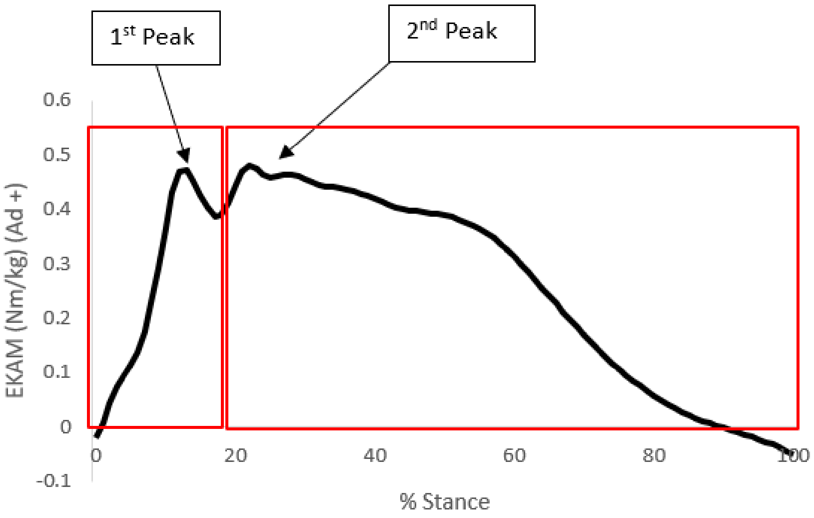


Figure 3.23: This graph shows the EKAM during running indicating the early (1st peak) and late (2nd peak) stance phases of loading

To calculate the moments for the drop landing, the peak value was taken for the whole stance phase as this was calculated to maximum knee flexion and therefore, did not need to be split any further (Figure 3.24).

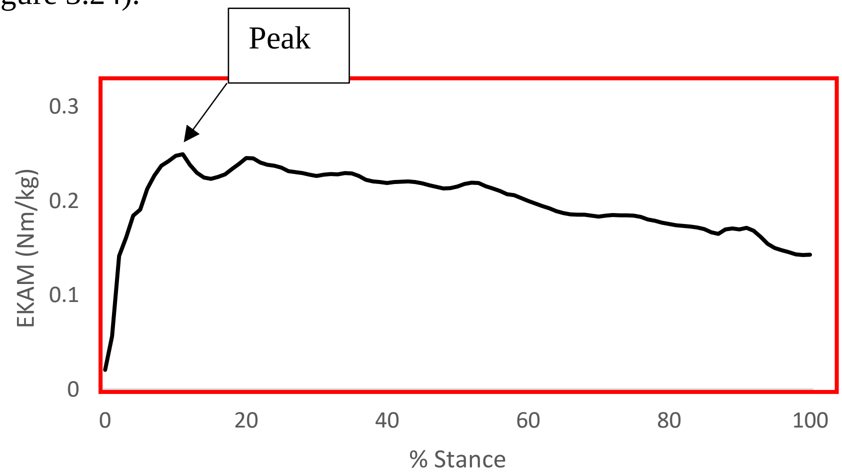


Figure 3.24: This graph shows the peak EKAM during drop landing

To calculate the moments for change of direction, the peak value was taken for the initial 50% of stance as this was of main interest when looking at knee loading as the individuals land on the force platform and initiates the movement into the opposite direction which generally occurs within the first 50% of the task rather than just looking at the point of maximum knee flexion as loading at this point may be different. This was chosen as the intitial impact and movement into the opposite direction is where most injuries normally occur (Figure 3.25).

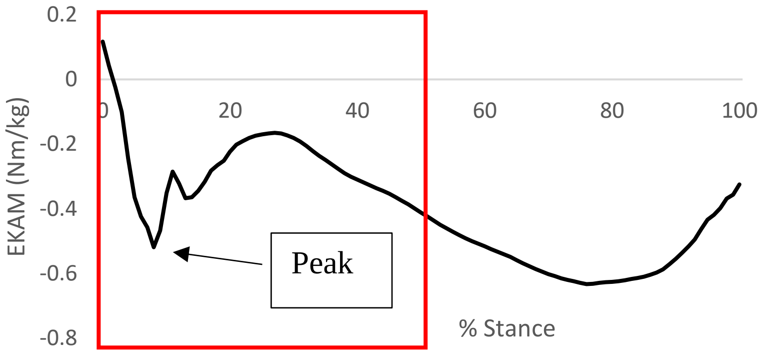


Figure 3.25: This graph shows the peak EKAM during change of direction in the first 50% of stance

3.6.1.2 KFM

Knee flexion moment (KFM) is used to highlight knee loading at the patellofemoral joint (Sturnieks et al., 2011). The KFM was calculated at the same time as the EKAM with the inverse dynamics looking at the maximum peak in early stance (1st peak) or late stance (2nd peak). During walking this was split 50-50% between early (1st peak) and late stance (2nd peak) (Figure 3.26).

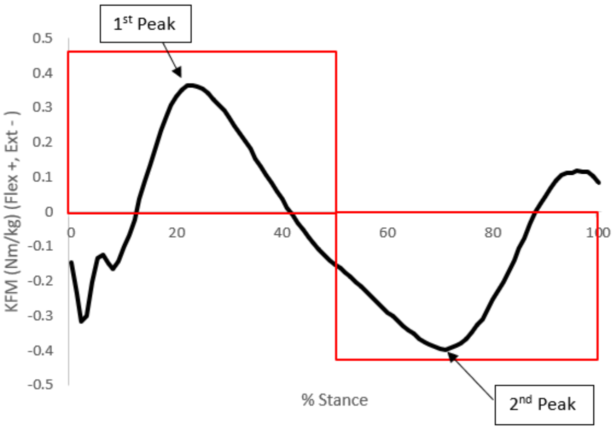


Figure 3.26: This graph shows the KFM during walking indicating the early (1st Peak) and late stance (2nd Peak) phases

3.6.1.3 KAAI

The knee adduction angular impulse (KAAI) has been considered as another important measure for medial knee loading. It takes into account the magnitude of the EKAM and the duration of the medial knee load during the stance phase (Thorp et al., 2006). The area under the EKAM curve was calculated between heel strike and toe off to calculate KAAI (Figure 3.27). The external knee adduction angular impulse was calculated as the integral of the external knee adduction moments for the overall stance phase. The KAAI (%Bw) was calculated using the metric integrate function which integrates a signal between events using the trapezoidal rule, where in this case it calculated the area under the knee moments curve from the ON and OFF events.

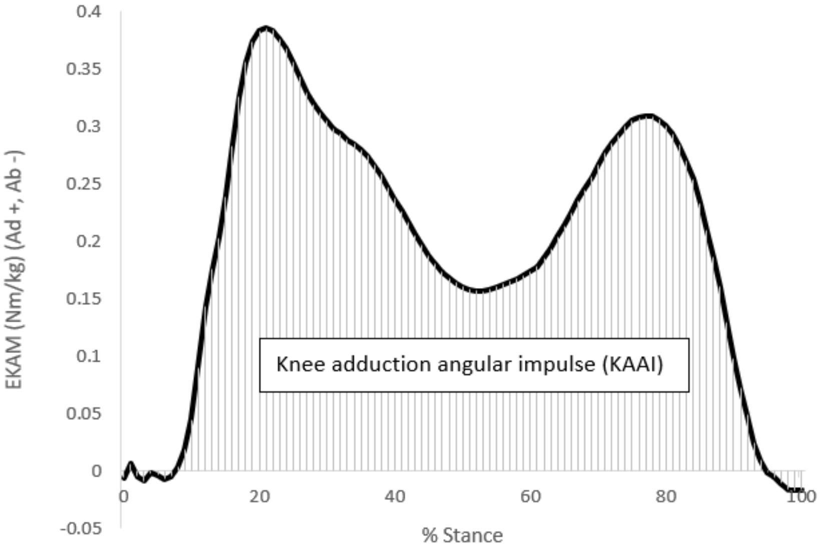


Figure 3.27: The external knee adduction angular impulse (KAAI) under the curve shown by shaded area

3.7 Secondary outcome measures

3.7.1 Isometric peak torque

Quadriceps muscle strength is also essential to control movements such as change of direction and landing which are involved in many sports (Rudolph and Snyder-Mackler., 2004). The quadriceps strength was analysed as muscle quadriceps weakness is common following injury and particularly following surgery (Sturnieks et al., 2008). The average from the three highest trials was taken from the isometric peak torque exported from the isokinetic dynamometer, and then normalising to body mass. The meniscectomy leg was compared to both the contralateral leg and the healthy control leg. The rate of force development was not analysed in this thesis although it was deemed an important output to look at how individuals produce force. The isokinetic dynamometer (Biodex) used in this thesis records the data at such a low sampling frequency, that important data would be missed in the analysis which may affect the rate of force development outcomes and therefore, this outcome could not be analysed for this thesis.

3.7.2 Muscle co-contraction

Knee load is not only determined by kinetic and kinematic variables, but also by muscle forces generated around the knee joint (Winby et al., 2013). The quadriceps and hamstrings contract simultaneously during the stance phase to control the joint and finally play an important role during knee joint loading (Winby et al., 2009). In the current thesis, the sum of the net activation was calculated from the sum of the knee extensors (vastus medialis, vastus lateralis) and the sum of the knee flexors (semimembranosus, biceps femoris) muscles in early and late stance during walking. All EMG was normalised to MVC as shown in section 3.2.4. The co-contraction was analysed between medial (vastus medialis, semimembranosus) and lateral (vastus lateralis, biceps femoris) muscles, and between extensors (vastus medialis) and flexors (biceps femoris) (Hodges et al., 2016). If Agonist (extensor/medial) is more active number is above zero. Max co-contraction is close to zero and min is close to 1/-1 (Heiden et al., 2009). The sum of the net activation was calculated from the sum of the knee extensors (vastus medialis, vastus lateralis) and the sum of the knee flexors (semimembranosus, biceps femoris) muscles in early and late stance during walking. Co-contraction ratios (CCR) between antagonist and agonist muscles were calculated between quadriceps and hamstring and medial compared to lateral co-contraction using the following formula (Heiden et al., 2009):

If agonist mean EMG > antagonistic mean EMG:

CCR= 1- antagonistic mean EMG/agonist mean EMG

If agonist mean EMG < antagonistic mean EMG:

CCR= agonist mean EMG/ antagonistic mean EMG -1

3.7.3 Centre of pressure

Both the medio-lateral centre of pressure position at touchdown (mm) and the antero-posterior centre of pressure (%foot length) were measured. The medio-lateral centre of pressure excursion was measured to look at the shift in the centre of pressure in relation to the foot. The COP was calculated by taking the X-Y co-ordinates of the force in relation to the foot to look at the general force distribution in the medio-lateral direction. This was then calculated in relation to the foot segment and the COP excursion was analysed by taking the min and max values during stance. A medial shift was classified as a positive value and a lateral shift in the COP was classified as a negative value (de Haart et al., 2005).

The antero-posterior centre of pressure was analysing the foot strike index, as originally defined by Cavanagh and Lafortune (1980), identifying whether an individual is a rearfoot, midfoot or forefoot striker. The strike index was calculated as the distance from the heel to the centre of pressure at impact relative to total foot length (Figure 3.28). The index was grouped into two categories: rearfoot strike (< 0.5) and forefoot strike (>0.5). The closer the number was to 0.0 the more of a rearfoot striker the individual was, the closer to 0.5 the more of a midfoot striker in individual was and the closer to 1.0 the more of a forefoot striker the individual was.

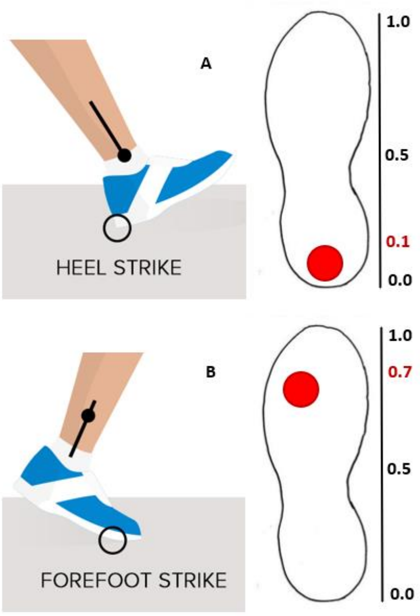


Figure 3.28: This shows the foot strike index highlighting that anything above 0.5 is forefoot strike and below 0.5 is rearfoot strike (Sanutz et al., 2017). This was a sagittal view of a typical rearfoot (A) and forefoot (B) strike patterns during running

3.7.4 Balance

The star excursion balance test (SEBT) is a simple, inexpensive test, used to measure dynamic balance (Gribble et al., 2012) that incorporate a single-leg stance with maximum reach of the other leg (Olmsted et al., 2002). The reach distance was calculated using the evaluate expression function on Visual 3D, measuring the distance between the right and left calcaneus at maximum extension (MAXD). The reach distance was normalised to leg length which was taken from the ASIS markers to the calcaneus markers, taken from the static in Qualisys. To normalise the reach distance was divided by limb length and multiplied by 100 to find the percentage (reach distance/leg length) * 100 = % MAXD (Robinson and Gribble, 2008)

3.7.5 KOOS

KOOS other subscales hold 33 items in symptoms, activity of daily living, sport and recreation, and QoL. All items have five possible answer scores from (0) no problem to (4) extreme problem. The KOOS pain, sport/rec and quality of life (QOL) subscales were of main interest. A normalized score (100 indicated no symptoms and 0 indicated extreme symptoms) was taken from each sub-section and a final score was added of the mean of these sections.

3.7.6 Tampa

The Tampa Scale of Kinesiophobia is a 17-item instrument assessing pain-related fear of movement. All questions are ranked on a 4-point Likert scale (from 1= strongly disagree, to 4= strongly agree). The total score was calculated, ranging from 17=no fear to 68=strong fear avoidance beliefs.

3.7.7 Physical activity

The physical activity questionnaire (Appendix 2.2) was calculated in a similar way as the International Knee Documentation Committee (IDKC) score calculator. Apart from Question 1, all other questions have a Likert scale and were recorded with a similar style as the IKDC. Questions 2-5 went to the scale of 10 (0 = not active at all. 10 = highly active) where question 5 was measured by activity level. Questions 6 and 7 went up to 5 (0 = much better than before injury/ 5 = much worse than before injury) point adding up to 10 in total.

$$\text{Questionnaire Score} = \left[\frac{\text{Raw Score} - \text{Lowest score}}{\text{Range of Score}} \right] \times 100$$

3.7.8 Rehabilitation questionnaire

The rehabilitation questionnaire was an open questionnaire which was analysed the rehabilitation that was provided to the individuals following meniscectomy and gave them the opportunity to give more detailed responses including how many times a week rehabilitation was performed, what exercises they underwent, and at what stage of rehabilitation they started doing the specific exercises (Appendix 2.3). This gave a basic outline how long ago the surgery was and, in this time, how much and how intense the rehabilitation was. This was to give an idea as to how good and thorough their rehabilitation was following meniscectomy.

3.7.9 Supporting data

The effect of meniscectomy on the vertical GRF (the first peak and the second peak), ankle, knee and hip joint angles in sagittal and frontal plane (first peak (loading) and second peak (propulsion), ankle, and hip joint moments in sagittal and frontal plane were all chosen as secondary outcomes to help support and explain findings that may occur at the knee.

3.8 Statistical approaches

Statistical analysis was carried out with SPSS (IBM SPSS Statistics 20), graphs and tables were produced using excel (Microsoft Office Excel 2013). Normality was assessed using Shapiro-Wilk test and normal detrended Q-Q-plots was examined. Subsequent parametric or non-parametric tests were run, including post-hoc tests to take into account the 95% confidence interval was chosen as the data was normally distributed. The specific statistical analysis was explained in further details specifying the tests run for each study in the following chapters.

The effect size for each significant variable was calculated using the Cohen's D effect sizes to give an indication of the magnitude of the effect of the intervention (>0.8 large effect, 0.5 moderate effect, <0.3 small effect) (Cohen, 1988). The effect size is just the standardised mean difference between the two groups. This was calculated by:

$$\text{Effect size} = \frac{[\text{Mean of experimental group}]-[\text{Mean of control group}]}{\text{Standard Deviation}}$$

3.9 Repeatability of marker placement

The overall aim of this thesis was to gain a more thorough understanding of loading at the knee in both healthy individuals and meniscus individuals, considering the effects of surgery on the movement of the joints and loading mechanisms. Therefore, in order for such a study to be successfully established, the repeatability of the investigator in placing reflective markers needed to be assessed prior to data collection of the study. The repeatability in both walking and running was also assessed to make sure any changes in data were solely due to the human effect and not the task difficulty. This repeatability study was therefore conducted to enable the researcher to understand the measurement error present in the results. The placement of markers should be as identical as possible over subsequent laboratory visits to ensure that any differences observed after the surgery is from the intervention itself and not from the experiment error in the marker placement.

3.9.1 Repeatability of marker placement background

Clinical gait analysis was first utilised in the 1940’s (Whittle, 1996) where it was found to be a very beneficial tool for the measurement of movement during walking. Since the 1940s, time advances have been made and everything has been computerised, and gait analysis has been split into four sections: kinematics, kinetics, electromyography, and engineering mathematics. Clinical gait is a both valuable and reliable technique which seeks to discriminate between normal and abnormal gait and to assess changes in gait over time (Schwartz et al., 2004). Repeated gait measurements in this day are mainly used to establish the responses to specific interventions such as surgery, physiotherapy and orthotics on kinematic and kinetic data, however, the results obtained can be affected by certain factors.

For kinematic and kinetic measurements to be valuable, it must provide valid and reproducible values with small measurement errors (Rankin & Stokes, 1998). Understanding of the repeatability and measurement errors associated with each screening tool is important (Batterham & George, 2003). As repeated gait measurements typically show some differences, these can be assumed to contain a proportion of error. Several factors that are vital for ensuring measurement errors are reduced and can be controlled include accuracy and consistency of marker position, task difficulty, and faults in data processing (Schwartz et al., 2004). Knowledge of the error magnitude can enable investigators to minimise the risk of over-interpreting small differences as significant, and the understanding of using unreliable measurements may lead to excessive noise in the data drowning out significant results.

The marker placement accounts for the greatest errors in 3D motion analysis (Malfait et al., 2014; Ford et al., 2007). Precise placement of reflective markers is imperative in accurately calculating the kinematic and kinetic outcomes as this calculates the joint centres and therefore markers location in relation to the surroundings. The calculation of the coordinate system is based for practical reasons on a bone frame and therefore, should meet requirements which are associated with the anatomy of the bone. As the markers are placed on the skin and not directly on the bone, the position of the marker is estimated and associated with the underlying bone. Depending on which marker set is used the repeatability of the data could also differ.

Cappozzo et al., (1996) implies that the placement of reflective markers on the body landmarks cause an elevated level of variability and greater measurement error, with these locations being more difficult to palpate, the position error in the reconstructed coordinate system relative to the global frame and skin artefacts caused by the movement of the skin relative to the bone. Cappozzo et al. (1996) revealed that the displacement with respect to the underlying bone during the movements amounted to up to 40 mm. One way in which these errors can be reduced is to use a calibration procedure, as briefly mentioned above, which involves both anatomical landmarks (markers on the bony landmarks) and anatomical frames (segment mounted rigid plates with markers attached). This calibrated anatomical system technique (CAST) model enables that during dynamic tasks only the segment mounted markers are used to decrease the skin artefacts of anatomical landmarks (Manal et al., 2000). This helps give more reliable and therefore valid kinematic data in all planes (Baker et al., 2003). Therefore, for this study, the CAST marker set was used, placing the shank and thigh tracking markers on rigid plates and were attached to the segment with extra straps attached to avoid slipping of the clusters.

The task also plays a crucial role when considering the repeatability of the study. High impact tasks have been found to create a greater error in measurement as this can cause a movement artefact from both the clusters but predominantly the muscle and adipose tissue movement with force (Winter, 2009). As the impact ripples through the body is can be assumed that some markers would move fractionally, causing a slight error in the measurement. Some errors in kinematic and kinetic data can be contributed to test design and data processing, however the aim of this study is to focus on the test-retest repeatability of the reflective marker placement by the investigator.

Between-day repeatability of kinetic and kinematic data was quantified using the correlation of multiple coefficient (CMC) and the standard error of the measurement (SEM). The CMC is a measure of the strength of the association between the two variables and was used in this study as it is the most widely reported measure for repeatability. Collins et al., (2009) stated that for the data to be reliable the CMC needs to be greater than 0.70. The SEM represents the standard deviation of errors of measurement within the study allowing quantification of the extent to which individual trials provide accurate results. Low levels of SEM indicate high levels of accuracy. The SEM is calculated, using a spreadsheet which was created by Richard Baker by carrying out a standard deviation of the trials multiplied by the square root of the gait cycle (Growney et al., 1997). McGinley et al., (2008) concluded that in previous studies an error of five degrees and less for all gait variables was acceptable and an error of less than two degrees was considered very reliable. When looking at more active sporting tasks this should be considered. This suggests that an error larger than five degrees may be enough to influence clinical interpretation of the data and therefore, should be carefully considered. For running, change of direction and the drop landing, the error is generally greater due to more movement occurring on the skin with the increased force (Wolf et al., 2009). Alenezi et al., (2016) showed that during running and change of direction the kinematics still showed a SEM under 5° for all joint angles and therefore McGinley et al., (2008) acceptable error level can be used for the more dynamic tasks as well. Kinetic analyses from Alenezi et al., (2016) showed a range from 0.13-0.56 Nm/kg during change of direction and 0.14-0.30 Nm/kg during running showing a greater error present in the hips compared to the ankle which may be due to the greater range of motion available at the hip.

The aims of the repeatability study were to firstly assess between-day repeatability of marker placement by the researcher and the change in the outcomes this may have. Secondly, to assess the between-day repeatability of measuring biomechanical variables during walking and running and finally to establish the standard error of measure (SEM) and the correlation of multiple coefficient (CMC).

3.9.2 Methods of repeatability

After approval from the Research ethics panel of the academic audit and governance committee at the University of Salford (Approval number: HSR1617-57), 17 healthy individuals between the ages of 18-40 were recruited through the University and sport teams (football, volleyball, hockey, basketball) where they participated in sports at least 2 times a week in sports which would include dynamic tasks such as landing and change of direction. Prior to the commencement of testing, each participant read and signed the participant information sheet and written informed consent sheet.

For the repeatability study, the participants attended the human performance laboratory at the University of Salford on two separate occasions, one week apart. Kinematic and kinetic motion data were collected by 12 infrared cameras and three force platforms which calculated the inverse dynamics of the hip, knee and ankle external moments. (Please refer to the full methodology above, including system calibration, reflective marker placement and data analysis). Coefficient of multiple correlation (CMC) which analyses the similarity of the waveform and the standard error of measurement (SEM) which analyses the amount of error between trials were used to analyse the repeatability of the tasks and the investigator marker placement. Only the main outcome measures were compared in this study which will be analysed in the main studies. This includes the sagittal plane (X) and frontal plane (Y) angles for the hip, and knee and only the X angle for the ankle and pelvis. For the moments only, the X and Y of the hip and knee were analysed as these were the most reported in meniscectomy studies. The strength measurements were also included in the repeatability study to allow the decision to be reached whether both isometric and isokinetic needed to be measured.

The data obtained in the repeatability study were used to calculate the maximum error. The maximum error within the study is less than, or very close to 2° for all kinematic data, and therefore can be deemed as acceptable when considering the recommendations by McGinley et al., (2009). McGinley et al., (2009) stated that an error between 2° and 5° should be regarded as reasonable and suggested that errors that exceed 5 could be large enough to be interpreted as meaningful results. For kinetics the values varied between joints, showing greater error the higher up the kinetic chain, i.e., the hip produced greater error compared to the ankle. This was also seen in Alenezi et al., (2016) study. The isokinetic torque was stated by Kean et al., (2010) to have an error of 0.27 Nm/kg and for isometric to have an error of 0.33 Nm/kg, which was used as the comparison in this study.

For the repeatability study the standard error of the measurement (SEM) was calculated which is the estimated standard deviation of the sample mean multiplied by the square root of 1 minus the reliability of the scores and was calculated using the following formula:

SEM = $SD \times \sqrt{1 - r}$

3.9.3 Results of repeatability

Overall, the repeatability results demonstrated high repeatability between the two sessions between walking and running. The SEM for kinematics was under 2° and greatest correlation was to be seen at 0.99 for the CMC. There was a greater variability with the more demanding tasks such as running, however, these values were still within the limits of repeatability, showing the CMC as close to 1 as possible and the SEM was under 5°.

3.9.4 Results of between-lab test

All temporal spatial data and gait event specific points during walking and running showed similar results, which is to be expected as humans are unable to replicate the same movement.

3.9.4.1 Between-test during walking

The comparison within individuals was most important as this showed the ability of the researcher to apply the markers accurately. Between lab is important as the repeatability and BOOM/Meni-Foot studies were conducted at different sites due to the time it took to set up the access to the MIHP and the lab availability at the University. The accuracy of marker placement is so important as if the markers are not placed correctly, the kinematics and therefore kinetics data may be off and therefore show insignificant or wrong results. Therefore, the between-session repeatability was so crucial to make sure marker placement from the researcher was accurate and outcome from the studies could be seen as accurate meaningful differences.

Test-retest results show high repeatability by the researcher during self-selected speed walking. This can be seen in both in SEM and CMC analysis. The SEM is under 2 degrees in all angles apart from the knee adduction angle which was at 2.25° (Table 3.1) and under 0.30 Nm/kg for the moments. The SEM was still under 5° which was stated to be the greatest error allowed whilst still producing a clinical meaningful difference. The CMC level ranged from 0.93 - 0.99 in the angles and 0.72 - 0.93 in the moments which showed moderate to high correlation. There was also no significance between values stating that they were all similar.

Table 3.1: Between sessions mean, SD, significance from paired t-test, SEM and CMCs for the stance phase in walking

	Mean, SD		***P Value***	**SEM**	**CMC intra-subject**
	Test 1	**Test 2**			
Speed (m/s)	2.04 ± 0.22	1.86 ± 0.10	.843	1.3	0.97
Ankle flexion angle (°)	12.08 ± 3.30	11.98 ± 3.52	.897	1.75	0.97
Knee flexion angle (°)	32.74 ± 5.27	32.48 ± 5.21	.998	1.80	0.99
Knee adduction angle (°)	-6.45 ± 5.45	-2.94 ± 7.36	.374	1.30	0.88
Knee flexion moment (Nm/kg)	0.55 ± 0.30	0.52 ± 0.30	.853	0.11	0.94
Knee adduction moment (Nm/kg)	0.48 ± 0.18	0.50 ± 0.19	.756	0.06	0.91
Knee int. rotation moment (Nm/kg)	0.40 ± 0.09	0.41 ± 0.1	.685	0.05	0.31
Hip flexion angle (°)	-16.21 ± 4.44	-17.19 ± 4.49	.482	1.95	0.99
Hip adduction angle (°)	8.26 ± 3.68	5.84 ± 3.57	.231	1.60	0.96
Hip flexion moment (Nm/kg)	0.86 ± 0.20	0.91 ± 0.19	.783	0.16	0.72
Hip adduction moment (Nm/kg)	0.97 ± 0.21	0.96 ± 0.13	.775	0.18	0.92
KAAI ((Nm/kg) *s)	0.82 ± 0.78	0.54 ± 0.53	.314	0.66	0.85

3.9.4.2 Repeatability of kinematic during running

The test-retest results for the running trials showed slightly lower repeatability compared to the walking with increased SEM values. The CMC during running were comparable to walking. The SEM were between 1.54° and 3.99° in the angles (Table 3.2). The SEMs were all under 0.30 Nm/kg in the moments during running. The CMC results for the knee and hip angles and moments during running were all moderate to very good 0.48-0.97.

Table 3.2: Between sessions mean, SD, significance from paired t-test, SEM and CMCs for the stance phase in running

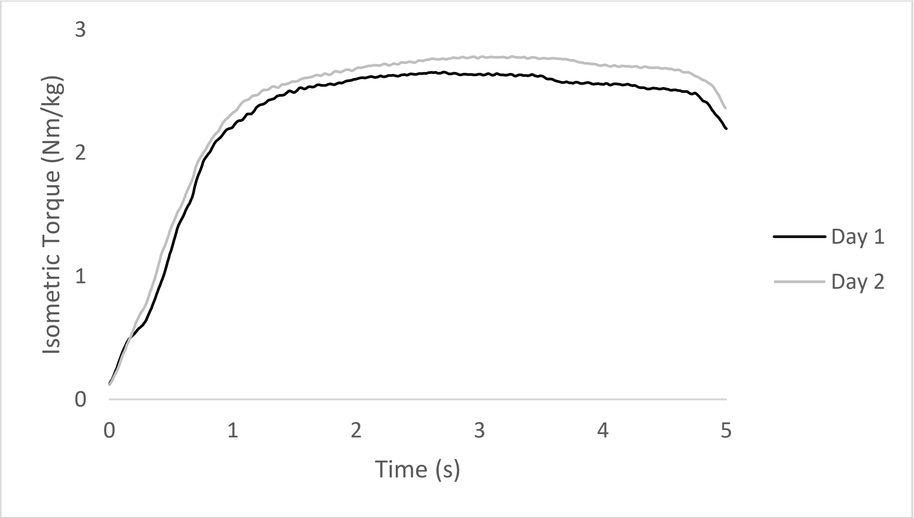
	Mean, SD		*P Value*	SEM	CMC intra-subject
	Test 1	**Test 2**			
Speed (m/s)	4.86 ± 1.23	5.22 ± 1.07	.653	1.22	0.83
Ankle flexion angle (°)	20.48 ± 7.08	20.77 ± 7.41	.998	2.20	0.94
Knee flexion angle (º)	25.24 ± 8.93	25.80 ± 9.53	.876	2.21	0.75
Knee adduction angle (º)	-0.84 ± 0.41	0.91 ± 0.56	.593	1.95	0.87
Knee int. rotation angle (º)	3.04 ± 4.93	5.9 ± 6.85	.005*****	3.99	0.52
Knee flexion moment (Nm/kg)	0.77 ± 0.30	1.00 ± 0.36	.374	0.20	0.95
Knee adduction moment (Nm/kg)	0.44 ± 0.14	0.43 ± 0.16	.973	0.25	0.92
Knee int. rotation moment (Nm/kg)	0.40 ± 0.18	0.39 ± 0.20	.774	0.06	0.48
Hip flexion angle (º)	35.65 ± 8.12	37.19 ± 7.20	.403	3.67	0.89
Hip adduction angle (º)	11.59 ± 5.93	11.47 ± 5.2	.834	1.75	0.92
Hip flexion moment (Nm/kg)	1.06 ± 0.24	1.13 ± 0.26	.621	0.25	0.91
Hip adduction moment (Nm/kg)	1.15 ± 0.34	0.98 ± 0.33	.217	0.20	0.94
KAAI ((Nm/kg) *s)	0.06 ± 0.06	0.04 ± 0.03	.668	0.04	0.48

3.9.4.3 Repeatability of strength measure

For the strength measurement only, the right leg was tested in the repeatability study. The findings showed that both isokinetic and isometric force measure for strength have high variability between tasks (Figure 3.29). The isokinetic concentric/eccentric task showed an SEM of 0.49 Nm/kg and the isometric showed and SEM of 0.30 Nm/kg.

Table 3.3: Between sessions mean, SD, significance from paired t-test, SEM and CMCs for the average peak isokinetic and isometric strength

	Mean, SD		*P Value*	SEM	CMC intra-subject
	Test 1	**Test 2**			
Isometric (Nm/kg)	1.23 ± 0.66	1.34 ± 0.69	.658	0.30	0.88
Concentric Isokinetic (Nm/kg)	0.74 ± 0.19	1.11 ± 0.19	.056	0.49	0.65



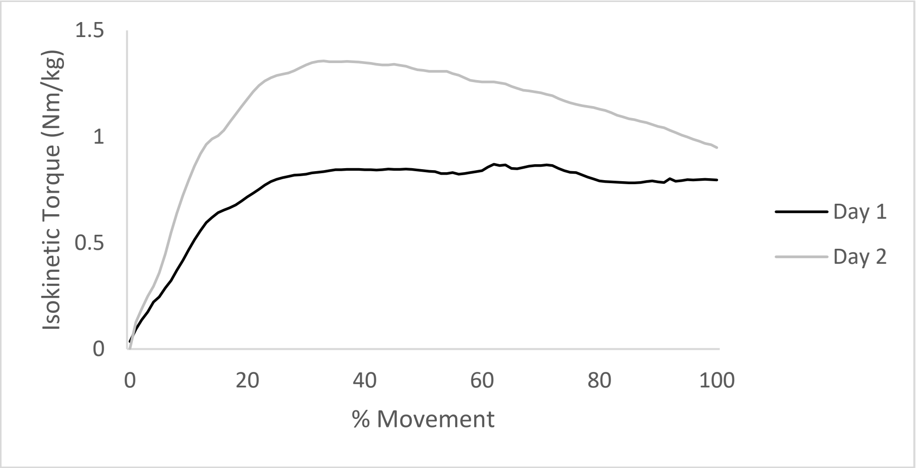


Figure 3.29: Graph of between session force curve for the isokinetic dynamometer strength test showing the isometric strength at during a 5 s contraction (top) and the concentric/eccentric isokinetic strength measure at 60 degrees/s normalised to 101 data points of trial (bottom)

3.9.5 Discussion of repeatability

There was a high repeatability between-session repeatability for walking and running, showing that marker placement was accurate, and the tasks were repeatable.

Although only one assessor applied the markers, variability between sessions became apparent. To reduce variability within the thesis, the CAST marker-based protocol (Cappozzo et al., 1995) was used, which attempts to reduce skin-movement artefacts by attaching markers to the centre of segments rather than single markers close to the joints, as in the Helen Hayes model (Collins et al., 2009). Variability could also be caused due to the individual moving differently on the second session as it is impossible to mimic a movement pattern completely. Less reliable results were seen during the running task compared to the walking task. The lower repeatability might be caused by different velocities during walking tasks, as it has been found that with a consistent speed and generally at a reduced speed, repeatability is shown to be higher (Alenezi et al., 2016). Time of day and fatigue may also affect the results, however the second session was booked at the same time as the first session and individuals were instructed to get as much rest as possible and were asked not to participate in any strenuous activity 24 hours before attending the laboratory session.

The primary outcome measure within this thesis was looking at lower limb motion and knee loading which demonstrated to have good test-retest repeatability in this thesis. The knee flexion moment (KFM) and knee adduction moment (EKAM) were found to have high repeatability in the healthy participants. When compared to previous studies, the SEM during walking was very similar and showed a difference between 0.04-0.06 Nm/kg for EKAM and 0.06-0.20 for KFM (Riley et al., 2007; Al-Amri et al., 2017) whereas in the current study the SEM showed a difference of 0.06 for EKAM and 0.11 Nm/kg for KFM during walking. As the results in the current study compared to those differences seen in previous studies, the current knee loading values have been shown to be repeatable in the current study. The CMC values were also between 0.86-0.97, showing great repeatability. These findings indicated high repeatability of the tasks and agreed with previous research, highlighting that any value close to 1 CMC is shown to be clinically repeatable (Tsushima et al., 2003, McGinley et al., 2007, Birmingham et al., 2007).

Alenezi et al., (2016) found similar results to the current repeatability study during the running task, showing SEM values for joint moments ranging between (0.07–0.39 Nm/kg) and joint angles ranging between (0.98–5.14°). In the current study, the joint moments ranged between (0.06–1.98 Nm/kg) and the joint angles between (1.47–3.99°). When considering solely the knee moments which will be the most important outcome in the following studies the SEM ranged between (0.06-0.23 Nm/kg) showing great similarity to Alenezi et al., (2016). In Alenezi et al., (2016) study the least repeatable values were also the hip angles (4.74°), which was seen in the current repeatability study (3.67°). The increase in SEM scores in the hip for the angles may be explained by the larger range of motion in the sagittal plane compared to other planes. In Sinclair et al., (2014) study they also showed similar results with the greatest SEM value for moments being 2.09 Nm/kg. Sinclair et al., (2014) compared an expert, intermediate and novice individual at applying marker placement and for the knee outcomes, the results in the current study aligned perfectly as those found in Sinclair et al., (2014) expert individuals.

Although the repeatability study was carried out on solely healthy individuals, it was assumed that the results would be similar for participant's post-meniscectomy. In previous studies, errors reported between sessions were due to marker placement variance (Kadaba et al., 1998). Several factors in participant testing were known to affect the between day and within-day repeatability, for instance, task difficulty, movement artefact of the markers on the skin and static alignment (Ford et al., 2007). Between the BOOM and Meni-Foot study, the principal investigator was the only one who attached the reflective markers to the participants to ensure high repeatability throughout the thesis. It is generally accepted that it is impossible to remove all error from a study, however, the investigator can gain some understanding of the amount of error and where it comes from which can help establish significantly meaningful results. The systematic review by McGinley et al., (2009) stated that the highest error within the reviewed studies was mostly found to be greater than 2. The highest error in the kinematics and kinetics in this study was 3.99° in running which was still deemed as an acceptable level of error.

The sagittal plane has previously been identified to be the most reliable across gait measurements (Ferber et al., 2002). On the contrary, the current repeatability study showed that the sagittal planes had the highest error compared to the frontal plane. The frontal plane values indicated the lowest occurrence of errors in all tasks with having the lowest SEM (0.04) in the walking moments and highest CMC (0.98) values. Although some errors were present in this study, most of the values were seen to be less than 2 for the SEM and close to 1 in the CMC, highlighting that 1 signifies identical gait traces.

The knee and hip angles and moments were reliable in both the low impact and high impact tasks. Røislien et al. (2012) described that kinematic curves with a larger range of motion (ROM) appeared more similar, which was reflected in a higher CMC result. This might be an explanation for the decreased CMC results, because the rotation and adduction angles and moments are relatively small during these tasks (Røislien et al., 2012). Thus, Røislien et al. (2012) concluded that the CMC results should be interpreted with caution. During the stance phase in running, the SEMs and CMCs were from 'moderate' to 'good' for the repeatability of the hip and knee angles and moments. The CMC results during the stance phase in running were from ‘moderate’ to ‘good’ and thereby in line with previous repeatability findings during running (Alenezi, Herrington, Jones, & Jones, 2016).

Increased error could be seen in the strength measure, predominantly when looking at the isokinetic concentric/eccentric strength assessment. The isokinetic concentric/eccentric strength assessment showed high variability between the sessions showing a familiarisation session should probably be had as this task feels very unnatural and is not easy to do when trying to produce force in full extension (Dyk et al., 2018). For the repeatability study the participants were allowed two practices for this task, however the results showed that this may not be enough with the SEM being (0.5 Nm/kg) and might be cause to exclude this task, due to the inability to grasp the task in the first place and apply force with a fully extended knee. The isometric task seemed a lot easier to grasp as the SEM (0.3 Nm/kg) was lower and therefore showed a lower error in the data. Between- day it has been shown that producing the same force is quite difficult and therefore the isometric task was accepted for this study. Although the sporting tasks may have some complexity, all individuals that participated in the study, are from a sporting background where these tasks are very common and therefore although the tasks are more complex, the individuals should feel comfortable performing them.

3.9.6 Conclusion of repeatability

In conclusion, the study undertaken shows that certain variables indicate high consistency within test-retest sessions with a relatively low standard error of measurement identified within all variables and tasks. Furthermore, the results showed that the repeatability of marker placement in all conditions was good and can be used to quantify kinematics and kinetics accurately by the investigator in future studies. The only task that should possibly be excluded due to lack of repeatability without an extensive familiarisation task is the concentric/eccentric quadriceps strength task.

Chapter 4 - **B**iomechanical **O**utcomes associated with **O**steoarthritis progression in individuals following **M**eniscectomy during athletic and functional tasks (**BOOM study**)

4.1 Background

Injuries to the meniscus are common in sport, often as a result of a traumatic event (Englund et al., 2016; Stanley et al., 2016; Yeh et al., 2012). Mitchell et al. (2016) reported 5.1 meniscal injuries per 100 000 athletic exposures, with a greater proportion reported during competition (11.9 injuries per 100 000 athletic exposures), compared to practice (2.7 injuries per 100 000 athletic exposures). Rotation around a planted/ inverted foot paired with greater knee loading such as seen in jumping, landing and change of direction tasks have been cited as a common mechanism for meniscal tears (Mitchell et al., 2016). The meniscus aids in stabilising the knee, acting as a shock absorber and transmitting load within the joint, with the lateral meniscus taking as much as 70% of the load in the lateral compartment and the medial meniscus carrying approximately 50% of the medial load (Fox et al., 2015; Kurosawa et al., 1980). Medial meniscectomies have been researched more frequently, which may be due to them being more common and reoperation rates being higher (Paxton et al., 2011). However, the lateral meniscectomies show greater functional deficits as the menisci stability properties are affected resulting in altered load transmission of the articular cartilage (Salata et al., 2010), which highlights that both medial and lateral meniscectomies need to be studied in detail. To date, there has only been one study that looked at the biomechanical outcomes post-lateral meniscectomy, and this was looking at bilateral drop landing (Ford et al., 2011).

Damage to the meniscus is suggested to be associated with altered knee mechanics leading to the initiation or acceleration of osteoarthritis (OA) development (Badlani et al., 2013; Englund et al., 2016). Prior meniscal tears were commonly reported in individuals with medial knee OA (Bhattacharyya et al., 2003), with reports suggesting a 4 to 14 times greater risk of developing knee OA following a meniscal injury (Khan et al., 2019; Mitchell et al., 2016; Kujala et al., 1995). Meniscectomies are widely used to manage the symptoms associated with meniscus injuries (McDermott, 2011). As many athletic individuals with a meniscal lesion undergo partial meniscectomy intend to return to sports, therefore, knowledge of the changes in knee joint loading during such activities are important to identify the implications that may affect the ability to return to their competitive level of activity, however, this is significantly under researched (Willy et al., 2016).

Indirect measures of medial knee loading, such as the external knee adductor moments (EKAM) and knee adduction angular impulses (KAAI) and knee flexion moment (KFM), have been associated with greater risk of developing knee OA (Hall et al., 2014; Mills et al., 2008; Hulet et al., 2015; Willy et al., 2017; Thorlund et al., 2017; Chang et al., 2014). Knee joint loading is also contributed by the coordination of muscle activity (Schmitt & Rudolph, 2008). Increased lateral quadriceps and hamstring muscle activation has been found following medial knee OA to help offload the medial compartment of the knee and reduce pain (Astephen Wilson et al., 2017). Despite information about contributing factors and underlying mechanisms of meniscus injuries and the progression to OA, there is still a lack of information in the current literature on sport-specific movement patterns and the effect on knee joint loading. The majority of studies examining meniscectomies have looked at knee joint loading during walking with only Willy et al. (2016) and Hall et al., (2014) assessing running, albeit at slow speeds and not over ground, while Ford et al., (2011) and Hsu et al., (2016) examined drop landing and single leg hop movements. Further research is needed to explore movement patterns and knee joint loading during more demanding sport-specific tasks post-meniscectomy and return-to-sport abilities for the young active populations.

Extensor and flexor muscle strength and co-contraction are also key aspects which are affected following injury and surgery (Lau et al., 2018). Following meniscectomy surgery, previous studies have reported greater quadriceps weakness (Becker et al., 2004; Sturnieks et al., 2011). Muscle strength is essential to control movement, including movements such as change of direction and landing, which are involved in many sports (Rudolph and Snyder-Mackler., 2004). It has also been demonstrated that following a meniscectomy, quadriceps weakness is often present, which has been related to increased pain, increased stiffness and kinesiophobia in individuals with knee OA (Becker et al., 2004; Sturnieks et al., 2011; Özmen et al., (2017). Ericsson et al., (2019) found that four years following a meniscectomy quadriceps muscle strength can be associated with joint space narrowing, highlighting that individuals with stronger muscles showed less severe osteoarthritic changes. Muscle strength recovery is also considered to be important for young individuals after an arthroscopic surgery in order to regain capacity to participate in sports (Zedde et al., 2015). Quadriceps weakness also leads to reduced eccentric control, reducing the ability for the knee to absorb shock and stabilise, reducing motor control (Lewek et al., 2004). Hart et al., (2014) also acknowledged the importance of testing muscle weakness in relation to change of direction tasks as there has been a link between muscle weakness and a predisposition to knee injury during change of direction tasks. Greater co-contraction of the medial muscles at the knee have demonstrated a faster progression of knee OA in individuals diagnosed with medial knee OA (Hodges et al., 2016), which was reported in individuals following medial meniscectomy (Hall et al., 2014). Therefore, it is important to understand whether individuals following meniscectomy have greater co-contraction and whether this could be a risk factor to lead on to future knee OA progression.

Measures of perceived function such as confidence in function (Chmielewski et al., 2008), pain catastrophizing (de Boer et al., 2012), Knee injury and Osteoarthritis Outcome Score (KOOS) (Collins et al., 2011), kinesiophobia (Kvist et al., 2005) are highly important when understanding re-injury and participation in dynamic sport following surgery (Brand and Nyland, 2009). KOOS has been utilised in several studies as it looks at the individual's perception of their own knee function in daily living, sport and recreation and analyses their perception of their quality of life following their surgery (Collins et al., 2011). Therefore, KOOS should be analysed and considered when looking at a meniscectomy population who wish to return to sport and partake in more dynamic movements, in addition to Tampa scale of kinesiophobia, as individual's negative attitudes toward their movement following meniscectomy can cause gait adaptations to occur and aid in compensatory movements to be established (Tichonova et al., 2016).

4.2 Aims and Hypotheses

The purpose of this study was to initially examine if there was a difference in knee joint loading between individuals following a medial and a lateral meniscectomy. Secondly, the aim was to identify the changes in clinical and biomechanical outcomes which have been linked to the risk factors of OA progression in individuals following meniscectomy compared to healthy individuals during functional and athletic tasks. A combination of assessment tools is crucial to develop a holistic approach to understand coping mechanisms post meniscectomy. Additionally, this study assessed balance, strength and quality of life following meniscectomy when compared to healthy individuals. Four hypotheses were tested in this study and have been presented as the alternative and null hypothesis.

$H_{1:}$ Individuals following medial and lateral meniscectomy show differences in knee loading demonstrated by the EKAM, KFM and KAAI

- H_0: there is no significant differences in knee loading between individuals following medial meniscectomy and individuals following lateral meniscectomy.

H_2: Individuals following meniscectomy show greater knee loading during dynamic tasks compared to healthy controls

- H_0 hypothesis, there is no differences in the knee loading during dynamic sport tasks in individuals following meniscectomy compared to healthy controls.

H_3: Individuals following meniscectomy show lower muscle strength, greater muscle co-contraction and lower balance compared to healthy controls.

- H_0 hypothesis, there is no differences in muscle strength, muscle co-contraction and balance in individuals following meniscectomy compared to healthy controls

H_4: Individuals following meniscectomy exhibit greater kinesiophobia compared to healthy controls

- H_0 hypothesis, there is no differences in kinesiophobia in individuals following meniscectomy compared to healthy controls

4.3 Methodology

This is a case-control study comparing individuals following a meniscectomy with healthy individuals. Ethical approval was granted from both the ethics panel of the academic audit and governance committee at the University of Salford (Approval number: HSR1617-56) and the NHS HRA approval was given (IRAS 239135; Appendix 1). Additionally, the trial was registered with clinicaltrials.gov (NCT03350204).

4.3.1 Recruitment

Individuals who underwent a meniscectomy were recruited through NHS clinics and private orthopaedic clinics of knee surgeons within the Greater Manchester area. Access to these individuals was approved by the relevant orthopaedic teams who provided details of individuals who were considered eligible for the study. Potential meniscectomy participants for this study were identified through the relevant orthopaedic clinics on attendance to consultations with surgeons. An invitation letter was sent to all eligible individuals. Individuals who responded to the invitational letters had the study explained to them and they received a participant information sheet and a health screening questionnaire. A minimum period of 24 hours was set between providing the information sheet and determining their decision to take part in the study. They were then asked to return the health screening questionnaire so full eligibility could be assessed. If potential risks to the participant were identified, then participation within the study was discussed and the individual was either asked to consult a physician to receive approval for the participation or were advised not to participate in this study.

Healthy, physically active staff and students from the University of Salford, were invited to take part in the current study as the healthy controls. The recruitment was undertaken through emails and posters. Participants needed to have experience in the tasks that were performed in the current study, for example, the individuals were asked if they participated in team sports which involved landing, running and change of direction manoeuvres. The posters were also at the University, fitness centres and sports clubs in Manchester and Salford to recruit healthy participants whereby an appointment at the Performance Capture Laboratory at the Manchester Institute of Health and Performance was made. If they agreed to participate and were eligible for the study, they were given an appointment at the Performance Capture Laboratory at the Manchester Institute of Health and Performance (MIHP) (Figure 4.1). To ensure that the anonymity of participants remains intact the data was coded, and only the principal examiner has access to the participants' details. The participants received a voucher of £15 as compensation for his/her time participating in this study.

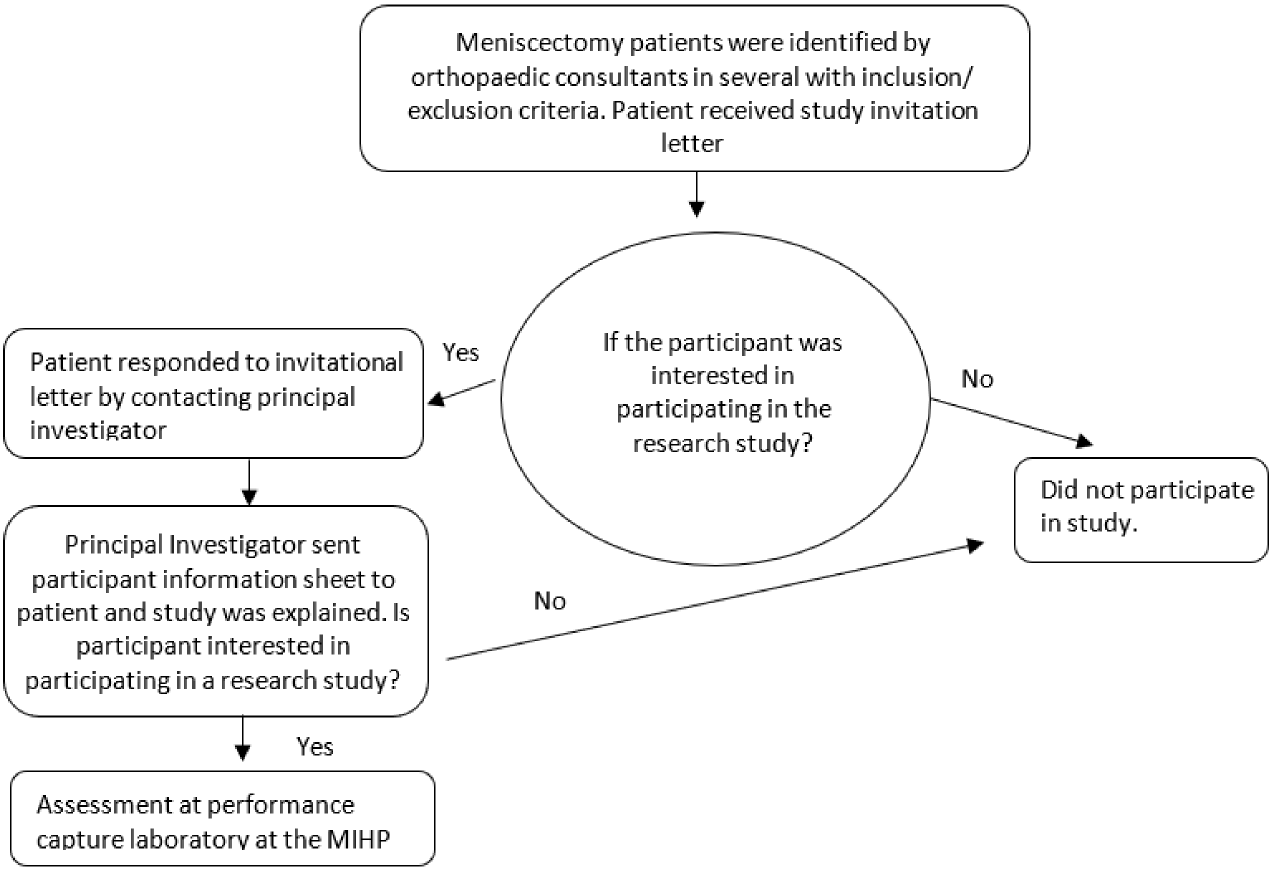


Figure 4.1: Flow chart of recruitment process

4.3.2 Participants

Individuals clinically diagnosed with a meniscal tear and had received a meniscectomy of the knee were asked to volunteer for the project. In the current study a post hoc power calculation conducted via G-power to investigate how many participants were needed in each group to find statistically significant different interaction effects with an 80% power and an alpha level equal to 0.05 (Prajapati, Dunne, & Armstrong, 2010). The power calculation was conducted on the walking and running task on the EKAM as this was seen to be the most reported variable for knee loading. The effect size (ES) was calculated by using the following equation (McCrum-Gardner, 2010):

$$\text{ES} = \frac{\text{(Mean of the EKAM in the meniscectomy individuals) - (Mean of EKAM in the controls)}}{\text{Standard deviation}}$$

The calculated effect size for the stance phase in walking was ES = 0.76 (medium) and running was ES = 0.54 (medium) and thus a power of 85% was reached. The results revealed that 49 participants were needed to achieve 80% power, which was rounded to 50, however only 49 individuals were achieved. Both medial and lateral meniscal tears were accepted. Healthy controls were also asked to volunteer if they have not sustained a knee injury or undergone knee surgery and matched the eligibility criteria. Eligibility for the study was based on the following inclusion and exclusion criteria:

Meniscectomy inclusion criteria

1. Aged between 18 and 40 years
2. Meniscal injury sustained during a sporting task e.g. sports cutting manoeuvre
3. Between 3 and 12 months post-surgery
4. Compete and or play sport a minimum of two times a week for a minimum of 60 minutes
5. Able to perform sport-specific tasks including running, single leg landing and change of direction
6. Medial or a lateral meniscectomy

Meniscectomy exclusion criteria

1. History of lower extremity surgeries e.g. ACL reconstruction except for meniscectomy
2. Bilateral meniscectomy
3. Longer than 12 months post-surgery
4. Evidence of knee osteoarthritis development either assessed clinically (based on ACR criteria) or radiographically (Kellgren-Lawrence grade >1)
5. Previous history of traumatic (other than the sustained meniscal injury), inflammatory or infectious pathology in the lower extremity
6. Evidence of ligament laxity

Control inclusion criteria

1. Aged between 18 and 40 years
2. Compete and or play sport a minimum two times a week for a minimum of 60 minutes
3. Able to perform sport-specific tasks including running, single-leg landing and change of direction

Control exclusion criteria

1. History of any lower extremity surgeries
2. Evidence of knee osteoarthritis development either assessed clinically (based on ACR criteria) or radiographically (Kellgren-Lawrence grade >1)
3. Previous history of traumatic, inflammatory, or infectious pathology in the lower extremity
4. Evidence of ligament laxity

4.3.3 Procedure

On arrival at the performance capture laboratory, participants had any final questions answered and were asked to sign the informed consent form (Appendix 2.1). The participants were informed that they were free to withdraw at any point of time from the study, without any disadvantage to them. One copy of the consent form was given to the participant and one was kept in the study filing cabinet.

Before the biomechanical data was collected participants completed several questionnaires to establish self-reported outcome measures including KOOS (Roos et al., 2003), sports activity questionnaire (Appendix 2.2), rehabilitation questionnaire (Appendix 2.3), Tampa Kinesiophobia, and body mass and height was taken (Figure 4.2). The isokinetic dynamometer was used first to make sure there was no fatigue present from the other tasks. Isometric strength of the quadriceps was measured at 60-degree knee flexion.

Three-dimensional movement data were collected using 28 Qualisys OQUS7 cameras (Qualisys AB, Sweden). The ground reaction forces were collected with four force plates (BP600900, Advanced Mechanical Technology, Inc. USA), which were embedded into the floor and synchronised with the Qualisys system. Markers were placed on the participants as per the image below and defined in the earlier methodology section (Chapter 3, section 3.2.3). Standardised footwear (Asics, Gel Windhawk) was worn.

Each subject was then asked to perform the Y-balance task, single leg drop landing, walking, running and 90 degrees change of direction tasks on a 60 m running track at the MIHP (see section 3.4.1-3.4.5). Walking and running speed was controlled and reported using timing gaits to ensure that each trial was within ±5% of their self-selected speed. The walking, running and change of direction tasks were performed until five successful trials were collected. This was due to needing at least three perfect trials and with a more dynamic movement sometimes it is hard to see any errors. For the landing only three successful trials were collected as it was easier to control and identify if a trial was unsuccessful. Unsuccessful trials were determined when less than three markers per segment were visible, speed changes were seen during the trials, or a partial/double contact with the force platforms occurred.

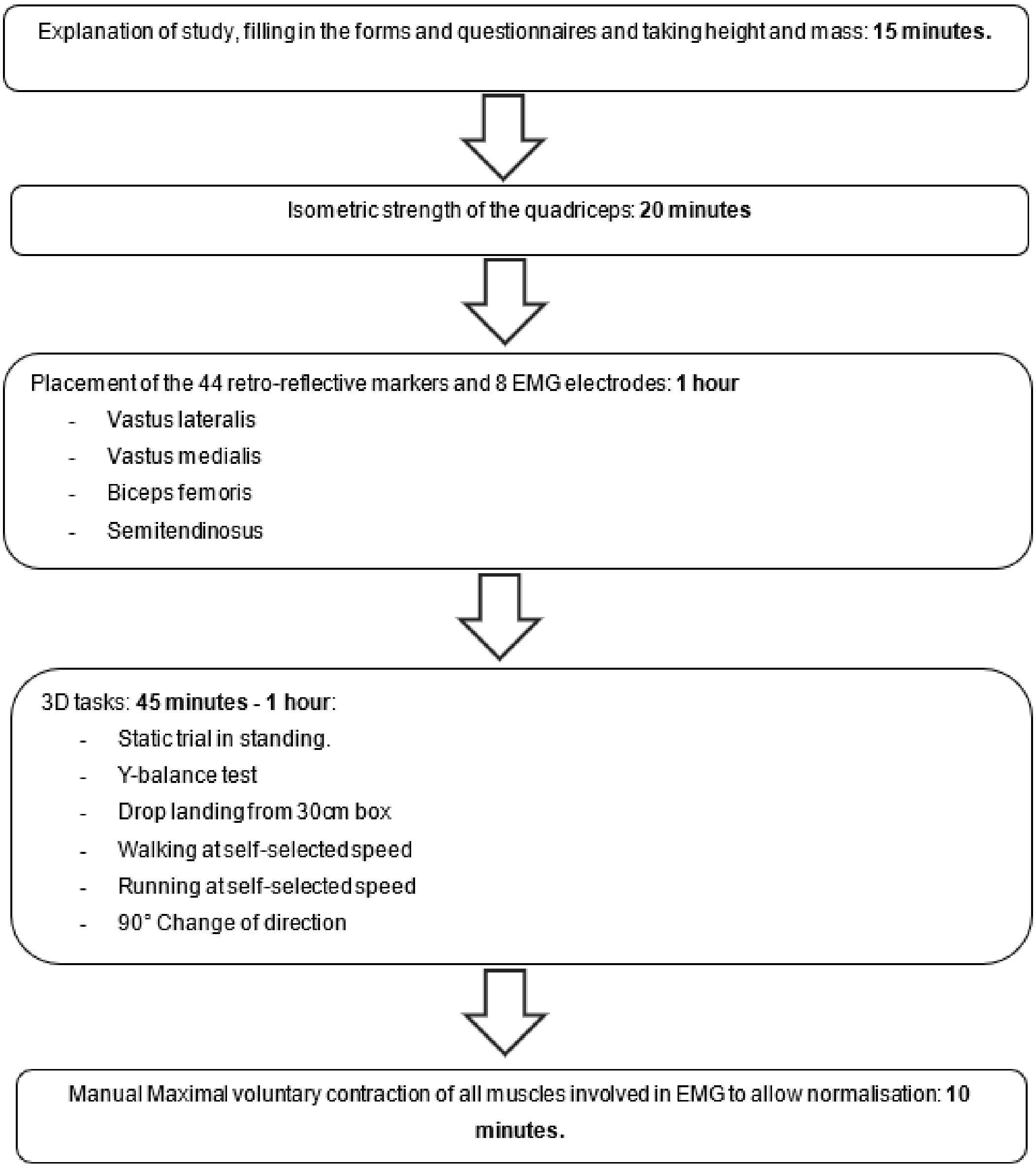


Figure 4.2: Flow chart of test procedure

4.3.4 Data processing

The kinematic and kinetic outcomes were calculated by utilising a six-degrees-of-freedom model in Visual3D (Version 5, C-motion Inc, USA). Motion and force plate data were filtered with a 4th order Butterworth filter with cut-off frequencies of 12Hz (Kristanslund et al., 2012). The Cardan sequence used in the kinematics calculation with Visual3D was the ordered sequence of rotations (x, y, z), with: x = flexion/extension, y = abduction/adduction, z = longitudinal rotation (R. B. Davis, Ounpuu, Tyburski, & Gage, 1991). The kinematics, kinetics, balance, muscle co-contraction and strength measures were all analysed using Visual 3D, Excel, and SPSS.

Joint moment data were calculated using a three-dimensional inverse dynamics algorithm. The joint moments were normalised to body mass and presented as external moments referenced to the proximal segment. The kinematic data were normalised to 100% of gait and kinetic data were normalised to 100% of stance phase, whereby the stance phase was sub-grouped in early-stance (0 - 20% of stance phase) and late stance (20 – 60% of stance phase) during walking. During running the stance phase is the first 40% and the swing phase is the last 60%, the stance phase was sub-grouped in early stance (0 - 20% of stance phase) and late stance (20 – 40% of stance phase) (see section 3.6.1). The change of direction was calculated from foot contact where the initial foot contact occurred on the force platform (CUT_ON_R/CUT_ON_L) to toe off where the foot contact finished on the force plactform (CUT_OFF_R/CUT_OFF_L). The early stance (initial 50%) of the change of direction was analysed for the kinematics and kinetics as the impact management was most important during this task. The peak values were then analysed. For landing the kinematics and kinetics were measured from foot contact on the force platform (RON/LON) until maximum knee flexion occurred (max_knee_flex_right/max_knee_flex_left) and the peak values were analysed.

4.3.5 Primary outcome measures

The following outcome measures were investigated which were explained in full in Chapter 3, section 3.7-3.8. The isometric quadriceps strength was measured in Nm and normalised to body mass (kg), the balance was measured the Y-balance test in the anterior, medio-posterior and latero-posterior direction measuring the reach distance in cm and then normalised to leg length. Peaks of hip and knee and ankle flexion, adduction angles and moments were measured during walking, running, change of direction and landing. The sum of net muscle activation of quadriceps (extensors) and hamstrings (flexors) was collected using the EMG and muscle co-activation between agonist and antagonist and medial and lateral muscles were calculated. Self-reported outcome measured of knee function were collected including the Tampa Scale of Kinesiophobia, the Knee Injury and Osteoarthritis Outcome Score (KOOS), the rehabilitation questionnaire and the physical activity questionnaire.

4.3.6 Statistical analysis

Statistical analysis was carried out with SPSS (IBM SPSS Statistics 20), graphs and tables were produced using excel (Microsoft Office Excel 2013). Normality was assessed using the Shapiro-Wilk test and normal detrended Q-Q-plots was examined. For the medial compared to lateral meniscectomy comparison, independent sample t-tests were performed with a 95% confidence interval to compare two samples. Once the medial and lateral sub-groups were combined, the statistical analysis was used to identify the main effect between the meniscectomy and the healthy controls. Following this, a one-way analysis of variance (ANOVA) was calculated with post-hoc Tukey. This was to show a comparison between all three groups in relation to the meniscectomy leg, contralateral leg and control leg. The post-hoc Tukey test considers the 95% confidence interval was chosen as the data was normally distributed. The effect size was calculated using the Cohen's D calculation where the mean difference is divided by the standard deviation of the difference to give an indication of the magnitude of the effect of the intervention (>0.8 large effect, 0.5 moderate effect, <0.3 small effect) (Cohen, 1988).

4.4 Results

A total of 50 participants were recruited for this study in total including healthy control and individuals following meniscectomy. Out of thirty, twenty-nine individuals following meniscectomy successfully completed all tasks and were included in this study as one individual was unable to perform the drop landing and change of direction task due to pain and did not feel comfortable doing the tasks (Figure 4.3). The twenty-nine individuals were between the ages of 18-40 ((mean ± SD), 29.53 ± 6.56 years, height 175.60 ± 9.03 cm and mass 82.33 ± 13.91 kg) and 20 healthy individuals (24.23 ± 5.00 years, height 174.44 ± 8.62 cm and mass 73.42 ± 11.78 kg). There was a significant difference between age, with the healthy controls being on average six years younger (Table 4.1). Of those who had a meniscectomy 13 were medial (age 30.93 ± 6.89 years, height 174.75 ± 11.28 cm, mass 79.23 ± 14.78 kg), and 16 lateral (age 27.67 ± 5.86 years, height 175.76 ± 8.02 cm, mass 84.52 ± 13.24 kg). The individuals were on average around six months post-surgery (5.73 ± 2.91 months), ranging from three to twelve months. All individuals were physically active individuals before the injury occurred where they trained at a competitive level at their chosen sport at least twice a week as shown in the eligibility criteria (Table 4.1).

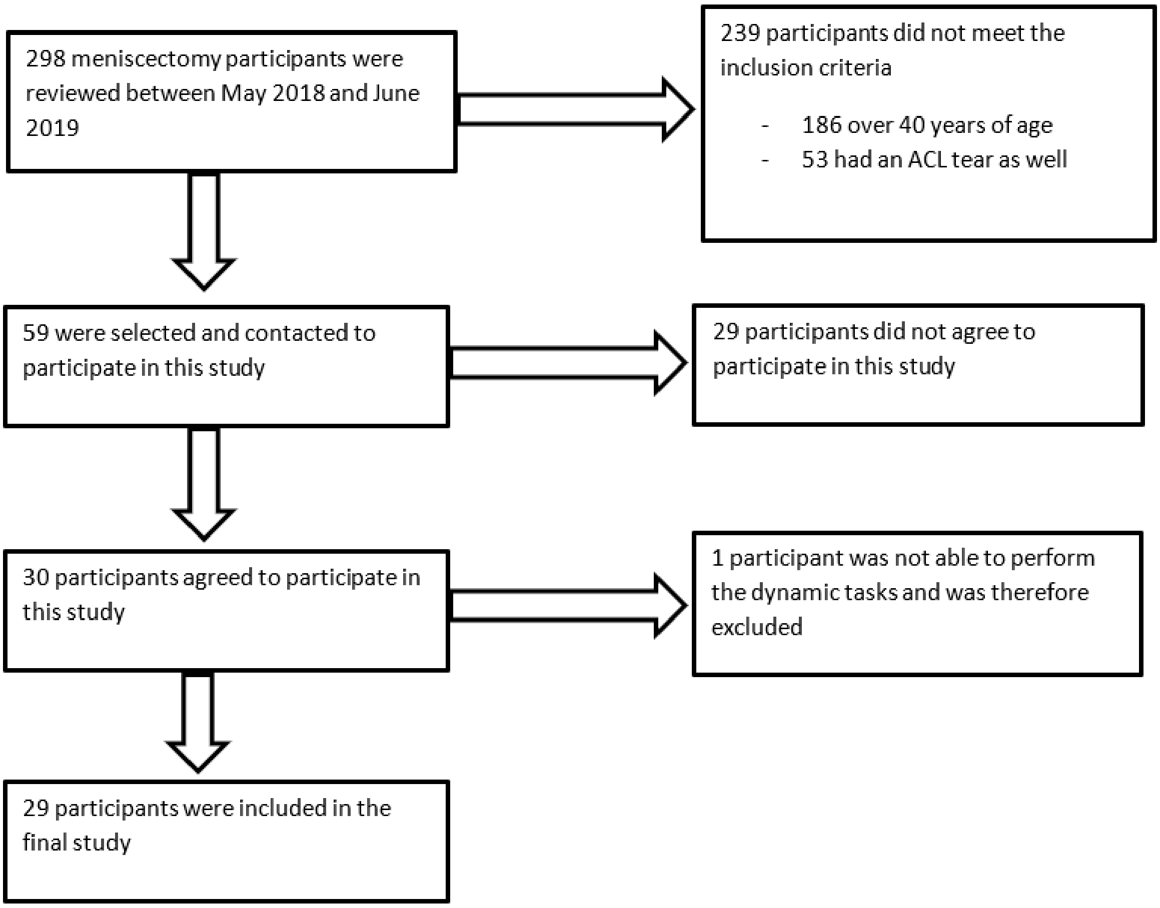


Figure 4.3: Flow chart of meniscectomy participant inclusion in this study

Table 4.1: The participant demographics (* is shows significant differences between meniscectomy and healthy controls), N/A = Not Applicable

		Number	Age (years)	BMI (kg/m^2)	Time since surgery (months)	Activity Level
Meniscectomy	**Total**	29	29.53 ± 7	26.54 ± 3.21	5.73 ± 2.91	8.03 ± 1.25
	Female	10	25.00 ± 3.85	24.18 ± 2.76	5.80 ± 3.88	8.80 ± 0.92
	Male	19	30.29 ± 6.31	27.71 ± 2.90	5.70 ± 2.41	7.68 ± 1.25
	Medial	13	30.93 ± 6.89	25.65 ± 2.97	6.00 ± 3.26	8.15 ± 1.57
	Lateral	16	27.67 ± 5.86	27.26 ± 3.31	5.620 ± 2.72	8.00 ± 2.91
P value			.402	.366	.611	.839
Controls	**Total**	20	24.23 ± 5.00	23.8 ± 2.42	N/A	6.77 ± 1.72
	Female	8	22.11 ± 3.48	24.01 ± 2.80	N/A	6.56 ± 1.81
	Male	12	25.69 ± 5.48	23.5 ± 1.87	N/A	6.92 ± 1.71
P value			**.030***	.458	N/A	.086

4.4.1 Self-reported outcome measures

In this study there was a significant difference between the level of physical activity pre- and post-meniscectomy, ($F_{1,48} = 6.948$, $p < 0.01$). The mean level of physical activity pre-meniscectomy surgery (8.03 ± 1.25 (out of 10)) was significantly higher than the mean level of physical activity following meniscectomy surgery (5.40 ± 2.28 (out of 10)). The physical activity questionnaire highlighted that all injuries were caused through physical activity which mainly consisted of football, rugby, skiing and bouldering. All sections of the KOOS questionnaire were significantly reduced between the individuals following meniscectomy to the controls. A lower score for all outcomes was found following meniscectomy compared to the healthy controls ($p < 0.001$; Table 4.2). Tampa scale of kinesiophobia showed a significantly greater kinesiophobia score following meniscectomy (35.83 ± 6.53) compared to healthy controls who have had no surgery (30.68 ± 4.77, $F_{1,48} = 3.054$, $p < 0.05$). There was also a large effect size for all questionnaires highlighting the importance of the significance found.

Table 4.2: The self-reported outcome measures from the questionnaires for each group (*indicated the results were significantly different between meniscectomy and control. High effect size was indicated in bold and underlined, N/A = Not Applicable)

	Questionnaires	**Medial Meniscectomy**	**Lateral Meniscectomy**	**Total Meniscectomy**	**Control**		
		Mean, SD	*Mean, SD*	*Mean, SD*	*Mean, SD*	*P value*	*ES*
KOOS	Pain	77.78 ± 14.48	73.22 ± 17.12	75.24 ± 15.24	99.05 ± 2.01	**.000***	**2.19**
	Symptoms	68.13 ± 24.02	62.28 ± 19.43	64.83 ± 21.10	94.71 ± 5.11	**.000***	**1.95**
	ADL	89.37 ± 12.29	83.73 ± 13.75	86.28 ± 13.27	99.91 ± 0.30	**.000***	**1.45**
	Sport/Recreation	66.92 ± 23.23	58.44 ± 23.00	62.24 ± 23.09	97.86 ± 5.61	**.000***	**2.12**
	Quality of Life	48.56 ± 20.44	49.61 ± 26.17	49.31 ± 23.39	98.86 ± 3.07	**.000***	**2.97**
	Total	70.15 ± 16.11	65.46 ± 18.08	67.59 ± 17.01	98.00 ± 2.35	**.000***	**2.50**
Tampa Scale		36.64 ± 6.03	35.60 ± 7.04	35.83 ± 6.53	30.68 ± 4.77	**.005***	**0.89**
Sport Activity	Pre-Injury	8.15 ± 1.57	8.00 ± 0.97	8.03 ± 1.25	6.77 ± 1.72	**.000***	**1.43**
	Pre-Surgery	4.00 ± 3.27	3.25 ± 2.91	3.60 ± 2.99	N/A	**.015***	**1.93**
	Post-Surgery	5.46 ± 2.22	5.56 ± 2.31	5.40 ± 2.28	N/A	**.000***	0.68

4.4.2 Walking

4.4.2.1 Medial and lateral meniscectomy comparisons

There was no significant main effect in any of the planes or joints when comparing the medial and the lateral meniscectomies (p > 0.05; Table 4.3). The knee adduction moment during late stance showed a high effect size (ES = 0.83) (although no significance) with greater knee adduction moments in the lateral meniscectomy group (0.25 ± 0.08, 0.83) compared to medial meniscectomy group (0.36 ± 0.17; Figure 4.5).

Table 4.3: Peak sagittal and frontal plane knee motion and moments, vertical GRF and lateral trunk lean comparing individuals following a medial (n = 13) and lateral (n = 16) meniscectomy during walking (*indicated significance. High effect size was indicated in bold and underlined)

	The knee variables during stance phase	**Medial meniscectomy**	**Lateral Meniscectomy**		
		Mean, SD	*Mean, SD*	*P value*	*ES*
Early stance phase (loading)	Peak knee flexion angle (º)	14.23 ± 4.73	16.53 ± 3.78	.923	0.54
	Peak knee adduction angle (º)	-2.26 ± 2.87	-3.95 ± 4.09	.206	0.48
	Peak knee flexion moment (Nm/kg)	0.37 ± 0.27	0.35 ± 0.25	.946	0.08
	Peak knee adduction moment (Nm/kg)	0.39 ± 0.12	0.42 ± 0.18	.849	0.20
	Trunk lateral flexion angle (º)	2.26 ± 3.93	3.97 ± 4.01	.257	0.43
	Peak vertical GRF (BW)	1.16 ± 0.07	1.13 ± 0.06	.251	0.46
Late Stance Phase (Propulsion)	Peak knee flexion angle (º)	36.74 ± 6.29	35.13 ± 6.27	.870	0.26
	Peak knee adduction (º)	-4.45 ± 4.32	-6.31 ± 5.01	.289	0.40
	Peak knee flexion moment (Nm/kg)	-0.35 ± 0.16	-0.41 ± 0.12	.601	0.01
	Peak knee adduction moment (Nm/kg)	0.25 ± 0.08	0.36 ± 0.17	.070	**<u>0.83</u>**
	Peak vertical GRF (BW)	1.14 ± 0.06	1.13 ± 0.08	.710	0.14

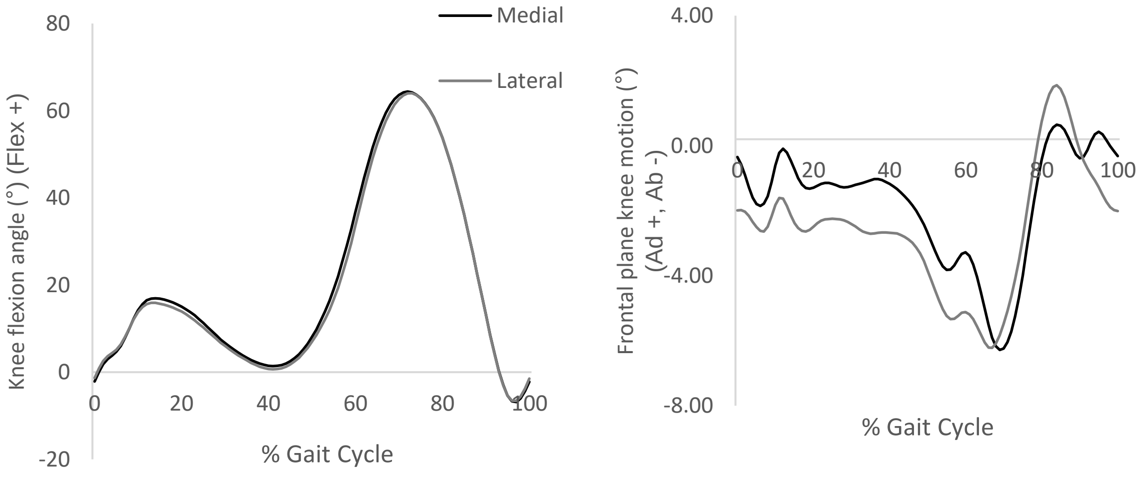


Figure 4.4:Ensemble average sagittal and frontal plane knee motion comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during walking

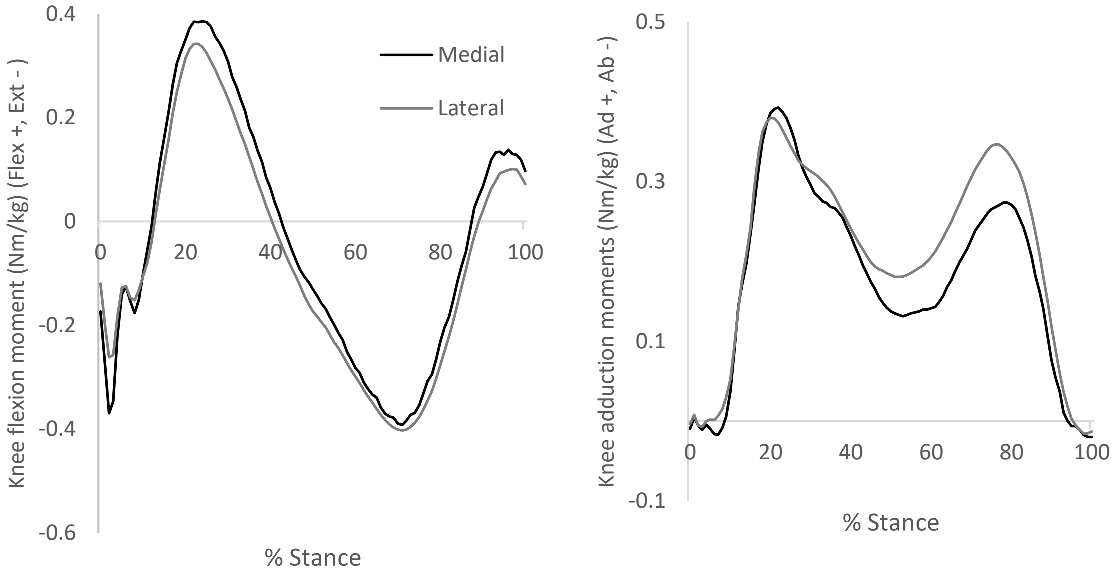


Figure 4.5: Ensemble average sagittal and frontal plane knee moments comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during walking

4.4.2.2 Meniscectomy and healthy comparisons

The walking speed between the individuals following meniscectomy (1.42 ± 0.15 m/s) and healthy controls (1.41 ± 0.15 m/s) was not significantly different ($F_{1,48}$ = .07, p = .790) with a low effect size 0.07 (Table 4.4). During walking there were no significant main effects in all planes for knee angles, both during early and late stance (p > 0.05; Figure 4.6; Appendix 3). There was a statistically significant main effect for ankle plantarflexion angle ($F_{2,77}$ = 2.570, p = 0.013) during late stance (Table 4.4). Greater dorsiflexion angle in late stance was observed for both the meniscectomy leg (13.42 ± 2.68°, p = .017) and the contralateral leg (13.24 ± 2.50°, p = .031) compared to the healthy control group (11.23 ± 3.01°). There was also a medium effect size in the meniscectomy leg (ES = 0.77) and the contralateral leg (ES = 0.73) in relation to the healthy control in ankle dorsiflexion in late stance. The knee adduction angle showed no significant main effect, however there was a significant difference in late stance between the meniscectomy leg (-5.44 ± 4.72°, p = 0.049) compared to the control individual (-2.90 ± 3.78°). The hip flexion angle showed a significant main effect in the early stance phase ($F_{2,77}$ = 3.304, p = 0.002) and in the late stance phase ($F_{2,77}$ = 3.158, p = 0.002), with greater hip flexion in the meniscectomy leg (33.58 ± 6.33°, p = .009) and contralateral leg (33.49 ± 6.96°, p = .010) compared to the healthy control group (28.14 ± 4.58°) during early. During late stance, the meniscectomy leg (-8.35 ± 7.90°, p = .011) and contralateral leg (-6.71° ± 8.32, p = .001) showed greater hip flexion compared to the healthy control group (-14.96 ± 6.11°). There was also a large effect size in early and late stance hip flexion angle showing a large effect in the meniscectomy leg and contralateral leg compared to the healthy controls (ES > 0.8). The trunk flexion angle showed a significant main effect during walking ($F_{2,44} = 10.406$, $p = 0.002$). There was significantly greater lateral trunk flexion in the meniscectomy leg (2.76 ± 2.13°, $p = 0.002$) and the contralateral leg during early stance (3.78 ± 4.85°, $p = 0.002$) compared to the healthy controls (0.59 ± 1.31°) and in late stance for the contralateral leg (5.76 ± 3.78, $p = 0.012$) compared to healthy controls (-0.10 ± 1.57°). There was also a large effect size during lateral trunk flexion (ES > 0.8) between the individuals following meniscectomy for both the meniscectomy leg and contralateral leg compared to the healthy controls in early and late stance.

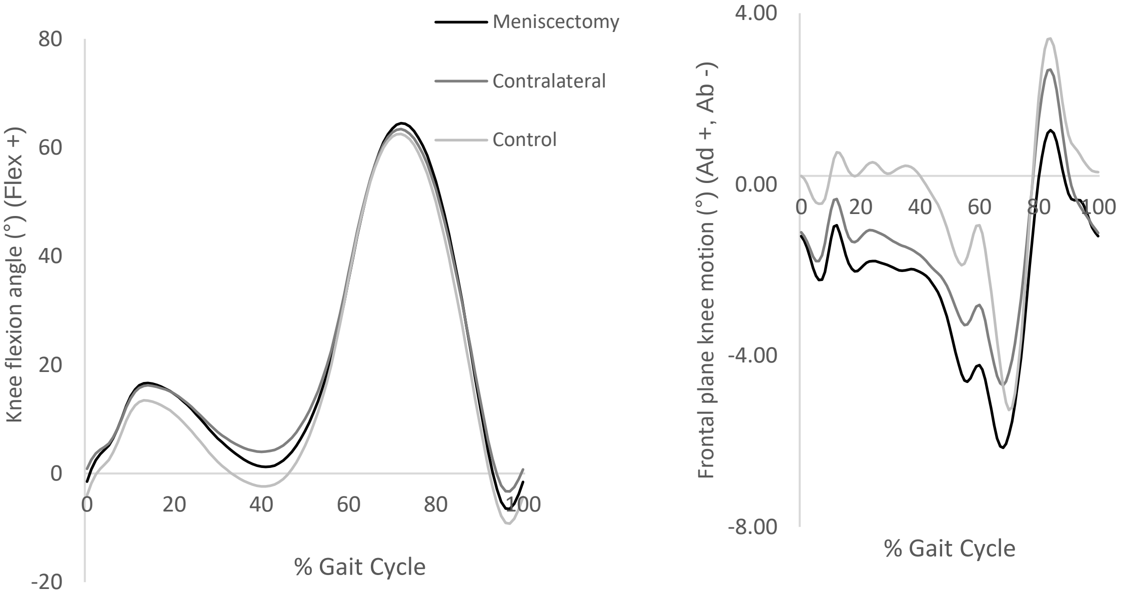


Figure 4.6: Ensemble average sagittal and frontal plane motion comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individual (n = 20) during walking

Table 4.4: Average speed and peak ankle, knee, hip, pelvis and trunk motion during early and late stance during walking (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control. High effect sizes were indicated in bold and underlined)**

	Variables	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
	Speed (m/s)	1.42 ± 0.15	N/A	1.41 ± 0.15	.790	0.07	N/A	N/A	N/A	N/A
Early Stance phase	Ankle flexion angle (º)	-5.21 ± 3.92	-5.88 ± 3.04	-6.18 ± 2.30	.558	0.30	.706	0.19	.945	0.11
	Ankle inversion angle (º)	-1.70 ± 12.19	-0.43 ± 5.76	-2.06 ± 7.06	.990	0.04	.848	0.13	.805	0.25
	Knee flexion angle (º)	16.86 ± 4.19	16.38 ± 5.53	13.52 ± 4.88	.054	0.73	.952	0.10	.114	0.55
	Knee adduction angle (º)	-3.16 ± 3.62	-2.85 ± 4.04	-1.16 ± 3.58	.061	0.56	.753	0.08	.138	0.44
	Hip flexion angle (º)	33.58 ± 6.33	33.49 ± 6.96	28.14 ± 4.58	**.009***	**0.98**	.998	0.01	**.010*****	**0.91**
	Hip adduction angle (º)	6.74 ± 3.65	7.26 ± 3.83	6.50 ± 4.44	.975	0.06	.867	0.14	.780	0.18
	Pelvis tilt angle (º)	11.50 ± 4.72	11.76 ± 4.73	8.92 ± 4.03	.050	0.59	.833	0.06	**.032*****	0.65
	Trunk lateral flexion angle (º)	2.76 ± 2.13	3.78 ± 4.85	0.59 ± 1.31	**.002***	**1.23**	.564	0.27	**.003*****	**0.89**
Late Stance phase	Ankle flexion angle (º)	13.42 ± 2.68	13.24 ± 2.50	11.23 ± 3.01	**.017***	0.77	.966	0.07	**.031*****	0.73
	Ankle inversion angle (º)	11.77 ± 12.77	12.46 ± 6.90	11.96 ± 6.95	.997	0.02	.958	0.07	.983	0.07
	Knee flexion angle (º)	35.88 ± 6.23	37.17 ± 6.71	39.17 ± 13.34	.392	0.32	.833	0.20	.706	0.19
	Knee adduction angle (º)	-5.44 ± 4.72	-4.40 ± 4.92	-2.90 ± 3.78	**.049***	0.59	.404	0.22	.254	0.34
	Hip flexion angle (º)	-8.35 ± 7.90	-6.71 ± 8.32	-14.96 ± 6.11	**.011***	**0.94**	.685	0.20	**.001*****	**1.13**
	Hip adduction angle (º)	6.61 ± 3.01	6.74 ± 3.28	6.11 ± 4.07	.866	0.14	.988	0.04	.798	0.17
	Pelvis tilt angle (º)	11.92 ± 4.77	11.99 ± 4.80	9.21 ± 3.98	**.042***	0.62	.953	0.01	**.037*****	0.63
	Trunk lateral flexion angle (º)	3.08 ± 2.00	4.08 ± 3.78	1.15 ± 1.68	.092	**1.04**	.562	0.33	.080	**1.00**

There was a significant main effect for knee flexion moment during walking in late stance phase ($F_{2,77}$ = 2.404, p = 0.020; Table 4.5). The knee flexion moment was significantly reduced in the meniscectomy leg (-0.38 ± 0.42 Nm/kg, p = .044) compared to the healthy control group (-0.49 ± 0.17 Nm/kg), however, there was no significant difference between either the meniscectomy leg and the control leg compared to the contralateral leg (-0.43 ± 0.15 Nm/kg, p > 0.05; Figure 4.7). This significant difference was seen to be the same as the SEM seen in the repeatability study, showing there is no minimal detectable difference highlighting no clinically meaningful result. There was also a large effect size in the late stance knee flexion moment comparing the individuals following meniscectomy to the healthy controls (ES = 1.09). The ankle plantarflexion moments showed a significant main effect in late stance during walking ($F_{2,77}$ = -2.591, p = 0.013). The plantarflexion moment was significantly lower in the meniscectomy leg during late stance (1.45 ± 0.17 Nm/kg, p = 0.015) compared to the healthy controls (1.59 ± 0.22 Nm/kg). The hip flexion moments showed a significant main effect in late stance during walking ($F_{2,77}$ = 3.769, p < 0.001; Appendix 3). The hip flexion moment was significantly lower in the meniscectomy leg during late stance (-0.79 ± 0.24 Nm/kg, p = 0.003) compared to the healthy controls (-1.04 ± 0.22 Nm/kg). There was no significant difference between the meniscectomy leg and the control leg compared to the contralateral leg in hip flexion moment during late stance (-0.89 ± 0.28 Nm/kg, p > 0.0; Table 4.5). The effect sizes were low to moderate during walking for the moments in early and late stance. KAAI did not show a significant difference in individuals following meniscectomy compared to healthy controls, however there was a moderate effect size (ES = 0.66).

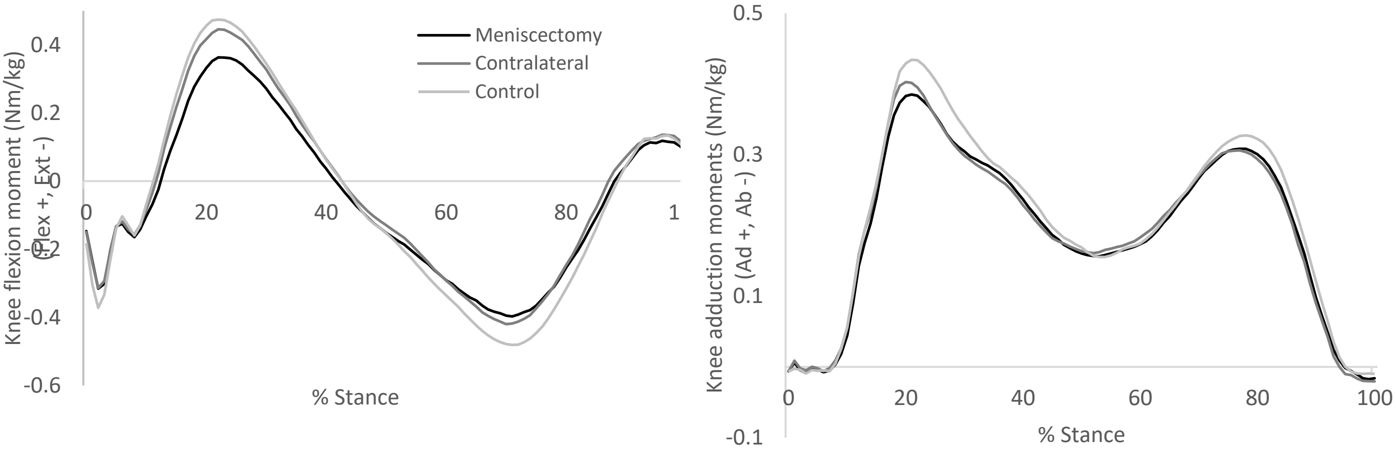


Figure 4.7: Ensemble average sagittal and frontal plane knee moments comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during walking

Table 4.5: Peak ankle, knee, hip moments, vertical GRF during early and late stance, KAAI and medio-lateral centre of pressure during walking (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control. High effect sizes were indicated in bold and underlined**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Early Stance phase	Ankle flexion moment (Nm/kg)	0.59 ± 0.14	0.57 ± 0.11	0.57 ± 0.13	.870	0.15	.684	0.16	.966	0.00
	Knee flexion moment (Nm/kg)	0.36± 0.25	0.45 ± 0.22	0.49 ± 0.21	.132	0.56	.343	0.38	.777	0.19
	Knee adduction moment (Nm/kg)	0.40 ± 0.16	0.41 ± 0.12	0.46 ± 0.11	.338	0.44	.993	0.07	.392	0.43
	Hip flexion moment (Nm/kg)	0.79 ± 0.23	0.82 ± 0.21	0.77 ± 0.26	.920	0.08	.914	0.14	.732	0.21
	Hip adduction moment (Nm/kg)	0.89 ± 0.15	0.87 ± 0.15	0.93 ± 0.12	.608	0.29	.942	0.13	.427	0.44
	Vertical GRF (BW)	1.14 ± 0.08	1.15 ± 0.07	1.19 ± 0.30	.420	0.23	.621	0.13	.518	0.18
Late Stance phase	Ankle flexion moment (Nm/kg)	1.45 ± 0.17	1.53 ± 0.14	1.59 ± 0.22	**.015***	0.71	.212	0.51	.386	0.33
	Knee flexion moment (Nm/kg)	-0.38 ± 0.14	-0.43 ± 0.15	-0.49 ± 0.17	**.044***	0.71	.506	0.34	.330	0.37
	Knee adduction moment (Nm/kg)	0.31± 0.15	0.32 ± 0.11	0.34 ± 0.14	.697	0.21	.933	0.08	.876	0.16
	Hip flexion moment (Nm/kg)	-0.79 ± 0.24	-0.89 ± 0.28	-1.04 ± 0.22	**.003***	**1.09**	.293	0.38	.098	0.60
	Hip adduction moment (Nm/kg)	0.83 ± 0.14	0.83 ± 0.16	0.88 ± 0.11	.398	0.40	1.00	0.00	.388	0.36
	Vertical GRF (BW)	1.13 ± 0.07	1.14 ± 0.07	1.15 ± 0.25	.757	0.11	.867	0.14	.804	0.05
	KAAI ((Nm/kg)*s)	0.12 ± 0.05	0.13 ± 0.06	0.15 ± 0.04	.089	0.66	.495	0.18	.505	0.39
	Medio-lateral centre of pressure position at touchdown (mm)	0.81 ± 0.26	0.82 ± 0.33	0.74 ± 0.25	.315	0.27	.959	0.03	.380	0.27

4.4.2.3 Muscle activation and co-contraction

There was no significant main effect in the co-contraction ratio between the extensors (vastus medialis) and the flexors (biceps femoris) in both early and late stance phase of walking when comparing the individuals following meniscectomy to the contralateral leg and the healthy controls ($p > 0.05$; Table 4.6). There was also a low effect size for the co-contraction between extensor and flexors muscles.

There was a significant main effect in the co-activation between the medial (vastus medialis) and the lateral (vastus lateralis) extensor muscles in early stance ($F_{2,77} = 8.396$, $p < 0.001$) and in late stance ($F_{2,77} = 8.557$, $p < 0.001$). There was a greater lateral knee extensor co-contraction ratio during early stance in the meniscectomy leg (-0.74 ± 0.12, $p < 0.001$) and contralateral leg (-0.70 ± 0.13, $p < 0.001$) compared to the healthy controls (0.13 ± 0.05*;* Table 4.6). There was also a significantly greater lateral knee extensor muscle activation ratio seen in late stance in the meniscectomy leg (-0.75 ± 0.07, $p < 0.001$) and contralateral leg (-0.71 ± 0.07, $p < 0.001$)

compared to the healthy controls (-0.24 ± 0.22). There was a large effect size in the co-contraction ratio between the medial and lateral extensor for early and late stance (ES >0.8; Table 4.6).

There was a significant main effect between the net muscle activation in early stance ($F_{2,77}$ = 7.550, P = 0.001) and in late stance ($F_{2,77}$ = 7.498, P = 0.001; Table 4.6). There was a significant increase in the net activation knee extensor muscle (vastus medialis, vastus lateralis*)* during early stance in the meniscectomy leg (0.69 ± 0.31 %MVC, p < 0.001) and contralateral leg (0.73 ± 0.43 %MVC, p = 0.002) compared to the healthy controls (0.35 ± 0.30 %MVC; Table 4.6). On the contrary, there was a significant increase in the net muscle knee flexor activation (semimembranosus, biceps femoris) during late stance in the meniscectomy leg (0.54 ± 0.24 %MVC, p < 0.001) and contralateral leg (0.63 ± 0.50 %MVC, p = 0.002) compared to the healthy controls (0.23 ± 0.16 %MVC; Figure 4.8). There was a large effect size in the net muscle activation for the extensor in early stance and flexors in late stance (ES > 0.8).

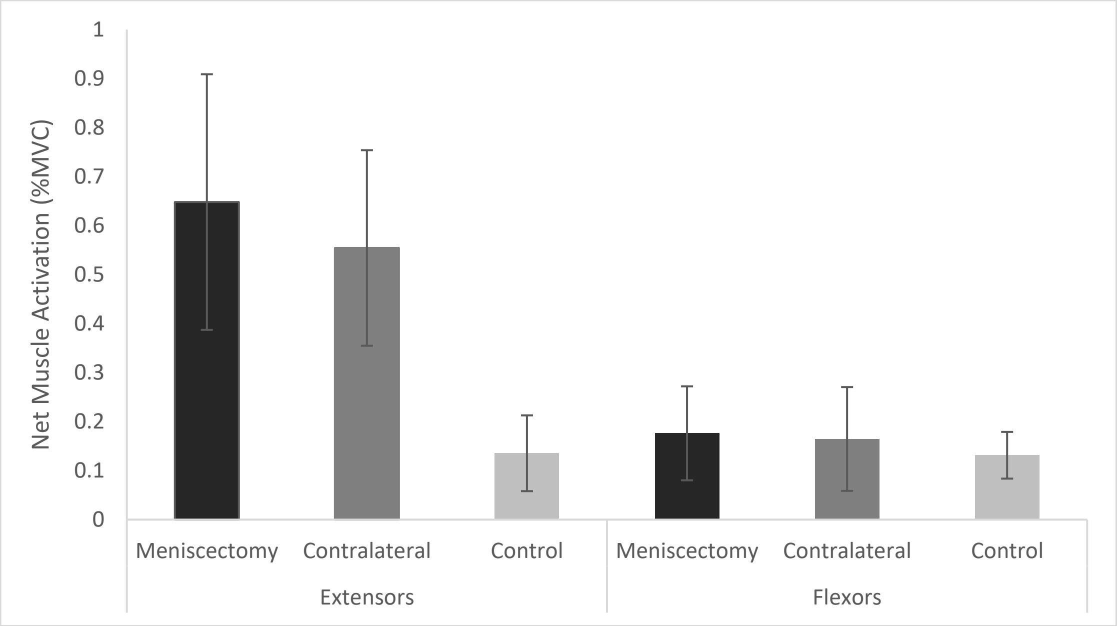


Figure 4.8: Sum of net activation of the knee extensors and flexors

Table 4.6: Co-contraction ratio, sum of net activation of the knee flexors and knee extensors during early and late stance phase in walking (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Early Stance phase	Co-contraction Extensor/Flexor ratio	0.27 ± 0.47	0.40 ± 0.45	0.29 ± 0.50	.851	0.04	.296	0.28	.456	0.23
	Co-contraction Medial/Lateral ratio	-0.75 ± 0.07	-0.71 ± 0.07	0.13 ± 0.05	**.000***	**14.45**	.259	0.57	**.000*****	**13.81**
	Net activation knee extensors (%MVC)	0.69 ± 0.31	0.73 ± 0.43	0.35 ± 0.30	**.000***	**1.11**	.737	0.11	**.002*****	**1.02**
	Net activation knee flexors (%MVC)	0.52 ± 0.37	0.52 ± 0.38	0.31 ± 0.36	.067	0.58	.957	0.00	.064	0.57
Late Stance phase	Co-contraction Extensor/Flexor ratio	0.02 ± 0.52	0.16 ± 0.45	-0.01 ± 0.45	.867	0.06	.320	0.29	.237	0.38
	Co-contraction Medial/Lateral ratio	-0.74 ± 0.12	-0.70 ± 0.13	-0.24 ± 0.22	**.000***	**2.82**	.557	0.32	**.000*****	**2.55**
	Net activation knee extensors (%MVC)	0.22 ± 0.13	0.21 ± 0.12	0.18 ± 0.12	.357	0.32	.814	0.08	.469	0.25
	Net activation knee flexors (%MVC)	0.54 ± 0.24	0.63 ± 0.50	0.23 ± 0.16	**.000***	**1.51**	.379	0.23	**.002*****	**1.08**

4.4.3 Running

4.4.3.1 Medial and lateral meniscectomy comparison

There was no significant main effect in any of the planes or joints when comparing the medial and the lateral meniscectomies (p > 0.05; Figure 4.10). The main outcomes of the knee were reported in Table 4.7 to highlight there was no significance. There were low to moderate effect sizes in individuals following medial and lateral meniscectomy.

Table 4.7: Peak sagittal and frontal plane knee motion and moments, vertical GRF and lateral trunk lean comparing individuals following a medial and lateral meniscectomy during running (*indicated the results were significantly different between medial and lateral meniscectomy. High effect size was indicated in bold and underlined)

	The knee variables during stance phase	**Medial meniscectomy**		**Lateral Meniscectomy**		
		Mean, SD		*Mean, SD*	*P value*	*ES*
Early stance phase (loading)	Knee flexion angle (º)	34.12 ± 6.88		35.15 ± 5.83	.885	0.16
	Knee adduction angle (º)	-5.77 ± 4.65		-5.65 ± 6.03	.953	0.02
	Knee flexion moment (Nm/kg)	0.86 ± 0.39		0.81 ± 0.39	.749	0.13
	Knee adduction moment (Nm/kg)	0.64 ± 0.31		0.56 ± 0.29	.740	0.27
	Trunk lateral flexion angle (º)	6.95 ± 5.13		5.38 ± 5.91	.290	0.44
	Vertical GRF (BW)	1.96 ± 0.37		1.86 ± 0.29	.415	0.30
Late Stance Phase (Propulsion)	Knee flexion angle (º)	31.98 ± 8.39		35.35 ± 9.18	.507	0.38
	Knee adduction (º)	-4.18 ± 5.23		-6.22 ± 5.14	.298	0.39
	Knee flexion moment (Nm/kg)	1.70 ± 0.38		1.64 ± 0.70	.956	0.11
	Knee adduction moment (Nm/kg)	0.65 ± 0.25		0.62 ± 0.35	.964	0.10
	Vertical GRF (BW)	2.33 ± 0.26		2.28 ± 0.34	.668	0.17

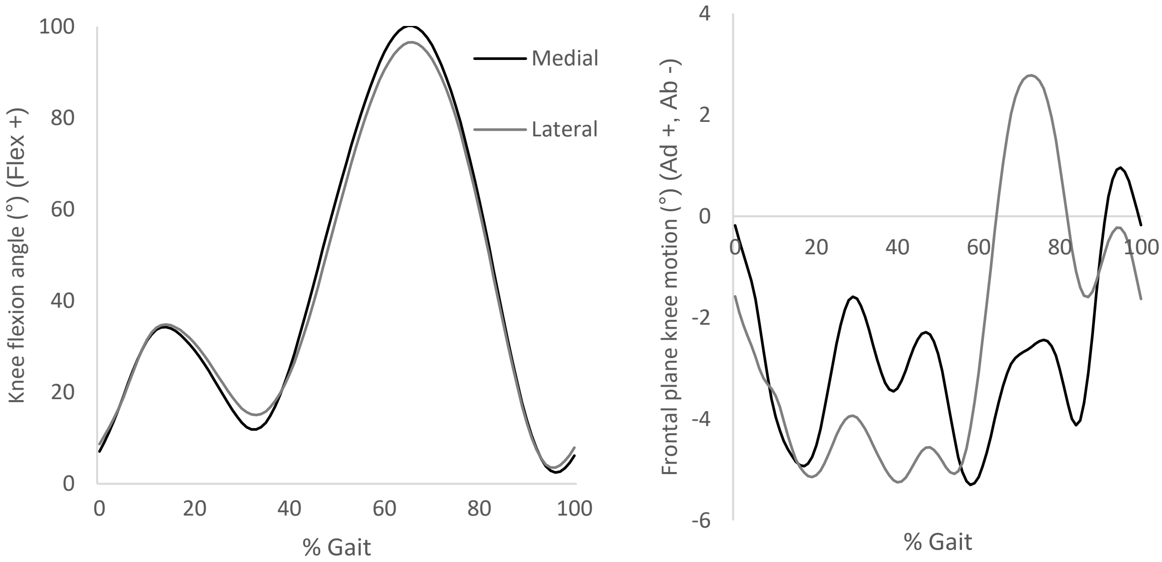


Figure 4.9: Ensemble average sagittal and frontal plane knee motion comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during running

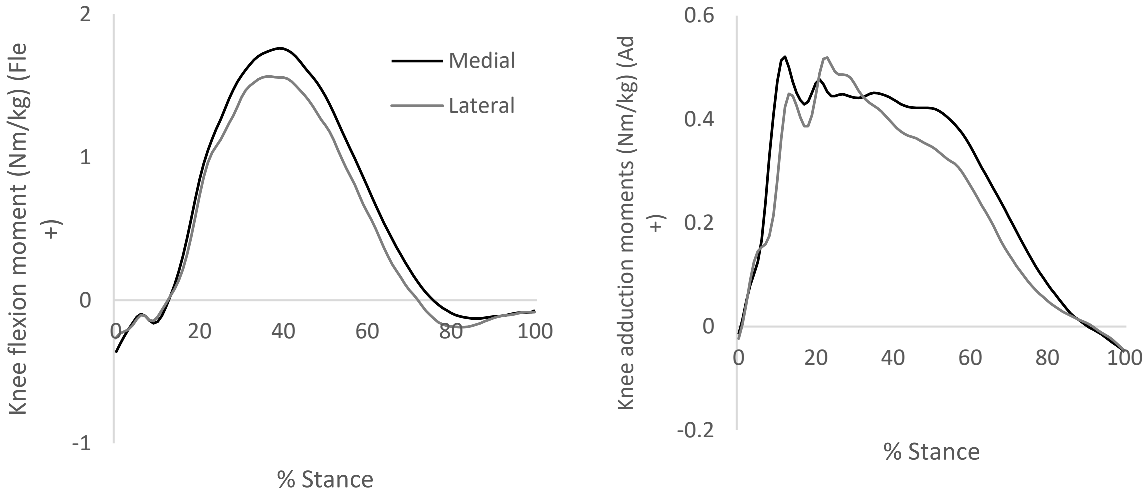


Figure 4.10: Sagittal and frontal plane knee moments comparing individuals following medial and lateral meniscectomy during running

4.4.3.2 Meniscectomy and healthy comparison

The running speed between individuals following meniscectomy (3.59 ± 0.67 m/s) and healthy controls (3.40 ± 0.51 m/s) was not significantly different ($F_{1,48} = 1.11$, p = 0.298) with a low effect size of 0.33 (Table 4.8). During running there were no statistically significant main effects for knee flexion and knee adduction angles ($p > 0.05$; Figure 4.11), nor was there a significant main effect for ankle plantarflexion ($p > 0.05$; Table 4.8). During running there was a statistically significant main effect for hip flexion angle during late stance phase ($F_{2,77} = 2.977$, p = 0.005; Appendix 3). There was also a large effect size for hip flexion angle during running in late stance between the individuals following meniscectomy and the healthy controls ($ES > 0.8$). Significantly reduced hip flexion angle in late stance was observed for both the meniscectomy leg (13.42 ± 2.68°, P = .017) and the contralateral leg (-2.99 ± 7.80°, $p < 0.001$) compared to the healthy control group (-11.61 ± 6.59°). The trunk flexion angle showed a significant main effect during walking ($F_{2,44} = 16.177$, $p < 0.001$). There was significantly greater lateral trunk flexion in the individuals following meniscectomy in early stance for the meniscectomy leg (6.27 ± 4.13°, $p < 0.001$) and contralateral leg (5.43 ± 3.64°, $p < 0.001$) compared to the healthy controls (1.05 ± 1.79°). There was significantly greater lateral trunk flexion in the individuals following meniscectomy in late stance for the meniscectomy leg (6.13 ± 3.43°, $p < 0.001$) and contralateral leg (5.40 ± 3.45°, $p < 0.001$) compared to the healthy controls (1.03 ± 2.58°). There was a large effect size in trunk lean between individuals following meniscectomy compared to healthy controls ($ES > 0.8$).

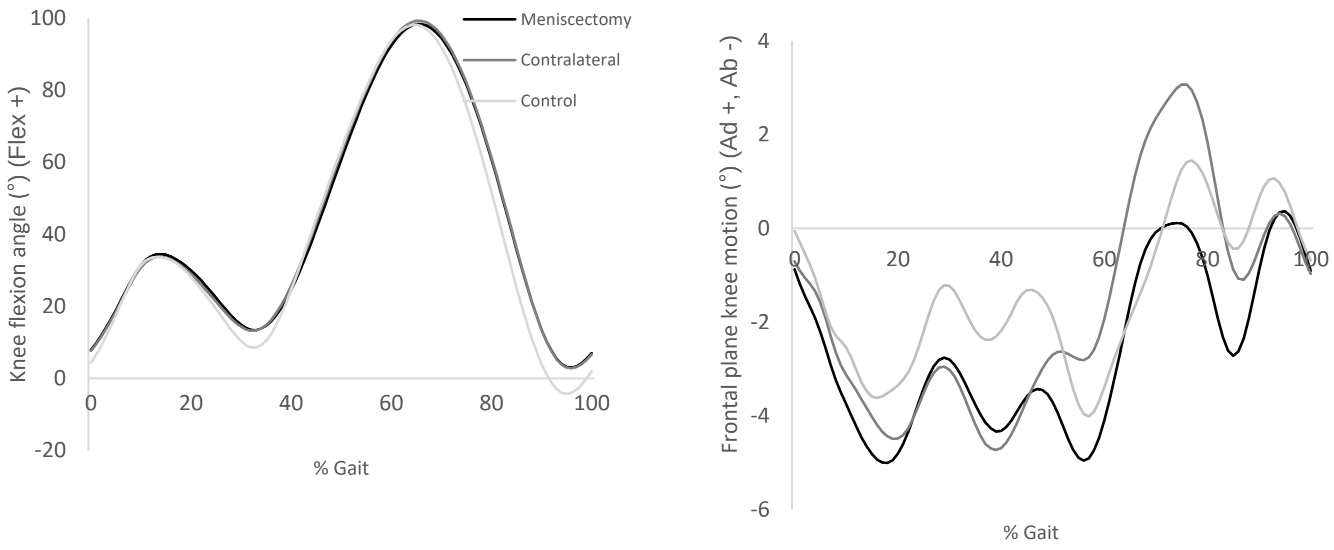


Figure 4.11: Ensemble average sagittal and frontal plane knee motion comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during running

Table 4.8: Average speed, peak ankle, knee, hip, pelvis and trunk motion during early and late stance of running (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control. High effect sizes were indicated in bold and underlined)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
	Speed (m/s)	3.59 ± .67		3.40 ± .51	.298	0.33	N/A	N/A	N/A	N/A
Early Stance phase	Ankle flexion angle (°)	21.04 ± 3.16	23.16 ± 3.32	21.96 ± 5.03	.678	0.22	.087	0.65	.517	0.28
	Ankle inversion angle (°)	7.61 ± 6.43	5.95 ± 6.08	5.68 ± 5.60	.525	0.32	.558	0.27	.987	0.05
	Knee flexion angle (°)	34.68 ± 6.22	33.90 ± 5.62	34.30 ± 5.57	.971	0.06	.866	0.13	.971	0.07
	Knee adduction angle (°)	-5.70 ± 5.36	-5.26 ± 4.92	-3.88 ± 3.48	.189	0.40	.746	0.09	.286	0.32
	Hip flexion angle (°)	37.31 ± 8.32	38.04 ± 8.77	32.12 ± 5.59	.068	0.73	.934	0.09	**.031*** **	**0.81**
	Hip adduction angle (°)	11.27 ± 4.60	11.68 ± 4.31	12.27 ± 3.67	.701	0.24	.928	0.09	.885	0.15
	Pelvis tilt angle (°)	20.39 ± 4.86	22.45 ± 4.59	16.29 ± 3.81	**.003***	**0.93**	.958	0.44	**.002*** **	**1.46**
	Trunk lateral flexion angle (°)	6.27 ± 4.13	5.43 ± 3.64	1.05 ± 1.79	**.000***	**1.64**	.510	0.22	**.000*** **	**1.53**
Late Stance phase	Ankle flexion angle (°)	-25.80 ± 8.11	-25.14 ± 7.81	-30.54 ± 5.17	.074	0.70	.938	0.08	**.036*** **	**0.82**
	Ankle inversion angle (°)	9.61 ± 6.08	8.73 ± 5.92	10.93 ± 6.40	.739	0.21	.845	0.15	.431	0.36
	Knee flexion angle (°)	33.84 ± 8.85	32.97 ± 8.23	31.59 ± 6.86	.610	0.28	.912	0.10	.831	0.18
	Knee adduction angle (°)	-5.31 ± 5.19	-5.92 ± 5.11	-4.19 ± 3.61	.411	0.25	.655	0.12	.201	0.39
	Hip flexion angle (°)	-5.39 ± 8.23	-2.99 ± 7.80	-11.61 ± 6.59	**.018***	**0.83**	.463	0.30	**.001*** **	**1.19**
	Hip adduction angle (°)	3.26 ± 4.39	3.43 ± 2.56	2.75 ± 3.73	.849	0.13	.978	0.05	.749	0.21
	Pelvis tilt angle (°)	21.79 ± 4.39	22.74 ± 4.56	19.63 ± 4.09	.089	0.51	.422	0.21	**.018*** **	0.71
	Trunk lateral flexion angle (°)	6.13 ± 3.43	5.40 ± 3.45	1.03 ± 2.58	**.000***	**1.68**	.518	0.21	**.000*** **	**1.43**

There was a significant main effect in the knee flexion moment during running in late stance phase ($F_{2,77}$ = -2.883, p = 0.006; Figure 4.12). The knee flexion moment was significantly lower in the meniscectomy leg (1.67 ± 0.57 Nm/kg, p = .018) compared to the healthy control group (2.08 ± 0.29 Nm/kg) during late stance phase. The contralateral leg was also significantly higher (2.17 ± 0.54 Nm/kg, p < .001) compared to the meniscectomy leg (1.67 ± 0.57 Nm/kg, Table 4.9). There was also a large effect size in knee flexion moment between the meniscectomy leg and the healthy controls in late stance (ES = 0.91). There was also a medium effect size in the knee adduction moment (ES = 0.57) with a greater knee adduction moment in the meniscectomy leg (0.59 ± 0.29 Nm/kg) compared to the control group (0.44 ± 0.23 Nm/kg), however, there was no significant difference. There was a significant main effect during ankle plantarflexion moment during running late stance phase ($F_{2,77}$ = -3.699, p = 0.001). The ankle plantarflexion moment was significantly lower in the meniscectomy leg (2.50 ± 0.48 Nm/kg, p = .002) compared to the healthy control group (3.00 ± 0.44 Nm/kg) and the contralateral leg was also significantly lower (2.52 ± 0.52 Nm/kg, p =.003) compared to the control group (Table 4.9). During running it can also be seen that the individuals following meniscectomy apply pressure on significantly less percentage of the foot, therefore showing greater heel strike foot strike patterns in the individuals following meniscectomy (28.80 ± 15.51 %footlength; p = .034) compared to the healthy controls (41.75 ± 22.88 %footlength).

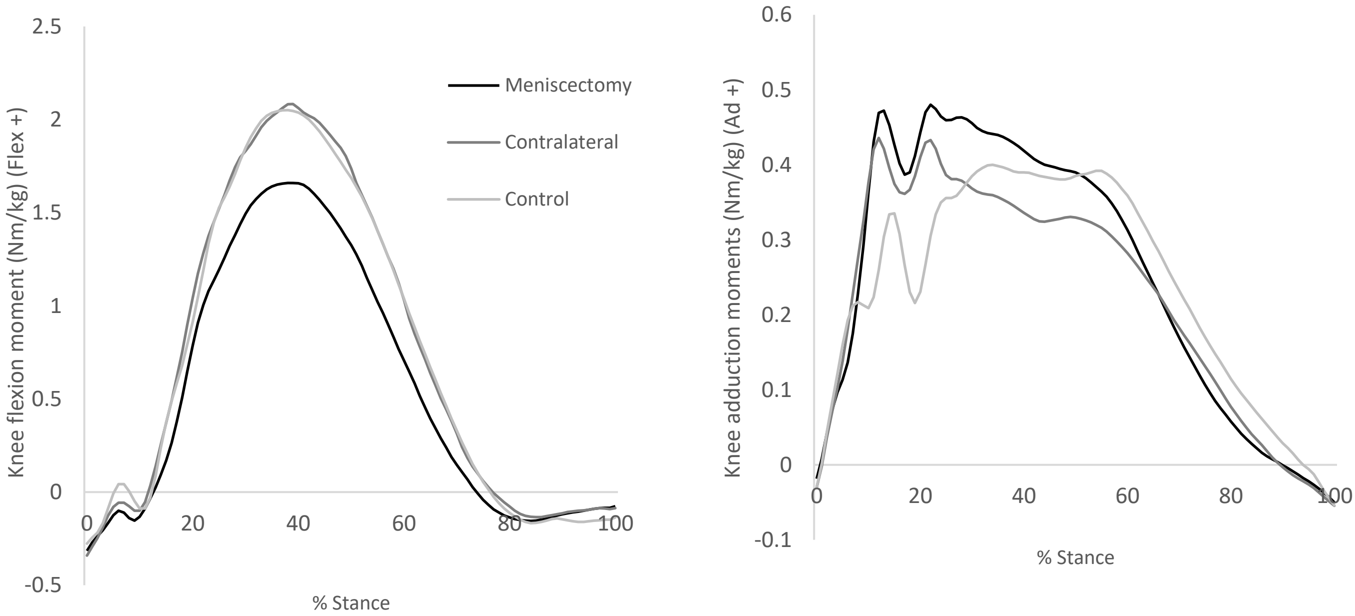


Figure 4.12: Ensemble average sagittal and frontal plane knee moments comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during running

Table 4.9: Peak ankle, knee, hip moments, vertical GRF during early and late stance, KAAI and medio-lateral centre of pressure during running (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control. High effect sizes were indicated in bold and underlined)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Early Stance phase	Ankle flexion moment (Nm/kg)	0.22 ± 0.34	0.21 ± 0.36	0.18 ± 0.36	.945	0.11	.999	0.03	.956	0.08
	Knee flexion moment (Nm/kg)	0.83 ± 0.39	0.95 ± 0.37	0.93 ± 0.33	.326	0.28	.236	0.32	.871	0.06
	Knee adduction moment (Nm/kg)	0.59 ± 0.29	0.55 ± 0.34	0.44 ± 0.23	.174	0.57	.838	0.13	.402	0.38
	Hip flexion moment (Nm/kg)	1.90 ± 0.73	1.78 ± 0.72	1.57 ± 0.56	.225	0.51	.798	0.17	.526	0.33
	Hip adduction moment (Nm/kg)	1.32 ± 0.37	1.25 ± 0.44	1.24 ± 0.41	.858	0.20	.850	0.17	.999	0.02
	Vertical GRF (BW)	1.91 ± 0.33	1.97 ± 0.38	1.91 ± 0.47	.985	0.00	.530	0.17	.641	0.14
Late Stance phase	Ankle flexion moment (Nm/kg)	2.50 ± 0.48	2.52 ± 0.52	3.00 ± 0.44	**.002***	**1.09**	.984	0.04	**.003*****	**1.00**
	Knee flexion moment (Nm/kg)	1.67 ± 0.57	2.17 ± 0.54	2.08 ± 0.29	**.018***	**0.91**	**.001****	**0.90**	.779	0.21
	Knee adduction moment (Nm/kg)	0.64 ± 0.30	0.52 ± 0.31	0.54 ± 0.30	.525	0.33	.287	0.39	.956	0.07
	Hip flexion moment (Nm/kg)	1.04 ± 0.72	0.94 ± 0.67	0.73 ± 0.50	.240	0.50	.831	0.14	.515	0.36
	Hip adduction moment (Nm/kg)	1.94 ± 0.33	1.90 ± 0.38	1.81 ± 0.34	.488	0.39	.938	0.11	.680	0.25
	Vertical GRF (BW)	2.30 ± 0.31	2.33 ± 0.29	2.44 ± 0.45	.189	0.36	.666	0.10	.305	0.29
	KAAI ((Nm/kg)*s)	0.05 ± 0.04	0.05 ± 0.05	0.05± 0.05	.965	0.00	.769	0.00	.930	0.00
	Medio-lateral centre of pressure position (mm)	0.87 ± 0.21	0.96 ± 0.26	0.88 ± 0.26	.917	0.04	.222	0.38	.327	0.31
	Antero-posterior centre of pressure (%foot length)	28.80 ± 15.51	29.26 ± 17.42	41.75 ± 22.88	**.034***	0.04	.916	0.38	.054	0.31

4.4.3.3 Muscle activation and co-contraction

There was no significant main effect in the co-activation between the extensors and flexors muscles in early stance ($F_{2,77} = 2.958$, $p > 0.05$). The knee extensors were more active compared to the flexors, showing a significantly lower co-activation ratio during early stance in the meniscectomy leg (0.34 ± 0.40, p = 0.011) compared to the healthy controls (0.62 ± 0.21*;* Table 4.10). There was a significantly lower knee extensor muscle activation ratio seen in late stance in the contralateral leg (0.39 ± 0.43, p = 0.023) compared to the healthy controls (0.10 ± 0.31).

There was a large effect size in the co-contraction ratio between the knee extensor and flexor in early stance (ES >0.8; Table 4.10).

There was no significant main effect between the net extensor and flexor muscle activation in late stance ($F_{2,77} = 1.184$, $p > 0.05$; Table 4.10). There was, however, a significant increase in the net muscle knee flexor activation (semimembranosus, biceps femoris) during late stance in the meniscectomy leg (1.35 ± 0.76 %MVC, $p < 0.001$) and contralateral leg (1.26 ± 0.69 %MVC, $p < 0.001$) compared to the healthy controls (0.54 ± 0.12 %MVC). There was a large effect size in the net muscle activation for the flexors in late stance (ES > 0.8)

Table 4.10: Co-contraction ratio, sum of net activation of the knee flexors and knee extensors during early and late stance of running (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Early Stance phase	Co-contraction Extensor/Flexor ratio	0.34 ± 0.40	0.48 ± 0.42	0.62 ± 0.21	**.011***	**0.88**	.278	0.34	.184	0.42
	Co-contraction Medial/Lateral ratio	-0.16 ± 0.52	-0.13 ± 0.42	0.03 ± 0.43	.240	0.40	.834	0.06	.264	0.38
	Net activation knee extensors (%MVC)	2.47 ± 2.50	2.41 ± 1.49	2.06 ± 0.78	.501	0.22	.928	0.03	.360	0.29
	Net activation knee flexors (%MVC)	1.42 ± 1.14	1.32 ± 1.35	0.86 ± 0.43	.087	0.65	.767	0.08	.232	0.46
Late Stance phase	Co-contraction Extensor/Flexor ratio	0.29 ± 0.48	0.39 ± 0.43	0.10 ± 0.31	.172	0.47	.470	0.22	**.023*****	0.77
	Co-contraction Medial/Lateral ratio	-0.17 ± 0.52	-0.14 ± 0.48	0.01 ± 0.45	.255	0.37	.795	0.06	.355	0.32
	Net activation knee extensors (%MVC)	0.39 ± 0.73	0.71 ± 0.82	0.46 ± 0.24	.660	0.13	.156	0.41	.220	0.41
	Net activation knee flexors (%MVC)	1.35 ± 0.76	1.26 ± 0.69	0.54 ± 0.12	**.000***	**1.49**	.640	0.12	**.000*****	**1.45**

4.4.4 Landing

4.4.4.1 Medial and lateral meniscectomy comparison

There was no significant main effect in any of the planes or joints when comparing the medial and the lateral meniscectomies during landing ($p > 0.05$; Figure 4.14). The main outcomes of the knee were reported in Table 4.11 to highlight there was no significance. There were low to medium effect sizes in the knee when comparing individuals following medial and lateral meniscectomy (ES < 0.8).

Table 4.11: Peak sagittal and frontal plane knee moments, vertical GRF and lateral trunk lean comparing individuals following a medial and lateral meniscectomy during landing (*indicated significance. High effect size was indicated in bold and underlined)

The knee variables during stance phase	**Medial meniscectomy**		**Lateral Meniscectomy**		
	Mean, SD		*Mean, SD*	*P value*	*ES*
Knee flexion angle (º)	62.70 ± 15.29		56.73 ± 11.60	.451	0.44
Frontal plane knee motion (º)	-1.00 ± 3.87		-0.73 ± 5.33	.988	0.06
Knee flexion moment (Nm/kg)	1.28 ± 0.39		1.08 ± 0.43	.313	0.49
Knee adduction moment (Nm/kg)	0.46 ± 0.14		0.44 ± 0.18	.979	0.12
Trunk lateral flexion angle (º)	3.66 ± 6.91		5.88 ± 8.67	.117	0.67
Vertical GRF (BW)	2.00 ± 0.40		2.00 ± 0.42	.991	0.00

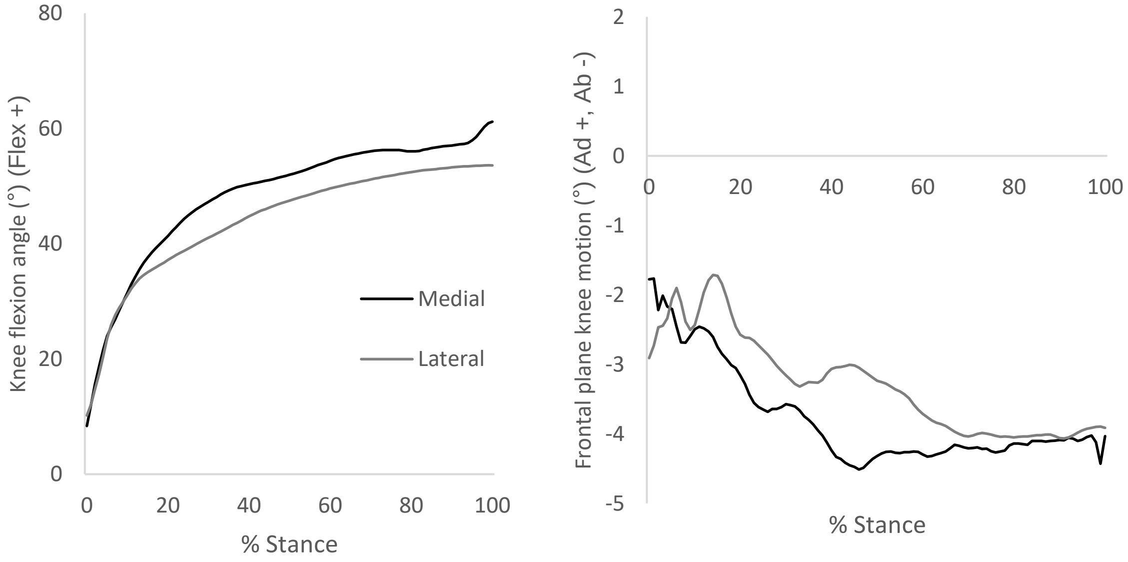


Figure 4.13: Ensemble average sagittal and frontal plane knee motion comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during landing

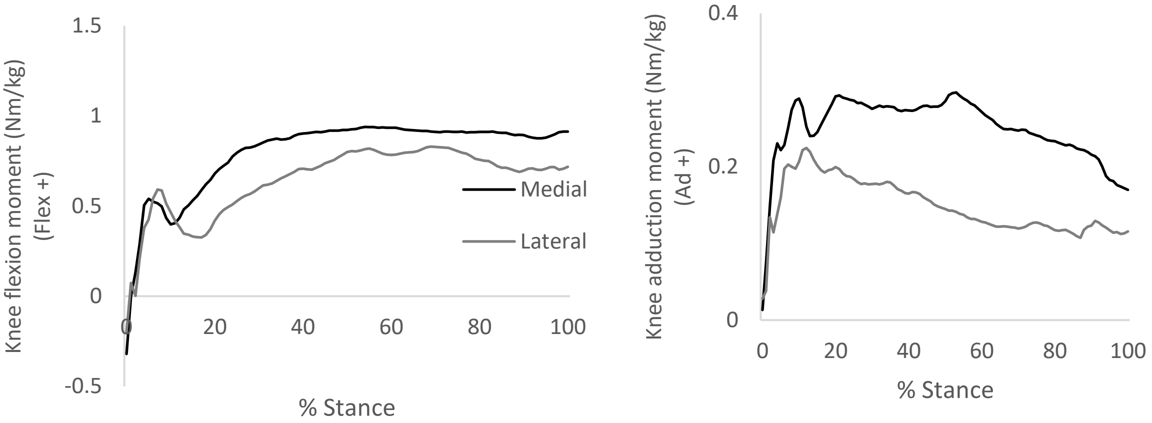


Figure 4.14: Ensemble average sagittal and frontal plane knee moments comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during landing

4.4.4.2 Meniscectomy and healthy comparison

During landing, there was a statistically significant main effect for knee adduction angle ($F_{2,77}$ = -0.442, p > 0.005; Figure 4.15). Lower knee adduction angle was observed in the meniscectomy leg (-0.85 ± 4.66°) compared to both the healthy control group (-3.42 ± 4.73°, p = 0.010) and compared to the contralateral leg (-2.78 ± 5.22°, p = 0.016; Table 4.12). There was a large effect size in the knee adduction angle between the individuals following meniscectomy and the healthy control (ES = 0.91). There was no significant main effect for ankle plantarflexion, knee flexion, hip flexion and hip adduction angles (p > 0.05; Appendix 3). There was a low effect size in ankle plantarflexion, knee flexion, hip flexion and hip adduction angles (ES < 0.5).

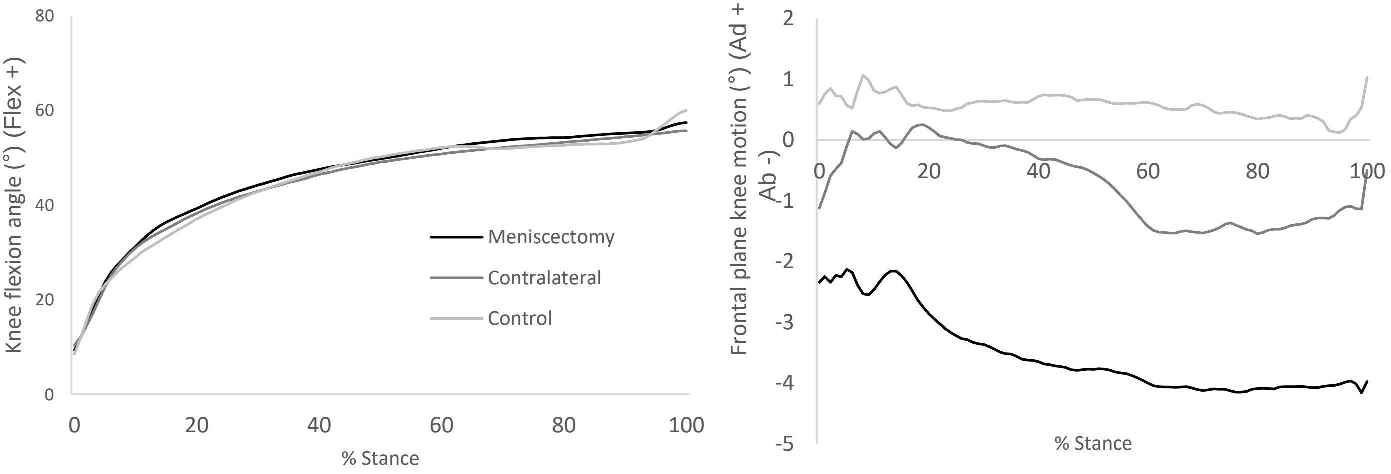


Figure 4.15: Ensemble average sagittal and frontal plane knee motion comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during landing

Table 4.12: Average speed, peak ankle, knee, hip and trunk motion during landing from foot contact until maximum knee flexion (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
	Ankle flexion angle (º)	20.90 ± 6.61	22.50 ± 6.92	19.40 ± 8.29	.754	0.20	.674	0.24	.304	0.41
	Frontal plane knee motion (º)	59.41 ± 13.47	55.43 ± 15.17	57.54 ± 9.76	.880	0.16	.494	0.28	.849	0.17
	Knee adduction angle (º)	-0.85 ± 4.66	2.78 ± 5.22	3.42 ± 4.73	**.010***	**0.91**	**.016****	0.73	.893	0.13
	Hip flexion angle (º)	53.87 ± 16.40	54.98 ± 19.42	49.34 ± 11.47	.616	0.32	.965	0.06	.474	0.35
	Hip adduction angle (º)	-0.17 ± 5.46	1.52 ± 9.08	1.12 ± 6.00	.810	0.22	.810	0.23	.640	0.05
	Trunk lateral flexion angle (º)	4.14 ± 4.39	3.48 ± 4.69	2.38 ± 2.55	.196	0.49	.723	0.15	.405	0.31

There was a significant main effect for maximum knee flexion moment during landing ($F_{2,77}$ = -3.585, p = 0.001; Table 4.13). The knee flexion moment was significantly lower in the meniscectomy leg (1.17 ± 0.42 Nm/kg, p = 0.003) compared to the healthy control group (1.54 ± 0.23 Nm/kg) and compared to the contralateral leg (1.60 ± 0.39 Nm/kg, p < 0.001; Figure 4.16). There was a large effect size in knee flexion moment between individuals following meniscectomy and healthy controls for both the meniscectomy leg (ES = 1.09) and contralateral leg (ES = 1.06). The ankle plantarflexion moments showed a significant main effect during landing ($F_{2,77}$ = -2.580, p = 0.013). There was a significantly lower plantarflexion moment in the meniscectomy leg (1.58 ± 0.35 Nm/kg, p = 0.047) compared to the healthy controls (1.82 ± 0.29 Nm/kg) and between the contralateral leg (1.58 ± 0.38 Nm/kg, p = 0.040) and the healthy control leg. The hip flexion moments showed a significant main effect during landing ($F_{2,77}$ = 3.360, p = 0.002). There was a significantly lower hip flexion moment in the meniscectomy leg (-0.54 ± 0.70 Nm/kg, p = 0.013) compared to the healthy controls (-1.29 ± 0.86 Nm/kg). There was a significantly greater vertical GRF in the contralateral leg (2.23 ± 0.33 BW; p = .022) compared to the meniscectomy leg (2.00 ± 0.40). There was a moderate effect size between the contralateral leg and the meniscectomy leg in vertical GRF (ES = 0.63).

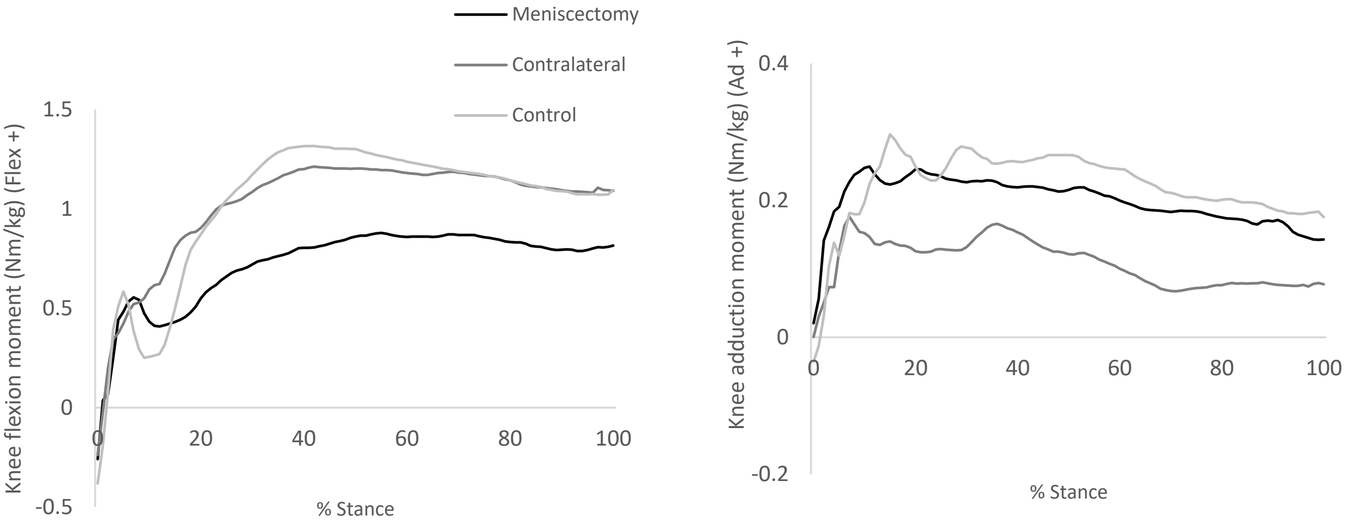


Figure 4.16: Ensemble average sagittal and frontal plane knee moments comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during landing

Table 4.13: Peak ankle, knee, hip moments and vertical GRF during landing between foot contact until maximum knee flexion (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
	Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Ankle flexion moment (Nm/kg)	1.58 ± 0.35	1.58 ± 0.38	1.82 ± 0.29	**.047***	0.75	.997	0.00	**.040*****	0.71
Knee flexion moment (Nm/kg)	1.17 ± 0.42	1.60 ± 0.39	1.54 ± 0.23	**.003***	**1.09**	**.000****	**1.06**	.884	0.19
Knee adduction moment (Nm/kg)	0.44 ± 0.16	0.33 ± 0.29	0.47 ± 0.33	.958	0.12	.243	0.47	.196	0.45
Hip flexion moment (Nm/kg)	-0.54 ± 0.70	-0.94 ± 1.06	-1.29 ± 0.86	**.013***	**0.96**	.217	0.44	.353	0.36
Hip adduction moment (Nm/kg)	1.15 ± 0.49	1.17 ± 0.40	1.11 ± 0.31	.943	0.10	.984	0.04	.881	0.17
Vertical GRF (BW)	2.00 ± 0.40	2.23 ± 0.33	1.97 ± 0.42	.891	0.07	**.022****	0.63	.080	0.69

4.4.4.3 Muscle activation and co-contraction

There was a significant main effect in the co-activation between the extensors and flexors muscles ($F_{2,77} = 7.303$, p = 0.002). The knee extensors were more active compared to the flexors, showing a significantly lower co-contraction ratio in the contralateral leg (0.74 ± 0.16, p = 0.002) compared to the healthy controls (0.26 ± 0.52*;*Table 4.14), with the values being closer to 1. There was also a large effect size in the co-contraction between knee extensor and flexor for both the meniscectomy leg and contralateral leg compared the healthy controls (ES > 0.8).

There was no significant main effect between the net extensor and flexor muscle activation ($F_{2,77}$ = 3.119, p = 0.053; Table 4.14). There was however, a significant increase in the net muscle knee flexor activation (semimembranosus, biceps femoris) in the contralateral leg (0.63 ± 0.45 %MVC, p = 0.007) compared to the healthy controls (0.36 ± 0.12 %MVC). There was a large effect size in the net muscle activation for the flexors in both the meniscectomy leg and contralateral leg compared to the healthy controls (ES > 0.8).

Table 4.14: Co-contraction ratio, sum of net activation of the knee flexors and knee extensors during landing (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
	Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Co-contraction Extensor/Flexor ratio	0.59 ± 0.22	0.74 ± 0.16	0.26 ± 0.52	.059	**<u>0.83</u>**	.058	0.78	**.002*** **	**<u>1.25</u>**
Co-contraction Medial/Lateral ratio	-0.11 ± 0.43	0.16 ± 0.39	0.13 ± 0.48	.163	0.53	.349	0.66	.502	0.07
Net activation knee extensors (%MVC)	1.93 ± 1.20	2.11 ± 1.27	1.43 ± 0.54	.156	0.54	.641	0.15	.070	0.70
Net activation knee flexors (%MVC)	0.63 ± 0.45	0.71 ± 0.33	0.36 ± 0.12	.078	**<u>0.82</u>**	.523	0.20	**.007*** **	**<u>1.41</u>**

4.4.5 Change of direction

4.4.5.1 Medial and lateral meniscectomy comparison

There was no significant main effect in any of the planes or joints when comparing the medial and the lateral meniscectomies (p > 0.05; Figure 4.18). The main outcomes for the knee were reported in Table 4.15. The knee abduction moment was significantly higher in the individuals following lateral meniscectomy (-0.31 ± 0.46 Nm/kg, p = 0.026) compared to the individuals following medial meniscectomy (-0.10 ± 0.56 Nm/kg). There was a moderate effect size for the adduction moment and medial trunk lean (ES > 0.50).

Table 4.15: Peak sagittal and frontal plane knee moments, vertical GRF and lateral trunk lean comparing individuals following a medial and lateral meniscectomy during change of direction (*indicated significance. High effect size was indicated in bold and underlined)

The knee variables during stance phase	Medial meniscectomy		Lateral Meniscectomy		
	Mean, SD		*Mean, SD*	*P value*	*ES*
Knee flexion angle (º)	47.23 ± 11.89		49.11 ± 11.16	.932	0.16
Frontal plane knee motion (º)	-8.56 ± 5.39		-8.87 ± 4.78	.879	0.03
Knee flexion moment (Nm/kg)	1.39 ± 0.39		1.52 ± 0.87	.849	0.19
Knee adduction moment (Nm/kg)	-0.52 ± 0.32		-0.78 ± 0.38	.070	0.74
Trunk lateral flexion angle (º)	-2.36 ± 9.81		-4.04 ± 7.57	.174	0.53
Vertical GRF (BW)	1.57 ± 0.21		1.69 ± 0.27	.232	0.50

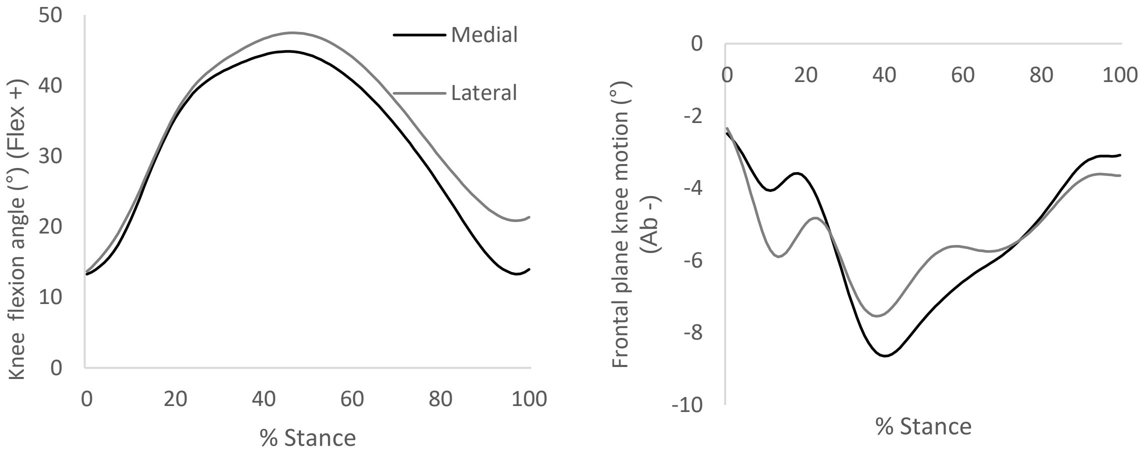


Figure 4.17: Ensemble average sagittal and frontal plane knee motion comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during change of direction

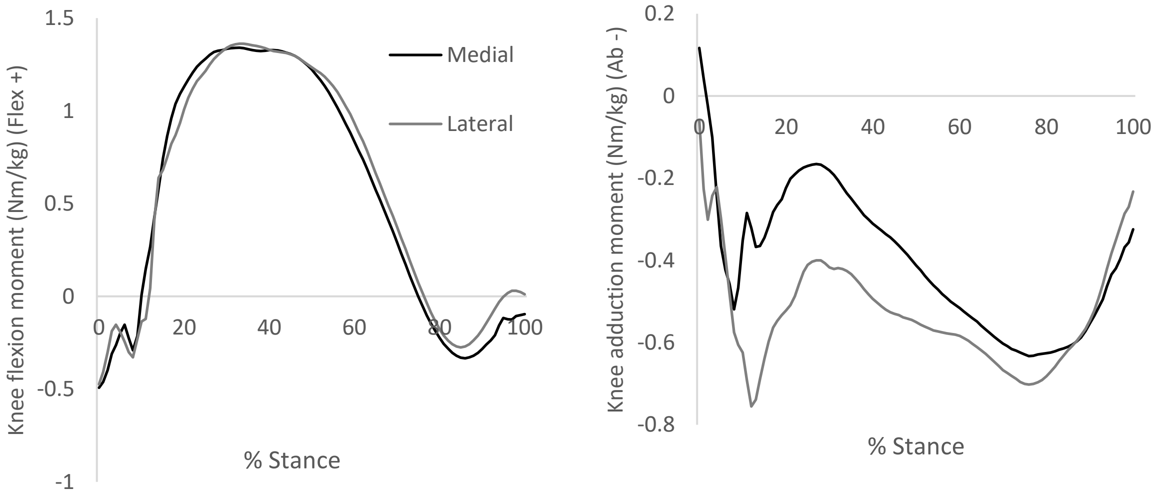


Figure 4.18: Ensemble average sagittal and frontal plane knee moments comparing individuals following medial (n = 13) and lateral (n = 16) meniscectomy during change of direction

4.4.5.2 Meniscectomy and healthy comparison

During the change of direction task, there were no statistically significant main effects for knee flexion or adduction angles ($p > 0.05$; Figure 4.19). There was no significance for ankle plantarflexion angle, hip flexion and hip adduction angle ($p > 0.05$; Table 4.16). There were low effect sizes for all joint angles (ES < 0.5). The trunk flexion angle showed a significant main effect during change of direction ($F_{2,44} = 8.903$, $p = 0.005$). There was significantly greater medial trunk flexion over the standing leg in the individuals following meniscectomy in both the meniscectomy leg (-10.22 ± 7.47°, $p = 0.025$) and contralateral leg (-11.07 ± 7.16°, $p = 0.011$) compared to the healthy controls (-4.59 ± 4.72°). The was also a large effect size in trunk lean angle between the meniscectomy leg and the healthy control (ES > 0.80).

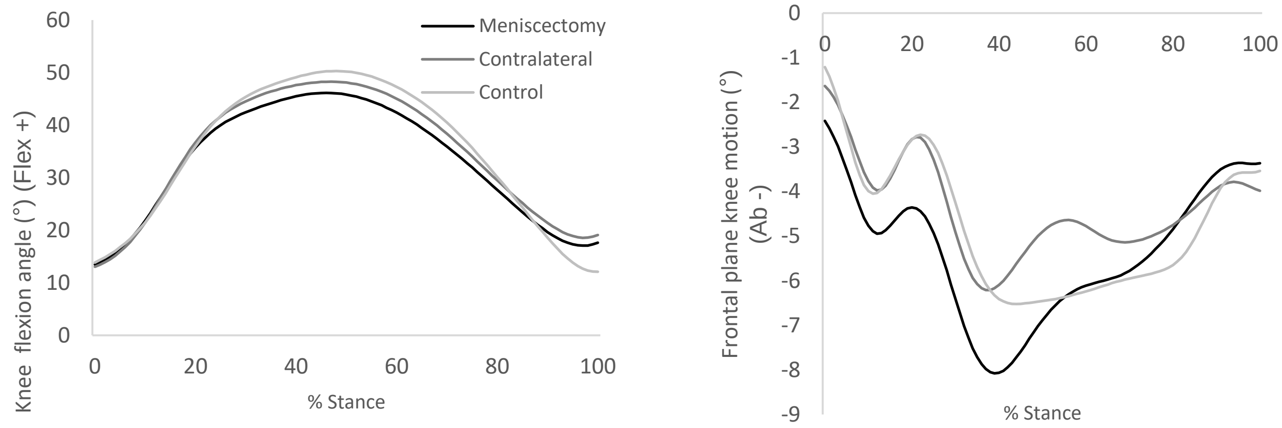


Figure 4.19: Ensemble average sagittal and frontal plane knee motion comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during change of direction

Table 4.16: Average approach and exit speed, peak ankle, knee, hip, pelvis and trunk motion during change of direction (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
	Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Approach Speed (m/s)	3.95 ± 0.60	3.99 ± 0.45	4.18 ± 0.67	.219	0.36	*.956*	0.11	*.456*	0.26
Exit Speed (m/s)	2.34 ± 0.32	2.25 ± 0.26	2.52 ± 0.35	.070	0.54	*.875*	0.24	*.238*	0.34
Ankle flexion angle (°)	9.80 ± 6.38	14.07 ± 8.03	11.87 ± 5.95	.523	0.34	.063	0.59	.568	0.31
Knee flexion angle (°)	48.27 ± 11.33	44.29 ± 18.47	50.25 ± 8.80	.877	0.20	.526	0.26	.311	0.41
Knee adduction angle (°)	-8.74 ± 4.95	-6.69 ± 6.16	-7.57 ± 4.97	.433	0.58	.183	0.48	.598	0.10
Hip flexion angle (°)	42.06 ± 10.90	38.82 ± 15.98	41.16 ± 10.43	.969	0.08	.607	0.24	.808	0.17
Hip adduction angle (°)	-6.55 ± 7.29	-5.30 ± 7.05	-7.37 ± 7.65	.927	0.11	.817	0.17	.608	0.28
Pelvic tilt angle (°)	22.78 ± 7.55	23.15 ± 6.23	21.23 ± 4.68	.679	0.25	.975	0.05	.572	0.35
Trunk flexion angle (°)	-10.22 ± 7.47	-11.07 ± 7.16	-4.59 ± 4.72	**.025***	**<u>0.90</u>**	.750	0.12	**.011*****	**<u>1.07</u>**

There was no significant main effect in the knee flexion and knee abduction moments, nor was there any significant difference in the hip flexion, hip adduction moments and ankle plantarflexion ($p > 0.05$; Figure 4.20). There was, however, a significantly lower plantarflexion moment in the contralateral leg (2.21 ± 0.29 Nm/kg, P = 0.035) compared to the healthy controls (1.89 ± 0.53 Nm/kg). There was a low to moderate effect size in all joint moments during change of direction. There was a moderate effect size (ES = 0.73) in knee flexion moment, showing a reduced knee flexion moment in the meniscectomy leg (1.47 ± 0.71 Nm/kg) compared to the healthy controls (1.89 ± 0.40 Nm/kg).

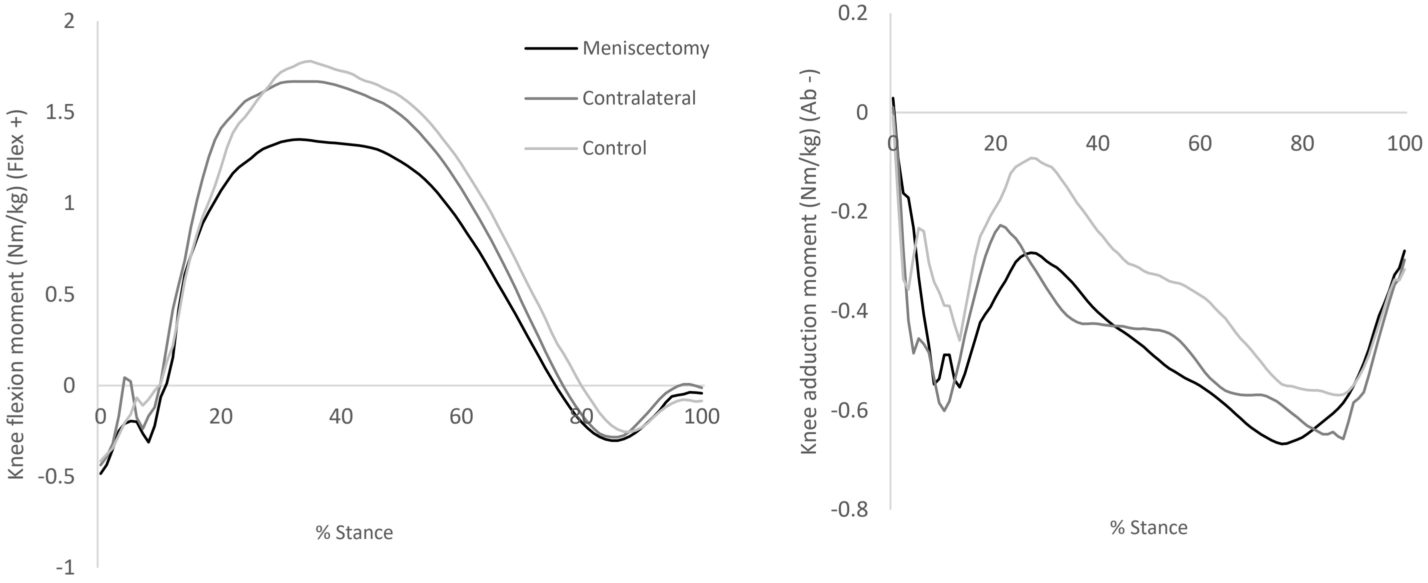


Figure 4.20: Ensemble average sagittal and frontal plane knee moments comparing the meniscectomy leg (n = 29), contralateral leg (n = 29) and control individuals (n = 20) during change of direction

Table 4.17: Peak ankle, knee, hip moments and vertical GRF during change of direction (*indicated the results were significantly different between meniscectomy (Meni) and control ** indicated significance between meniscectomy and contralateral (Contra) * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

	Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
	Ankle flexion moment (Nm/kg)	2.01 ± 0.41	2.21 ± 0.29	1.89 ± 0.53	.586	0.25	.218	0.56	**.035*****	0.75
	Knee flexion moment (Nm/kg)	1.47 ± 0.71	1.80 ± 0.64	1.89 ± 0.40	.059	0.73	.153	0.49	.866	0.17
	Knee adduction moment (Nm/kg)	-0.67 ± 0.37	-0.59 ± 0.46	-0.53 ± 0.63	.366	0.27	.529	0.19	.724	0.11
	Hip flexion moment (Nm/kg)	2.30 ± 0.94	2.36 ± 1.15	2.07 ± 0.89	.736	0.25	.971	0.06	.615	0.28
	Hip adduction moment (Nm/kg)	0.42 ± 0.45	0.39 ± 0.78	0.78 ± 0.79	.197	0.56	.990	0.05	.160	0.50
	Vertical GRF (BW)	1.63 ± 0.25	1.61 ± 0.41	1.73 ± 0.28	.276	0.38	.819	0.06	.330	0.34

4.4.5.3 Muscle activation and co-contraction

There was a significant main effect in the co-contraction ratio between the extensors (vastus medialis) and the flexors (biceps femoris) in for change of direction when comparing the individuals following meniscectomy to the contralateral leg and the healthy controls ($F_{2,77}$ = 12.194, p < 0.001). The extensors were seen to be more active than the flexors, showing a significantly greater co-contraction ratio in the meniscectomy leg (0.27± 0.30, p < 0.001) and contralateral leg (0.33 ± 0.31, p = 0.001) compared to the healthy controls (0.78 ± 0.36;Table 4.18). There was also a large effect size for the co-contraction ratio between extensor and flexors muscles (ES >0.8). There was a significant main effect in the co-contraction ratio between the medial (vastus medialis) and the lateral (vastus lateralis) extensor muscles ($F_{2,77}$ = 30.233, p < 0.001). There was a significantly greater lateral knee extensor muscle co-contraction ratio seen in the meniscectomy leg (-0.11 ± 0.39, p < 0.001) and contralateral leg (-0.07 ± 0.37, p < 0.001) compared to the healthy controls (0.71± 0.25). There was a large effect size in the co-contraction ratio between the medial and lateral extensor for change of direction (ES >0.8).

There was no significant main effect between the net extensor and flexor muscle activation in late stance ($F_{2,77}$ = 1.196, P >0.05; Table 4.18). There was however, a significant increase in the net muscle knee extensor activation (vastus medialis, vastus lateralis) in the contralateral leg (1.75 ± 0.63 %MVC, p = 0.022) compared to the healthy controls (2.47 ± 0.92 %MVC).

Table 4.18: Co-contraction ratio, sum of net activation of the knee flexors and knee extensors during change of direction (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

Variable	**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
	Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Co-contraction Extensor/Flexor ratio	0.27± 0.30	0.33± 0.31	0.78 ± 0.36	**.000***	**<u>1.54</u>**	.616	0.20	**.001*****	**<u>1.34</u>**
Co-contraction Medial/Lateral ratio	-0.11 ± 0.39	-0.07 ± 0.37	0.71 ± 0.25	**.000***	**<u>2.50</u>**	.731	0.11	**.000*****	**<u>2.47</u>**
Net activation knee extensors (%MVC)	2.37 ± 1.40	1.75 ± 0.63	2.47 ± 0.92	.819	0.08	.123	0.57	**.022*****	**<u>0.91</u>**
Net activation knee flexors (%MVC)	1.36 ± 0.67	1.49 ± 0.77	1.06 ± 0.51	.207	0.50	.586	0.18	.111	0.66

4.4.6 Functional measures

There was a significant main effect between the isometric peak torque ($F_{2,77} = 7.057$, P = 0.002). There was a significantly lower peak torque in the individuals following meniscectomy (2.46 ± 0.56 Nm/kg, P = 0.002) and contralateral leg (2.77 ± 0.80 Nm/kg, P = 0.045) compared to the healthy controls (3.23 ± 0.59 Nm/kg; Table 4.19). There was a large effect size in peak torque between the individuals following meniscectomy and the healthy controls (ES > 0.8). There was a significantly lower reach distance during the Y balance task in the anterior direction in the meniscectomy leg (97.03 ± 6.81 %Leg length, P = 0.048) compared to the control leg (103.71 ± 3.52 %Leg length). There was also a significant reduction in reach distance during the Y balance task in the posterolateral direction in the meniscectomy leg (93.33 ± 4.35 % Leg length, P = 0.049) compared to the control leg (97.40 ± 5.77 % Leg length) and the contralateral leg (98.15 ± 6.66 % Leg length, P = 0.033). There was a large effect size in reach distance between the meniscectomy leg and the healthy leg during anterior reach (ES = 1.23), and there was a large effect size in the contralateral leg compared to the healthy controls for anterior reach distance (ES = 1.35) and mediolateral reach distance (ES = 1.39).

Table 4.19: Peak isometric torque and average peak y-balance reach distance comparing the meniscectomy leg, contralateral leg and control individual (*indicated the results were significantly different between meniscectomy and control ** indicated significance between meniscectomy and contralateral and * indicated significance between contralateral and control. High effect size was indicated in bold and underlined)**

Variable		**Meni**	**Contra**	**Control**	**Meni vs Control**		**Meni vs Contra**		**Contra vs Control**	
		Mean, SD	Mean, SD	Mean, SD	*P Value*	ES	*P Value*	ES	*P Value*	ES
Peak Torque (Nm/kg)		2.46 ± 0.56	2.77 ± 0.80	3.23 ± 0.59	**.000***	**1.34**	.120	0.45	**.045*****	0.65
Y-Balance (% leg length)	Anterior	97.03 ± 6.81	97.54 ± 5.43	103.71 ± 3.52	**.048***	**1.23**	.763	0.08	.185	**1.35**
	Posterolateral	93.33 ± 4.35	98.15 ± 6.66	97.40 ± 5.77	.428	0.33	.384	0.43	.477	0.12
	Mediolateral	91.11 ± 9.01	87.22 ± 5.89	95.56 ± 6.08	.710	0.58	.123	0.51	.074	**1.39**

4.5 Discussion

Despite information about contributing factors and underlying mechanisms of meniscus injuries and the progression to knee OA, there is still a lack in the current literature on specific movement patterns and the effect of how loads are applied in sports in individual’s post-meniscectomy. To the authors knowledge, this is the first study to look at the biomechanical differences between individuals following medial and lateral meniscectomy and a combination of sport-specific tasks such as running, landing and particularly change of direction in individuals following meniscectomy. Therefore, the first aim of this study was to compare knee loading and offloading strategies between individuals following medial meniscectomy and individuals following lateral meniscectomy. The second aim was to analyse knee loading during functional and sport-specific tasks and the third objective was looking at outcomes that influence knee loading following meniscectomy such as balance, muscle weakness and activity, kinesiophobia, and quality of life. The findings show that there were no significant differences in outcomes between individuals following medial and lateral meniscectomies. In relation to knee loading, there were significant differences in individuals following meniscectomy in sport-specific movements compared to healthy controls. An increase in knee loading was found with the reduced knee flexion moment (KFM), increased muscle activation, joint stiffness, and poor self-reported outcomes following meniscectomy compared to healthy controls were observed. In this study, the external knee adduction moments (EKAM) were not significantly greater as demonstrated in previous research, which may be due to the early stages of rehabilitation and could be indicators for future OA progression (Hall et al., 2015; Sturnieks et al., 2008; Thorlund et al., 2016).

4.5.1 Medial and lateral meniscectomy comparisons

When considering knee loading, the medial and lateral compartments of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004). On the contrary to H_1 hypothesis, there were no significant differences in kinetic or kinematics for running, landing and change of direction tasks between the individuals following medial meniscectomy and the individuals following lateral meniscectomy. During walking there was no significant differences between medial and lateral meniscectomies in any lower limb joints. There was however, a large effect size (ES = 0.83) in the EKAM during walking. Wilken et al., (2012) analysed the meaningful detectable difference in walking and found for the EKAM in early stance the meaningful detectable difference was 0.10 Nm/kg and in late stance it was 0.15 Nm/kg. In the current study, there was a difference of 0.11Nm/kg in late stance for EKAM between individuals following medial meniscectomy and individuals following lateral meniscectomy. The difference was also greater than the 0.06 Nm/kg seen in the SEM of the repeatability study, showing that the results have importance and therefore with a larger population size may show significance.

The greater EKAM in the individuals following lateral meniscectomy could be due to offloading mechanisms for the lateral compartment such as the greater lateral trunk lean to reduce the loading on the lateral compartment, shifting the GRF medially and therefore increasing the EKAM. In the current study, there was a greater lateral trunk lean in the individuals following meniscectomy during walking, running and landing compared to the healthy controls, showing an offloading mechanism taking place, which could explain the lower than expected EKAM. That linked with the increased lateral co-contraction of the leg aids in offloading the medial compartment of the knee. Fox et al., (2018) highlighted that proximal motion at the trunk appears to have a large effect in managing the loads experienced at the knee following ACL reconstruction. Lateral flexion of the trunk over the weight bearing ‘plant’ leg during the change of direction task were frequently linked to increased external knee abduction moment as it shifts the centre of mass away from the midline of the body, increasing the lever arm distance of the force vector relative to the knee joint axis (Mornieux et al., 2014, Jones et al., 2016). Increased trunk lean may be necessary to help evade an opponent (feint) during match play, although is also linked to re-injury as individuals overcompensate (Kristianslund et al., 2014). Therefore, may not be recommended for individuals following meniscectomy, rather the trunk should stay as upright as possible (Dempsey et al., 2009). As the outcomes for all tasks did not see any significant difference in isolation when looking at the results comparing individuals following a medial meniscectomy and individuals following a lateral meniscectomy, further analysis was conducted with both medial and lateral groups combined.

4.5.2 Comparison of knee loading between meniscectomy and healthy individuals

Once an individual sustains a meniscal tear, the most common treatment is a partial meniscectomy, leaving the cartilage exposed and increasing knee loading through the whole tibiofemoral joint (Barrios et al., 2012, Hurwitz et al., 2002; Asay et al., 2018). On contrary to previous research, in the current study, there were no significant differences in the EKAM during walking when comparing individuals following meniscectomy to healthy controls. The lack of significant differences in EKAM could be explained due to the length of time following meniscectomy as EKAM may increase over a longer period of time. In the current study, on average the length of time following meniscectomy was six months, in comparison to the two years of Hall et al., (2014) and the 22 years of Hulet et al., (2015). The EKAM value during walking in the current study (0.31 Nm/kg) was similar to that found in several OA studies (0.24

– 0.38 Nm/kg) where the individuals were in the early stages of OA and could still exercise highlighting that although there was no significant difference in the individuals following meniscectomy, the EKAM was still similar to that of early stages of OA (Gerbrands et l., 2017; Khlaifat et al., 2015; Jones et al., 2013). In several studies which looked at reducing pain in later stage OA, the EKAM was seen to be higher averaging between 0.48 to 0.57 Nm/kg, indicating that following meniscectomy they are following similar trends in knee loading as individuals with knee OA (Fu et al., 2015; Arazpour et al., 2013; Toriyama et al., 2011; Jones et al., 2013).

In the current study, during running, the findings were comparable to what was found by Hall et al., (2017), however the EKAM was greater in both their meniscectomy group and control group compared to the current study. Hall et al., (2017) showed an EKAM of 0.71 Nm/kg at three months post-meniscectomy compared to 0.64 Nm/kg in healthy controls. In the current study at six months post-meniscectomy the EKAM was seen to be 0.64 Nm/kg which was the same as the control group in Hall et al., (2017) study, whereas the healthy controls EKAM was 0.54 Nm/kg. The lower EKAM values in the current study, could be due to the BMI and age being greater in Hall et al., (2017) study. Englund and Lohmander (2004) found that there was a correlation with joint degeneration and increased BMI (>30), highlighting that individuals with obesity showed greater chances of developing knee OA which may be due to the increased loads applied by the body weight. Voinier at al., (2020) found that greater tibiofemoral loads were also seen in individuals with a moderate to high BMI and therefore, this should be considered, specifically when individuals have not been able to exercise regularly due to treatment. In the current study, there was not a significant difference in BMI between the individuals following meniscectomy and the healthy controls, indicating that the lack of significant differences in EKAM could be due to the individuals still having a BMI < 30. Additionally, there was a significant difference in age in the current study showing that the individuals following meniscectomy were on average five years older compared to the healthy controls, however this is not enough to cause significant differences in knee joint loading and risk of degeneration.

In the current study, during running, the foot strike index indicated that the individuals following meniscectomy were heel strikers as their COP at touchdown was 28.80% from the heel to toe, indicating a rear-foot contact and the healthy controls were more mid-foot strikers as indicated by the 41.75% of COP from the heel (Santuz et al., 2017). In previous research, EKAM has been found to be smaller during 60° change of direction tasks when performed with an apparent fore-foot strike pattern compared to a rear-foot strike pattern (Kristianslund et al., 2014; Yoshida et al., 2016). During the 90° change of direction task, the individuals following meniscectomy had an ankle dorsiflexion of on average 9.80° which suggests a forefoot strike pattern as shown by Almeida et al., (2015), with lower ankle dorsiflexion indicating a forefoot strike pattern. Fox et al., (2018) suggested that a with a forefoot touchdown during running, toe landing aids athletes to better align the lower extremity to reduce the moment arm of the ground reaction force in the frontal plane. In the current study, there was a greater knee abduction moment during the change of direction task can be seen although a forefoot strike is present seen by the ankle dorsiflexion angle. There was also a greater adduction angle at the knee during change of direction and a greater trunk lean over the supporting knee, which would aid in shifting the GRF and therefore greater the knee abduction moment. Mündermann et al., (2008), analysed the impact of medio-lateral trunk lean and found that it can be used to lower the knee adduction moment in healthy individuals. Lateral trunk lean was observed to be greater following meniscectomy during all tasks, with a greater increase in trunk lean in the more dynamic tasks such as running and landing. This supports previous research showing a clear lateral trunk lean over the support leg (Hunt et al., 2007; Hall et al., 2014).

In the current study, KFM was significantly lower in the meniscectomy group compared to healthy controls for walking (29%), running (25%), landing (32%) and change of direction (29%). The significantly reduced KFM was seen to have a greater difference than that stated by the repeatability SEM results where the SEM was 0.11 Nm/kg and the smallest difference in the KFM for all tasks was 0.23 Nm/kg in late stance, showing that the outcomes seen in the current study are greater than the error and therefore can be taken as meaningful differences.

When looking at the KFM from Hall et al., (2017), where the KFM was reduced at three months post-meniscectomy (1.86 Nm/kg) but increased at two years post-meniscectomy (2.13 Nm/kg) to similar values as the healthy controls (2.03 Nm/kg). The values again line up with those in the current study showing the KFM in the meniscectomy at six months post-meniscectomy were lower (1.67 Nm/kg) compared to the healthy controls (2.08 Nm/kg). This allows us to hypothesise that knee loading shifts in the early stages of rehabilitation due to muscle weakness and that the initial KFM reduction may just be a short-term effect to alleviate post-surgical pain as seen in Hall et al., (2017). The KOOS self-reported pain score showed that individuals following meniscectomy perceived significantly greater pain in their knee compared to healthy controls in the current study and may be linked to quadriceps muscle weakness as seen in previous ACL studies following surgery (Thomas et al., 2016).

It is understood that reductions in the knee flexion moment are partially caused by changes in the movement patterns such as greater knee flexion angle in early stance to avoid full extension and greater moments as the load is amplified (Bae et al., 2012). If the knee flexion angle is greater whilst running, an individual can accept greater load at the knee and therefore have better eccentric load dissipation. In the current study, knee flexion angle was not shown to be significantly different between individuals following meniscectomy and healthy controls during running, however, significant differences were observed in the antero-posterior centre of pressure, offering a potential explanation for the differences in the reduced KFM. With the centre of pressure being placed more posterior highlighting rear foot running, the GRF lever arm would have been behind the knee and closer to the knee joint centre of mass, therefore reducing the KFM.

In the current study, the main significant differences in knee joint motion were in the sagittal plane for walking and running. In the meniscectomy group, there was a significantly greater ankle dorsiflexion angle during the propulsion phase, a significantly reduced hip extension angle and a reduced knee flexion angle. The difference in sagittal plane joint motion highlights compensatory mechanisms that are being used bringing the leg into a more stiff stance which may be due to muscle weakness and can be linked to fear of movement shown by the TSK (Steele et al., 2012) and is often implemented to help ground clearance with a stiffer knee (Yavuzer et al., 2011). The greater ankle dorsiflexion in late stance is used to increase the push off momentum with the reduced hip extension, to help protect the knee and reduce following meniscectomy. Knee motion is an important outcome measure for individuals who have suffered an injury and following surgery, as reduced range of motion is often linked to pain, swelling, stiffness, muscle weakness and fear avoidance (Lau et al., 2018).

Although there was not a significant difference in knee and hip flexion angle during landing, individuals following meniscectomy showed slightly greater knee (4°) and hip (2°) flexion angle during landing compared to healthy controls which may be due to softer, more careful landing strategy being used. Slater et al., (2015) analysed landing strategies in gymnastics to reduce GRF and found that increased hip and knee flexion helped reduce the forces going through the lower limb. In addition, the hip flexor moment was significantly greater in the individuals following meniscectomy, which might indicate increased activity of the hip stabilisers such as the glute medius muscles, whilst the knee flexion moment was significantly reduced. The knee flexion angle was not significantly different in the individuals following meniscectomy compared to the healthy controls which could indicate that individuals following meniscectomy were able to perform the landing task without restrictions during dynamic sports. A more-sport specific landing and jumping tasks such as landing from the counter-movement-jump should be analysed which contains a greater momentum and therefore can be replicated in a dynamic sporting environment rather than just in a controlled laboratory environment. Ford et al., (2011) supported the findings in the current study and adopted a softer landing strategy at three months post-lateral meniscectomy, which was found by the greater knee flexion angle when landing compared to in healthy controls. The landing strategy applied by the individuals who participated in the current study was controlled as to avoid pain and discomfort. Individuals were instructed to drop off the box and land with a bent knee, this may be the reason why the landing task was the only task that did not show a stiff leg strategy. In future, the landing strategy should not be influenced by the researcher and the outcomes may have been slightly different. Several studies looked at the changes in knee kinematics during landing following a ACL injury and found similarly that muscle weakness was an important cause in changes in knee kinematics whilst landing, which caused a stiffer landing mechanisms with a reduced knee flexion angle (Ward et al., 2018; Lisee et al., 2019).

4.5.3 Muscle activation, weakness, and balance

The main limitation of using solely frontal and sagittal plane moments to interpret joint loading is that external joint moments do not account for the contribution of muscle forces to joint loading (Starkey et al., 2020). In the current study, it was found that there was no increase in the co-contraction ratio between extensors and flexors and there was no significant difference when looking at the comparison to healthy controls during walking. This was in agreement with Sturnieks et al., (2011) study where although there was a greater lateral co-contraction and a greater hamstring muscle activation, knee extensor and flexor co-contraction was not significantly different compared to healthy controls. When comparing these findings to OA studies, they show the opposite results, as co-contraction following OA has been found to be greater in the extensors compared to flexors to brace the knee in anticipation of pain (Hortobagyi et al., 2005; Bouchouras et al., 2015; Na and Buchanan., 2019). During running, however, the knee extensors were seen to be more active than the flexors in the co-contraction ratio in the current study. There was a significantly greater knee extensor/flexor co-contraction ratio in the meniscectomy individuals compared to the controls in early stance of running. The extensors also show greater net activation in early stance in the meniscectomy leg (2.47 %MVC) compared to the healthy controls (2.06 %MVC) which support that at impact the meniscectomy individuals brace their knee more, increasing the activation and therefore a greater co-contraction ratio. During landing, there was a 56% lower extensor/flexor co-contraction ratio in the meniscectomy individuals compared to the healthy control, which can be explained as both the knee extensors and knee flexors show greater net muscle activation during landing in the individuals following meniscectomy compared to healthy controls. There was a significantly increased knee flexor net activation during landing which goes back to the supporting findings in ACL research where greater knee flexor activity have been used as an effective compensatory mechanism to stabilise the knee, improve function, activity levels, and enable normal kinematics (Boerboom et al., 2001).

When considering the medial compared to lateral co-contraction, the current study showed a greater lateral relative to medial co-contraction in both the meniscectomy leg and the contralateral leg compared to matched controls (Heiden et al., 2009). Sturnieks et al., (2011) reported that greater lateral co-contraction relative to medial is a compensatory mechanism often seen in individuals with knee OA to try and reduce medial knee loading and lower the EKAM. This could help explain the lower than expected values for EKAM in the current study and could cause the lateral shift of the GRF moving the load away from the medial compartment. The greater lateral co-contraction highlights that there is greater loading in the knee when considering the reduced knee flexion moments and stiffer gait in unison, which allows the H_3 hypothesis to be accepted stating that there was a significant increase in knee loading during dynamic tasks in individuals following meniscectomy.

In the current study, there was also a significantly different medial/lateral co-contraction during the change of direction task, showing a greater lateral co-contraction in the individuals following meniscectomy compared to the healthy controls. The healthy controls had a greater medial knee extensor activation and the individuals following meniscectomy had greater lateral knee extensor activation bilaterally. The greater lateral activation of the knee extensors could be linked to increased trunk lean over the knee, aiding in offloading the medial compartment, potentially explaining the lower than expected EKAM. Bencke et al., (2018) did a literature review, looking at muscle activation during change of direction and landing tasks and the link to ACL injury. The review found greater lateral knee extensor activation during change of direction, which was linked to increased knee abduction and was identified as being a risk factor for sustaining non-contact ACL injury (Hewett et al., 2005).

During a change of direction, the swing limb is placed laterally, away from the stance limb, toward the new direction of movement. Studies have shown that during change direction tasks, the braking forces (anterior/posterior GRF) increase during early stance due to the need to decelerate to change direction (Rand and Ohtsuki, 2000). These breaking forces are associated with increased quadriceps activation. This is seen in the current study as the quadriceps activation increases with change of direction, compared to walking and landing. The contralateral leg in the meniscectomy individuals during landing had greater knee extensor activation compared to meniscectomy leg and there was greater medial activation whereas in the meniscectomy leg there was greater lateral contraction which may align with pain and wanting to offload the medial compartment of the affected knee. There was also increased quad and hamstring activation in the meniscectomy leg and contralateral leg. There was a significant increased hamstring activation in the contralateral leg compared to the control.

Higher overall knee muscle activation has previously been reported in clinical populations such as individuals following meniscectomy (Glatthorn et al., 2010; Sturnieks et al., 2011), individuals with knee OA (Lewek et al., 2004) and individuals following an anterior cruciate ligament injury (Boerboom et al., 2001). In the current study, a greater knee extensor activation was found in early stance of walking compared to healthy controls. Equally greater knee flexor activation was seen in late stance as the individuals would be preparing for swing and where the hamstring is most active. There was a large effect size in the knee extensor and flexor net muscle activation which aligned with the statistical significance highlights the extent of the difference in findings. In early stance of running, there was a 17% greater net extensor activation in the meniscectomy leg compared to the healthy controls and in late stance there was a 60% greater knee flexor activation which aligns what would be expected during running showing great extensor activation during the early stance phase at impact and greater hamstring activation during the late stance phase of running (Besier et al., 2003).

The greater net muscle activation could be due to a bracing strategy being used in anticipation of the knee loading for fear- avoidance (Jones et al., 2015). The fear-avoidance model often occurs in relation to the fear of pain or with athletes the fear of re-injury, which therefore causes maladaptive and restrictive compensatory mechanisms to occur to avoid anything that may cause the individuals pain or re-injury (Fischerauer et al., 2018). Sturnieks et al., (2011) found similar results stating that the quadriceps and hamstring activity, relative to the MVC was greater in individuals following meniscectomy compared to control throughout different parts of the stance phase. The greater muscle activity has been hypothesised to be used to brace the knee joint and is mostly seen in correlation with a stiffer leg during walking which is generally due to pain, kinesiophobia or muscle weakness also seen in this study (Starkey et al., 2020). Özmen et al., (2017) found that there was a clear link among quadriceps muscle weakness, increased pain, increased stiffness and kinesiophobia in individuals with OA.

The knee extensors show a significant difference but showing a reduced knee extensor activation in the meniscectomy individuals compared to the control during the change of direction task, which demonstrates that pain might result in a quadriceps avoidance strategy and is capable of modulating the movement pattern significantly (Henriksen et al., 2007; Henriksen et al., 2009). Overall reduced co-contraction of the extensors and flexors might result in knee instability and thus also might be responsible for the development of pain and the greater reduction and variability of the knee flexor moment (Besier et al., 2003; Henriksen et al., 2007; Henriksen et al., 2009). The greater extensor muscle activation during the landing and change of direction task could also be a compensatory strategy to reduce knee joint forces during painful activities (Nadeau et al., 1997).

Sturnieks et al., (2011) found that the hamstrings muscle group, on average was 40% greater following meniscectomy compared to healthy controls during walking. In the current study, the hamstring showed a greater activity in the meniscectomy leg compared to control with a minimum of 20% increased hamstring activity during change of direction and an increase of 60% in the running task. During walking in accordance with Sturnieks et al., (2011) study the hamstring was 40% more active in individuals following meniscectomy compared to healthy controls. The hamstrings have been stated to work as a synergist for the ACL to help in stabilisation and protecting the knee joint during landing and change of direction in ACL injured individuals (Ebben et al., 2010; Zebis et al., 2016). ACL injuries often occur alongside meniscus injuries, therefore, it can be assumed that the muscle activation may have the same benefits and detriments in meniscectomy individuals as seen in ACL individuals. In the current study, there is greater hamstring activation during running, landing and change of direction in individuals following meniscectomy compared to control.

Muscle weakness is also interconnected with other muscular dysfunctional factors, such as atrophy (Frontera and Ochala., 2015). Furthermore, poor neuromuscular activation can result in reduced muscle strength and power (Hewett et al., 2007). Knee injuries can lead to an increased muscle inhibition, an impaired neuromuscular activation or a reduced muscle mass after immobilisation and thereby result in muscle weakness (Karatzaferi and Chase, 2013). Muscle weakness and reduced neuromuscular function as shown by the balance task could be seen in the current study following meniscectomy. In the individuals following meniscectomy lower isometric muscle strength of 31% was present six months post-meniscectomy compared to healthy controls and a difference of anterior balance by 7% in the meniscectomy leg compared to healthy controls. Studies showed that quadriceps weakness is a common problem with injury and the weakness of the vastus medialis has been frequently addressed in patellofemoral pain studies (Callaghan et al., 2014; Lin et al., 2010). A weak vastus medialis is assumed to be associated with an increased lateral pull on the patella increasing knee joint loading (Sawatsky et al., 2012). In the current study, during net muscle activation, a weakness of the muscles was not present, however it was shown that the lateral knee extensor (vastus lateralis), was more active than the medial knee extensor, supporting the findings seen in the patellofemoral pain studies.

In the current study, there was a significantly lower isometric strength in the meniscectomy leg (31%) and contralateral leg (17%) in the individuals following meniscectomy compared to the healthy controls, which is considered to be a clinically relevant amount as it is more than 10% (Vaidya et al., 2018). Ericsson et al., (2009) found that hamstring strength was not reduced following meniscectomy. However, the quadriceps strength was still 9% lower in the meniscectomy leg compared to the contralateral leg, but after a four-month functional exercise program, quadriceps strength was fully regained. When compared to the repeatability study, the difference in isometric strength also shows a greater difference as the error of 0.30 Nm/kg compared to the healthy controls. The minimal detectable difference was also stated by Kean et al., (2010) to be 0.33 Nm/kg. In the current study the isometric strength difference between the individuals following meniscectomy and the healthy controls was 0.77 Nm/kg, showing a greater difference than the SEM in the current repeatability study and the minimal detectable difference in Kean et al., (2010) study. This accepts the H_5 hypothesis showing that there was a reduction in muscle strength following meniscectomy compared to healthy controls. Hall et al., (2015) undertook a review on muscle strength following meniscectomy and found that there was reduced muscle strength following six months, whereas at two years post-meniscectomy the muscle strength increased again to a similar level compared to healthy controls. Ganderup et al., (2017) highlighted that three months following meniscectomy there was reduced isometric quadriceps strength, this was however not evident after one year. There was also a significant difference between the contralateral limb and the healthy controls, showing that although one leg is stronger in individuals following meniscectomy, bilateral muscle weakness was present. The strength deficit seen in the current study, shows that the current individuals following meniscectomy would not be allowed to go back to competitive sport and are at a higher risk of re-injury (Noyes and Barber-Westin., 2019). Muscle strength recovery is considered important for young individuals after an arthroscopic surgery to regain the capacity to participate in sports (Ericsson et al., 2006; Pietrosimone et al., 2016). Ericsson et al., (2006) stated that four years following meniscectomy muscle weakness is still present and found that individuals with less weakness also showed less pain and a better quality of life, highlighting the importance of muscle strength even in the long term.

Quadriceps weakness also leads to reduced eccentric control, reducing the ability for the knee to absorb shock and stabilise (Lewek et al., 2004). Eccentric muscle strength although important was not collected during the current study, as the results for the data collected on the isokinetic dynamometer was found to be unreliable, particularly without a familiarisation period as the task is often too uncomfortable for individuals where they have to produce a maximum force on a fully extended leg. Spencer et al., (2020) found that quadriceps strength and force steadiness during knee flexion in ACLR individuals was due to the quadriceps not being able to contract for a prolonged period of time. This can be supported by the study when looking at the Y-balance results showing a significantly reduced reach distance (97.03 % leg length) in the individuals following meniscectomy compared to the healthy controls (103.71 Reach % leg length) due to the lack of control of the standing leg to support the forward lean motion. This suggests that initial rehabilitation and muscle weakness are highly important when considering movement changes and loading alterations. Early rehabilitation to avoid immediate muscle atrophy and maintain strength is a key factor for individuals returning to full function and potentially the return to physical activity at the desired level. Magyar et al., (2012) analysed perturbations in the knee to analyse balance in individuals following meniscectomy at three-month post-op and 12 months post-op compared to healthy controls. They found that individuals following meniscectomy were significantly worse at dealing with multidirectional perturbations compared to healthy controls even at 12 months post-op. Mallious et al., (2011) found that following meniscectomy both balance and functional capabilities were reduced compared to the contralateral leg up to two years following meniscectomy. Balance has also been shown to be a indicator for knee joint degeneration and therefore, can be used as a precursor for knee OA following meniscectomy (Hatfield et al., 2016; Kim et al., 2018; Porter et al., 2016).

4.5.4 Physical activity following meniscectomy

Individuals that aim to return to full competitive sport as soon as possible post-meniscectomy place a high demand on meniscus function to manage loads following surgery (Eberbach et al., 2018). After analysing the physical activity survey, the data showed that individuals following meniscectomy can regain some level of physical activity, however, the level of activity only increased from a low level of activity post-injury (3.6) to moderate level of activity post-surgery (5.4). The level of activity was still significantly lower than the pre-injury level of activity which started at a high level (8). The physical activity survey represents a level of function and although the level of activity increased following surgery the type of activity itself changed. Most individuals went from participating in a dynamic sport such as football, rugby or netball, to changing their activity either solely training in the gym or running as their main weekly activity due to fear of re-injury or not feeling fit enough.

In the current study, 87% of individuals who previously participated in competitive sport were not able to return to their sport at their previous level six months post-meniscectomy which may be linked to muscle weakness, kinesiophobia or the KOOS pain score. Roos et al., (2000) found that from 74 individuals 63% of them participated in sport before injury, however following meniscectomy surgery only 30% continued. Brophy et al., (2009) found that the career length was shortened substantially in American football athletes following a meniscectomy. The two-year follow up study that found 54.4% of individuals either needed a follow up surgery or developed OA and therefore becoming unable to compete at the same level of activity as before (Brophy et al., 2009). Ekhtiari et al., (2018) stated that out of 244 individuals who had undergone a meniscectomy, 80.4% of them returned to their preoperative level playing their sport as soon as 4.3 months post-rehabilitation, however this can be related to the individuals having a very good and comprehensive level of physiotherapy as they were training at a high level.

Lack of rehabilitation following ACL reconstruction, specifically including muscle strength, neuromuscular function and range of motion was highlighted by Noyes and Barber-Westin., (2019) to lead to reinjury as sport specific tasks are not targeted in general rehabilitation programmes. The individuals in the current study, were all physically active before the injury and tore their meniscus during their sport which included football, rugby, netball, bouldering and skiing. Due to the variety of these sports, rehabilitation should have been individualised including sport specific exercises for landing, jumping, pivoting, and any other exercise related specifically to their sport. Unfortunately, as shown by our rehabilitation questionnaire, the rehabilitation programme in the National Health Service (NHS) either gave a standard sheet with only a few key exercises on it following surgery or rehabilitation starts once every two weeks at a 2-3 month post-surgery point and is not sport specific. Individuals are therefore not prepared to return to their specific sports. Wilk et al., (2019) highlighted that rehabilitation has become a large challenge due to limited visits allowed to the patient, partly due to the cost of supervised therapy, which can highly influence the successful return to, and participation in sport at the pre-injury level. This can be demonstrated in the current study as individuals only saw their physiotherapists on average once every 2 weeks which was either a one on one or a group session and may, therefore, contribute to kinesiophobia, stiffer joints and therefore a delay in returning to, or avoidance of, their pre-injury sport. Tichonova et al., (2016) found that kinesiophobia was improved from 22.7 to 18.4 following 16 sessions of rehabilitation, demonstrating that with an adequate rehabilitation programme confidence in their movement improves.

Jahan et al., (2018) developed a validated rehabilitation protocol following extensive research and found that rehabilitation following a meniscectomy should start three days post-surgery for the best functional outcomes. They established an eight-week rehabilitation protocol after reviewing literature and consulting leading experts in the field and found with starting rehabilitation as early as possible and focusing on healing at the start and progressively building up the rehabilitation strength measures improved by increase by 28% in the quadriceps and an increase of 59% in the hamstrings following meniscectomy. The rehabilitation programme from Jahan et al., (2018) unfortunately not comparable to the current study as the individuals from Jahan et al., (2018) study were asked to go to rehabilitation sessions three times a week for two hours and attend massage and hydrotherapy session in addition to the already existing three session. In the current study, rehabilitation did not start immediately and was seen to take as long as four months to start following surgery, in addition session would generally only be once a week for a maximum of one hour. Similarly, Ebert et al., (2017) observed that in ACL reconstruction (ACLR) individuals limb symmetry indices were largely associated with rehabilitation and stated that a good rehabilitation programme is required to address post-operative strength and functional deficits, particularly when wanting to return to sport. Samitier et al., (2015) stated that the mean timeframe of the individuals to go back to competitive sports was 10 months post-ACL reconstruction, however it took several individuals almost three years to get back to a semi-professional level due to pain and muscle weakness.

Jahan et al., (2018) also stated the importance of knee range of motion and increasing knee flexion as soon as possible with this being the central focus in the first four weeks of their eight-week program. They showed a 59% greater knee flexion angle following the focused rehabilitation protocol. The reduction in knee flexion capacity during all tasks, particularly change of direction has been seen in previous ACL literature to indicate a reduced ability to absorb loads through the knee (Fox et al., 2018). This can be linked to the current study, where knee flexion is reduced and therefore, a reduced ability to absorb load may also be seen. The knee at initial foot contact during foot strike stays in a more extended position and can therefore influence the re-injury susceptibility on return to their competitive sports (Dos'Santos et al., 2018). In the current study, out of the four individuals that went back to participating at a competitive level of their sport, one participant reinjured their knee during a football game and had another surgery after this study was completed, which may be caused by the lack of knee flexion during the game and therefore not managing the loads properly in the dynamic tasks. This demonstrates that leg stiffness, knee loading, strength and kinesiophobia need to be considered carefully before returning back to any level of competitive sport.

4.5.5 Patient-reported outcomes

Fear of re-injury is one of the most common reasons that active individuals following surgery do not to return to sport (Kvist et al., 2005) and the fear-avoidance model may help to explain the patient's decision not to return to sport (Trigsted et al., 2018). Some individuals associate the trauma and pain with certain movements or activities and will therefore, try to avoid them and often alter movement patterns in the attempt to do so (Vlaeyen et al., 2000). The Tampa scale of kinesiophobia (TSK) was used to establish fear of movement or fear or re-injury as seen in patient groups such as ACL individuals following surgery, which could alter movement patterns, particularly when returning to activity (Chmielewski et al., 2008). In the current study, individuals who had a meniscectomy reported 5.2 points greater on the TSK than healthy controls ($p = 0.005$). Previous studies reported that a change of 5.5 points is a clinically meaningful difference for the TSK (Monticone, Ambrosini, Rocca, Foti, & Ferrante, 2016).

Although statistically individuals following meniscectomy reported a significantly higher score on the TSK, this did not meet the threshold for the clinically meaningful difference. Previous studies have shown that high fear of reinjury has been linked to low rates of return to sport (Lentz et al., 2015), reduced self-reported activity levels (Paterno et al., 2017), reduced knee function (Chmielewski et al., 2008), altered sagittal plane movement (Trigsted et al., 2018), lower quadriceps strength and in turn a greater risk of reinjury in ACL individuals following reconstruction (Paterno et al., 2017). All fear avoidance techniques could be seen in the current study with low physical activity levels following meniscectomy, low return to sport, reduced muscle strength, reduced knee and hip flexion creating a stiffer movement and therefore may be at a greater risk of reinjury. Tichonova et al., (2016) found that kinesiophobia decreased in individuals following meniscectomy following a good rehabilitation program, however, a high level of kinesiophobia was significantly correlated with more difficulties experienced in daily activities and poorer knee-related quality of life before and after rehabilitation.

The KOOS is structured into five separately scored subscales: Pain, other symptoms, function in daily living (ADL), function in sports and recreation (Sport/ Rec) and knee-related Quality of Life (QOL). In this study, individuals following meniscectomy had significantly reduced KOOS values compared to healthy, with 30.41-point difference in total KOOS value showing a lower value in individuals following meniscectomy compared to healthy controls. There was a difference of 23.81 points for pain, 29.88 points for symptoms, and 133.63 points for ADL, 35.62 points for Sport / Rec and 49.55 points for QOL in the subscales of the KOOS questionnaire showing lower scores in the individuals following meniscectomy compared to controls. The meaningful difference of the KOOS is reflected by a change of the score between 8- 10 points (Roos & Lohmander, 2003). In the current study, the lowest differences between groups were for pain with a 14-point difference. Thus, the result of this study shows an overall clinically meaningful reduction of function in the knee in individuals following a meniscectomy compared to healthy controls. The total change in knee function between control and individuals following meniscectomy was 30 points from 98 to 68. Thorlund et al., (2017) study was relatable to the current study as the scores for each group of the KOOS scale showed similar results 12 weeks following meniscectomy in the traumatic individuals following meniscectomy: pain (70.4), symptoms (67.1), ADL (77.3), Sport/ Rec (43.7) and QOL (48.3), compared to the current study: pain (75.2), symptoms (64.8), ADL (86.3), Sport/ Rec (62.2) and QOL (49.3). The Sport/ Rec and ADL were higher, however, this may be due to the age being on average 10 years younger in the current study. This may therefore lead to the assumption that 52 weeks following meniscectomy the score in all groups may improve even more as they did in Thorlund et al., (2017) study. Hall et al., (2013) found that individuals following meniscectomy on average 2 years post-surgery had low pain levels (86) and good function (92) when looking at the self-reported KOOS scale. Hall et al., (2013) highlighted that at early-stage post-meniscectomy pain may be greater, however, this is reduced until joint degeneration starts causing a degenerative pain.

4.6 Limitation/Future direction

Long term clinical and radiographical consequences of a lateral meniscectomy are seen to be different from a medial meniscectomy (Chatain et al., 2003), however lateral meniscectomies have not been as commonly reported, similarly to lateral knee OA in comparison to medial knee OA, and therefore long-term outcomes following medial and lateral meniscectomy need to be analysed. In this study, although there were no significant differences in the outcomes compared to medial and lateral meniscectomy, these findings may differ longer term. This needs to be looked at longitudinally with a greater sample size. Understanding what occurs in the lateral meniscectomy could be clinically beneficial to help understand the difference in movement patterns between these injuries and why medial meniscectomies were more likely to end up developing OA.

The current study did not look at the exact rehabilitation plan which is a limitation. It would have been more accurate and beneficial if the consultants could have provided the rehabilitation program following the meniscectomy, including the exact date it started and length of treatment. All the data collected was from word of mouth or from the rehabilitation questionnaire which was quite lengthy including exercises that were put together from several different programs online, however, were not specific to meniscectomy. With the word-of-mouth interpretations, there could have been a bias from the researcher in interpreting what the individuals are saying to support outcomes in the current study. As the rehabilitation questionnaire was quite long and this was not the only questionnaire to be completed, there were some questions which were not filled out in detail or even missing for some individuals. This was put down to length of questionnaire and it being an open questionnaire as this was not seen in the other questionnaires. Eisele et al., (2020) showed that increased length of questionnaires was stated to increase burden on individuals and therefore effect the time invested in the questionnaire and therefore the depth of the outcomes. With the rehabilitation questionnaire there is also a chance for retrospective bias which may affect the answers in the questionnaire depending on how they felt about their rehabilitation, for instance if they really enjoyed it and perceived it to be worth the time to undertake the questionnaire the answers may be more detailed in comparison to an individual who did not have a good rehabilitation experience and did not want to invest the time to think about the answers (Solhan et al., 2009). Creating a qualitative approach to understanding current rehabilitation processes could be a impactful study to consider in the future as rehabilitation seems to be a key factor for improvement in short-term outcomes such as muscle strength and knee flexion range of motion following meniscectomy which may lead on to long-term joint degeneration.

4.7 Summary

To the author's knowledge, this was the first study to analyse the biomechanical difference between individuals following medial meniscectomy and lateral meniscectomy. Frontal and sagittal knee loading were similar between individuals following medial meniscectomy compared to lateral meniscectomy during all tasks. Combining medial and lateral meniscectomy groups was applicable when assessing knee loading in the short period following surgery. When analysing knee loading following meniscectomy, results showed that the EKAM was not significantly different at six-months post-meniscectomy compared to healthy controls. However, altered knee mechanics were still present which was seen by knee motion stiffness, reduced KFM, greater lateral co-contraction of the knee extensor muscles and reduced net activation of the extensor and flexor throughout stance.

Muscle weakness was associated to be linked to pain, kinesiophobia and return to activity. Individuals following meniscectomy were not ready to return to sport six-months following surgery as compensatory mechanisms were seen during dynamic tasks such as lateral trunk lean with greater knee loading compared to walking. This may have been affected by the lack of rehabilitation in the current cohort. Improved early rehabilitation should be considered to limit differences in knee loading following a meniscectomy and therefore reduce risk for medial knee joint degeneration progression. Further research needs to be done looking at the link to rehabilitation and return to sport and whether a proper rehabilitation programme can slow the risk of joint degeneration in a young and active population.

To the authors knowledge this is the first study to look at a combination of dynamic sport-specific tasks following meniscectomy and it could be seen that individuals are at greater risk with high intensity tasks which needs to be considered when thinking about return to sport criteria. As natural compensatory mechanisms have been employed following meniscectomy, implementing the use of offloading mechanisms such as footwear may be highly beneficial, particularly in dynamic sport-specific tasks. Therefore, the second study in this thesis has focused on the use of different footwear as a means to offload the knee joint in individuals following meniscectomy.

Chapter 5 - The effect of commercially available **Foot**wear on biomechanical outcomes associated with knee osteoarthritis in individuals following **Meni**scectomy. (**Meni-Foot study**)

5.1 Background

The role of the meniscus in knee joint health, and its function in weight-bearing, load transmission, shock absorption and lubrication of the articular cartilage, is well understood (Sturnieks et al., 2008; Arno et al., 2013; Makris et al., 2011). Meniscal injuries are one of the most common injuries to occur in the knee, specifically in a sporting population, with a meniscectomy being the most common treatment due to the lowest recovery time (Grassi et al., 2019). Young active populations who sustain a sporting meniscal injury are likely to and want to return to sport following treatment (Eberbach et al., 2018). Noyes et al., (2019) review of previous studies found that on average 80% of athletes who had meniscectomy returned to their previous sport at either the same level of competition as prior to the injury or a lower level. In a cohort study of 90 professional football players the return to play rate was nearly six times greater following medial meniscectomy compared to following lateral meniscectomy, which was found to be due to individuals following lateral meniscectomy experiencing more adverse effects related to pain and swelling (Nawabi et al., 2014).

When participating in sports, it can be assumed that post-meniscectomy generally the same footwear is worn as before the injury occurred. During physical activity, as seen in many individuals who suffer from a meniscal tear, finding the right footwear while considering the scope of injuries is important (Nigg et al., 2015). Trainers/running footwear and other footwear have evolved dramatically over the past few decades (Subotnick., 2017). Whilst there are many different types of footwear on the market, the three primary categories are motion control, cushioning footwear, and stability footwear. Understanding the loads and compressive forces that go through the knee is essential when choosing your footwear, particularly following injury, or surgery (Wang et al., 2018). Therefore, it can be assumed that more cushioning, support or wedges should be implemented to try and offload the affected part of the knee to help either reduce load, reduce movement or shift the loads (Levinger et al., 2013). The evaluation of different types of footwear has not been researched following a meniscectomy, however, it has been widely investigated in knee joint degeneration to try and offload the affected compartment (Voloshin, Wosk, & Brull, 1981; Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018).

Following on from the previous study, knee loading was seen to be greater with greater muscle co-contraction, greater knee stiffness and reduced knee flexor moments following meniscectomy in comparison to healthy controls, specifically in the sporting dynamic tasks. Recent studies have demonstrated that individuals following meniscectomy have demonstrated greater knee loading determined by greater EKAM and or KFM, specifically long-term following meniscectomy (Hall et al., 2014; Willy et al., 2016; Zedde et al., 2015). Greater EKAM and KFM have been associated with greater risk to lead on to osteoarthritis developments (Englund et al., 2016; Wolski et al., 2020). Therefore, looking at offloading the knee joint early on to prevent or slow knee joint degeneration is vital. When considering knee loading, the medial and lateral properties of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004). The lateral meniscus deals with 70% of the load in the lateral compartment, whereas the medial meniscus deals only with 40% of the load (Seedhom et al., 1974). Therefore, the medial and lateral compartments of the knee may need different offloading strategies, in particular when compromised.

Recent evidence suggests that non-invasive interventions such as modern footwear have substantial influence on knee loading, particularly in people with a compromised knee joint such as post-surgery or in knee OA individuals (Shakoor et al., 2010; Paterson et al., 2015). Yet, the role of footwear to manage knee loading post-meniscectomy has not been previously documented. Footwear interventions have been used to alter knee loading and pain included increased stability, cushioning or a lateral wedge insole in knee OA individuals (Paterson et al., 2014; Shakoor et al., 2010; Hinman et al., 2012). Following injury or surgery, the stability in the knee is often reduced (Almekinders et al., 2004), however is seems that adding more stability or stiffness to footwear may not be the most beneficial for an active clinical population (Paterson et al., 2018). It has been well established that stable supportive footwear styles increase knee loads significantly more in individuals with OA compared to flat flexible footwear styles (Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). Stability footwear typically possess medial, midfoot, and longitudinal stiffness and support (medial arch support) and similarly to cushioning footwear, have an increased pitch which likely influence sagittal plane knee moments (Sayer et al., 2019).

Footwear has been seen to alter foot knee pathology in individuals with OA and is a comfortable and cost-effective way to reduce symptomatic pain and possibly slow OA progression (Bennell et al., 2009). Comfort is an important aspect of athletic footwear since it has been associated with health and performance benefits (Hoerzer et al., 2016). Understanding the effect of commonly available footwear on knee loading and the link with comfort could identify appropriate footwear features for conservative management of knee loading following a meniscectomy. Four different commercially available trainers were compared including the Asics Melbourne OA trainer which has been specifically designed for joint degeneration with a lateral wedge implemented. The other trainers included a stability and cushioning trainer which was compared to a neutral trainer to identify which might be more appropriate whilst participating in sports.

Evidence on footwear interventions in individuals following meniscectomy is currently non-existent, particularly in a sporting aspect, however, evidence suggests that modern footwear have substantial influence on knee loading, particularly in people with a compromised knee joint such as post-surgery or in knee OA individuals (Shakoor et al., 2010). It is likely that athletes who sustain a meniscal injury would return to sport and therefore be required to perform movements that require a greater demand and muscular control then reported during walking. Footwear during running has previously been widely researched, however many studies show very varied results and therefore the best running footwear, particularly for clinical populations has not yet been established (Theisen et al., 2016). It is unclear whether footwear interventions can alleviate the risk factors associated with the progression of OA following a meniscal injury in a younger athletic population. Understanding knee loading during sport-specific movements and between sports footwear can provide a greater insight to the risk of OA development for athletic populations. This relatively low-cost strategy of a pair of trainers could be used to help offload the affected knee post-meniscectomy and possibly help slow joint degeneration by alleviating the affected compartment of the knee.

5.2 Aims and Hypotheses

The primary aim of this study was to compare biomechanical outcome measures in individuals following meniscectomy to evaluate changes in knee loading during dynamic tasks while wearing three different commercially available footwear. Secondly, this study aimed to understand the different effects of cushioning, stability, and lateral wedge footwear compared to neutral trainers on knee loading in individuals following medial and lateral meniscectomy, which can lead to future footwear recommendations for these populations. Lastly, the comfort of the footwear was measured to see whether these types of footwear would benefit individuals in a non-laboratory based setting.

H_1: Stability, cushioning and lateral wedge footwear show differences in knee loading compared to neutral footwear in individuals following meniscectomy
- H_0: there is no difference in knee loading between stability, cushioning and lateral wedge footwear compared to neutral footwear in individuals following meniscectomy

H_2: Stability, cushioning and lateral wedge footwear show a difference in knee loading during dynamic tasks compared to neutral footwear in individuals following meniscectomy
- H_0: There is no difference in knee loading during dynamic tasks whilst wearing stability, cushioning and lateral wedge footwear during dynamic tasks in individuals following meniscectomy.

H_3: Individuals following both medial and lateral meniscectomy show a differences in knee loading whilst wearing stability, cushioning and lateral wedge footwear
- H_0: There is no difference in knee loading whilst wearing different footwear for individuals following medial meniscectomy compared to individuals following lateral meniscectomy.

H_4: Stability, cushioning and lateral wedge footwear show a difference in comfort rating during dynamic tasks compared to neutral footwear in individuals following meniscectomy
- H_0: There is no significant difference in comfort whilst wearing different commercially available footwear during dynamic tasks in individuals following meniscectomy.

5.3 Methods

Ethical approval was granted from both the ethics panel of the academic audit and governance committee at the University of Salford (Approval number: HSR1617-140) and the NHS HRA (IRAS 231370; Appendix 1) approval was given. Additionally, the trial was registered with clinicaltrials.gov (NCT03379415).

5.3.1 Recruitment

The individuals following meniscectomy who participated in the previous BOOM study were asked if they were interested in returning for a second session on a separate day to participate in the Meni-Foot study. Potential meniscectomy participants who did not participate in the previous study were also identified through the relevant NHS clinics and private orthopaedic clinics on attendance to consultations within the Greater Manchester area. An invitation letter was sent to all individuals. Individuals who responded to the invitational letters had the study explained to them and they received a participant information sheet and a health screening questionnaire. A minimum of 24 hours was given before they were contacted to determine if they were interested to participate. They were then asked to return the health screening questionnaire so full eligibility could be assessed. If they agreed to participate and were eligible for the study, they were given an appointment at the Performance Capture Laboratory at the Manchester Institute of Health and Performance.

5.3.2 Participants

Individuals diagnosed with a meniscectomy were asked to volunteer for the project. Both medial and lateral meniscal tears were accepted and compared. These individuals were all participants from the previous BOOM study who were happy to return for a second session and therefore eligibility for the study was already accepted as it was based on the following

<u>Meniscectomy inclusion criteria</u>

1. Aged between 18 and 40 years
2. Meniscal injury sustained during a sporting task e.g. sports cutting manoeuvre
3. Compete and or play sport a minimum of two times a week for a minimum of 60 minutes
4. Able to perform sport-specific tasks including running, single leg landing and change of direction
5. Medial or a lateral meniscectomy
6. Individuals between 3-12 months post-meniscectomy

<u>Meniscectomy exclusion criteria</u>

1. History of lower extremity surgeries e.g., ACL reconstruction
2. Evidence of knee osteoarthritis development either assessed clinically (based on ACR criteria) or radiographically (Kellgren-Lawrence grade >1)
3. Previous history of traumatic, inflammatory, or infectious pathology in the lower extremity
4. Evidence of ligament laxity

5.3.3 Procedure

On arrival to the performance capture laboratory, the participants had any final questions answered and were asked to sign the informed consent form (Figure 5.1). The participants were informed that they were free to withdraw at any point of time from the study, without any disadvantage to them. One copy of the consent form was given to the participant and one was kept in the study filing cabinet.

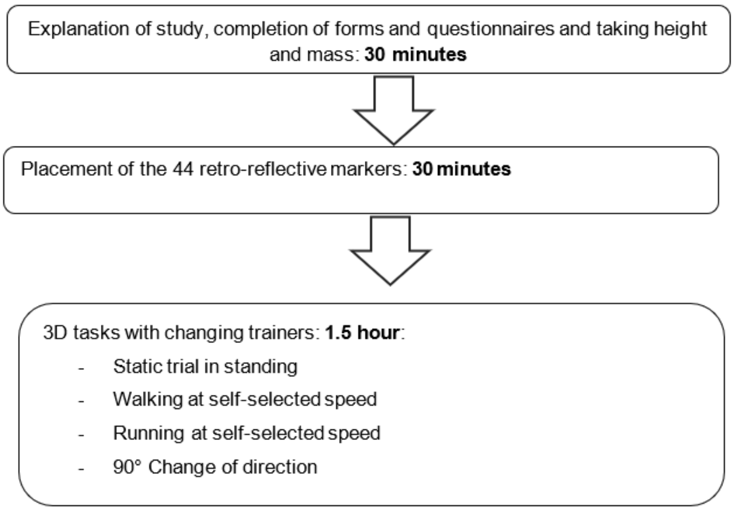


Figure 5.1: The testing protocol including the timing

Prior to the biomechanical data collection participants body mass and height were taken. Three-dimensional movement data were collected using 28 Qualisys OQUS7 cameras (Qualisys AB, Sweden). The ground reaction forces were collected with four force plates (BP600900, Advanced Mechanical Technology, Inc.USA), which were embedded into the floor and synchronised with the Qualisys system.

Each subject was then asked to perform walking, running and a 90-degree change of direction task on a 60 m running track at the MIHP (see section 3.4.1-3.4.5). These tasks were chosen because they gave a comparable indication for previous studies compared to the walking, however as a meniscal tear is generally a sporting injury, the more dynamic fast paces tasks were chosen. Walking and running speed were controlled and reported using timing gates to ensure that each trial was within ±5% of their self-selected speed. The walking, running and change of direction tasks were performed until five successful trials were collected. This was due to needing at least three perfect trials and with a more dynamic movement sometimes it is hard to see any errors. All individuals were comfortable with the tasks as they were repeated from the previous study.

Four commercially available Asics trainers were worn during the testing (Melbourne OA, GT2000, Foundation and Pursue). These trainers reflect the common classifications used in running footwear such as, cushioning, stability and neutral footwear with the Melbourne OA having a lateral wedge. The Melbourne OA trainer was specifically designed to lower loading of the medial compartment of the knee for joint medial compartment joint degeneration with a lateral wedge plus medial support implemented (Hinman et al., 2016). The Pursue was used as our control as it was neutral footwear with a slight medial arch support. The GT2000 equally had a medial arch support with an increased pitch (heel) and cushioning in the heel and finally, the Foundation footwear also had a medial arch support with increased pitch and a more rigid sole as it was stability footwear (Figure 5.2). The minimalist index was calculated using the equations by Esculier et al., (2015) which was stated to be the most efficient way to analyse minimalist footwear. This equation calculated the percentage of minimalist footwear by taking into account shoe flexibility, weight, stack height (distance of where foot sits and most external part of outsole), stability and motion control technologies and heel drop. The lower the score (closer to 0) was for the footwear, the more minimalist the footwear was. The running clinic established a webpage to easily calculate this equation. https://therunningclinic.com/minimalist-index/#calculate. The Minimalist Index showed that the lateral wedge, cushioning and stability footwear were all at 12% and the neutral footwear was at 20%.


Pursue (Neutral)
GT2000 (Cushioning)
Melbourne OA (Lateral Wedge)
Foundation (Stability)

Figure 5.2: The four commercially available trainers used

The order of footwear conditions was randomised, using computer-generated permutations (www.randomization.com/) prior to participant enrolment. At the start of each trainer condition, a normalisation protocol was orchestrated involving the participant running 300 m in the neutral footwear (Pursue) to allow their perception of the following trainer to not be impacted by the previous trainer (Melvin et al., 2014). Following this the trainer was changed to the one which was first on the list, then the four tasks were performed. This was repeated for all four trainers, starting with the normalisation trainer, then the protocol including the next trainer on the list. Individuals were not informed about what type of trainers they were but the individuals were not blinded to the actual colour of the trainer.

5.3.4 Data processing

The kinematic and kinetic outcomes were calculated by utilising a six-degrees-of-freedom model in Visual3D (Version 5, C-motion Inc, USA). Motion and force plate data were filtered with a 4th order Butterworth filter with cut-off frequencies of 12Hz (Kristanslund et al., 2012). The Cardan sequence used in the kinematics calculation with Visual3D was the ordered sequence of rotations (x, y, z), with: x = flexion/extension, y = abduction/adduction, z = longitudinal rotation (R. B. Davis, Ounpuu, Tyburski, & Gage, 1991).

Joint moment data were calculated using a three-dimensional inverse dynamics algorithm. The joint moments were normalised to body mass and presented as external moments referenced to the proximal segment. The kinematic and kinetic data were normalised to 100% of the stance phase, whereby the stance phase was sub-grouped in early-stance (0 - 20% of stance phase) and late stance (20 – 60% of stance phase) during walking. During running the stance phase is the first 40% and the swing phase is the last 60%, the stance phase was sub-grouped in early stance (0 - 20% of stance phase) and late stance (20 – 40% of stance phase) (see section 3.6.1). The change of direction was calculated from heel strike where the foot contact occurred on the force platform (CUT_ON_R/CUT_ON_L) to toe off where the foot contact finished on the force plactform (CUT_OFF_R/CUT_OFF_L). The early stance (initial 50%) of the change of direction was analysed for the kinematics and kinetics as the impact management was most important during this task. The peak values were then analysed. (see section 3.6.1).

5.3.5 Primary outcomes

Similarly, to the previous study, the following outcome measures were investigated minus the strength, balance and EMG which can be found explained in more detail in the methodology chapter 3.7-3.8. Lower limb kinematics and kinetics for three footwear conditions were analysed with a main focus on the knee and knee joint mechanics during dynamic tasks in individuals following meniscectomy. The comfort score was collected using a visual analogue scale for each footwear.

These outcomes were chosen to identify any specific movement changes whilst wearing the footwear conditions and whether they can be used to offload the knee. To identify what happens at the knee, the other joints need to be included in the analysis. Comfort was measured on a visual analogue scale which was handed to the individuals after each footwear condition was worn.

5.3.6 Statistical analysis

Statistical analysis was carried out with SPSS (IBM SPSS Statistics 20), graphs and tables were produced using excel (Microsoft Office Excel 2013). Normality was assessed using the Shapiro-Wilk test and normal detrended Q-Q-plots was examined. A repeated-measures ANOVA was conducted for the MENI-FOOT study to compare differences in the outcome measures between footwear conditions. In addition, a two-way ANOVA was conducted to examine differences between control, individuals following meniscectomy, footwear conditions and between the medial and lateral menisci. An alpha level 0.05 was used to identify significance and Cohen’s D effect sizes and partial eta squared effect sizes will be calculated and reported. The effect size was calculated using the Cohen’s D calculation where the mean difference is divided by the standard deviation of the difference to give an indication of the magnitude of the effect of the intervention (>0.8 large effect, 0.5 moderate effect, <0.3 small effect) (Cohen, 1988).

5.4 Results

Thirty participants were recruited for this study from the previous BOOM study, however ten declined to return due to personal reasons (Figure 5.3). The individuals that participated were between the ages of 18-40 ((mean ± SD), 28.65 ± 6.56 years, height 172.1 ± 8.2cm and mass

78.1 ± 10.7) (Table 5.1). There were 10 individuals following medial meniscectomy (age 29.30 ± 6.68 years, height 171.4 ± 8.4cm, mass 73.7 ± 9.9kg), and 10 individuals following lateral meniscectomy (age 28.00 ± 6.73 years, height 172.9 ± 8.3cm, mass 82.6 ± 10.1kg) included in the twenty. The individuals following meniscectomy were on between three- and twelve-months post-surgery (7.20 ± 3.38 months*)*.

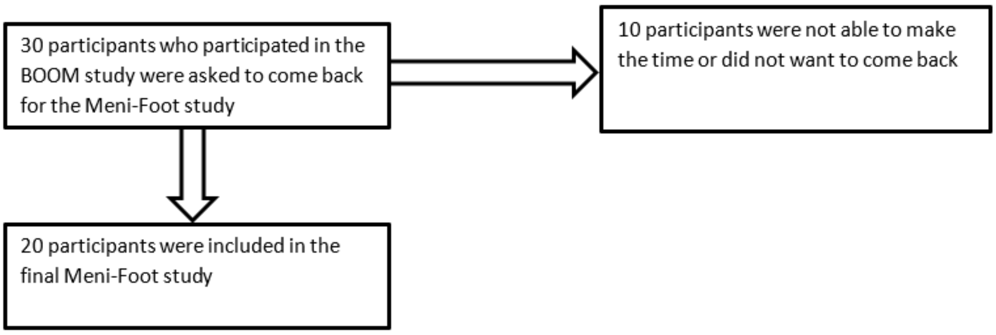


Figure 5.3: Flow chart of meniscectomy participant inclusion in this study

Table 5.1: The participant demographics

	Number	*Age (years)*	*Height (cm)*	*Mass (kg)*	*BMI (kg/m^2)*	*Time since surgery (months)*
Total	20	28.65 ± 6.56	172.1 ± 8.2	78.1 ± 10.7	26.3 ± 3.76	7.20 ± 3.38
Medial	10	29.30 ± 6.68	171.4 ± 8.4	73.7 ± 9.9	25.2 ± 2.86	7.10 ± 3.60
Lateral	10	28.00 ± 6.73	172.9 ± 8.3	82.6 ± 10.1	27.9 ± 3.53	7.30 ± 3.33

5.4.1 Walking

During walking there were no statistically significant main effects for ankle plantarflexion, knee flexion, knee adduction, hip flexion and hip adduction angles ($p > 0.05$; Table 5.2). There was a significant difference in the knee flexion angle between the lateral wedge footwear and the neutral footwear ($p < 0.05$). The knee was significantly more flexed in the lateral wedge footwear (38.03 ± 6.53°, $p = 0.019$) compared to the neutral footwear during late stance (35.97± 7.25°). There was no statistically significant main effect for ankle eversion angle during early and late stance phase ($p > 0.05$), however, there was a significant difference between the lateral wedge footwear compared to the neutral footwear. The ankle was significantly more everted in the lateral wedge footwear (8.75 ± 5.07°, $p = 0.015$) compared to the neutral footwear in late stance (10.89 ± 6.16°).

Table 5.2: Mean ± SD speed, peak ankle, knee and hip motion during walking comparing cushioning, stability and lateral wedge trainers to a neutral trainer (* indicated significance, large effect size indicated by bold and underlined value)

	The kinematic variables (º) during stance phase	**Neutral**		**Cushioning**			**Lateral Wedge**			**Stability**		
		Mean, SD		*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
	Speed (m/s)	1.43 ± 0.10										
Early Stance phase	Ankle flexion angle	-6.40 ± 4.35		-7.37 ± 5.24	.340	0.20	-6.38 ± 4.15	.974	0.01	-7.34 ± 4.84	.266	0.20
	Ankle inversion angle	-2.04 ± 6.03		-3.40 ± 7.77	.675	0.20	-3.18 ± 6.03	.114	0.19	-2.13 ± 4.93	.951	0.02
	Knee flexion angle	13.16 ± 8.05		12.08 ± 8.12	.255	0.13	12.58 ± 6.05	.483	0.08	13.98 ± 6.52	.466	0.11
	Knee adduction angle	-0.14 ± 3.28		0.03 ± 3.61	.542	0.05	-0.30 ± 3.91	.708	0.04	0.15 ± 3.56	.574	0.08
	Hip flexion angle	34.94 ± 7.98		32.86 ± 10.50	.554	0.22	33.82 ± 7.16	.344	0.15	33.47 ± 6.52	.119	0.20
	Hip adduction angle	7.71 ± 2.04		8.10 ± 3.03	.599	0.15	8.36 ± 2.62	.178	0.28	7.88 ± 2.67	.717	0.07
Late Stance phase	Ankle flexion angle	11.84 ± 3.12		11.23 ± 3.13	.740	0.20	12.78 ± 3.24	.077	0.30	12.98 ± 3.80	.118	0.33
	Ankle inversion angle	10.89 ± 6.16		9.75 ± 6.99	.630	0.17	8.75 ± 5.07	**.015***	0.38	11.73 ± 5.01	.582	0.15
	Knee flexion angle	35.97 ± 7.25		33.33 ± 10.47	.167	0.29	38.03 ± 6.53	**.019***	0.30	35.38 ± 7.68	.490	0.08
	Knee adduction angle	0.78 ± 3.21		0.80 ± 3.46	.365	0.01	0.82 ± 3.85	.941	0.01	0.86 ± 3.61	.898	0.02
	Hip flexion angle	-7.70 ± 9.26		-7.25 ± 8.97	.425	0.05	-7.24 ± 9.51	.657	0.05	-9.17 ± 8.84	.122	0.16
	Hip adduction angle	7.03 ± 2.01		7.49 ± 3.18	.205	0.17	7.47 ± 2.88	.326	0.18	7.64 ± 2.90	.126	0.24

There was no significant main effect for footwear in knee adduction moment during walking ($p > 0.05$). There was however a significant difference between the knee adduction moment of the lateral wedge footwear and the neutral footwear. The lateral wedge footwear showed a significantly lower knee adduction moment (0.38 ± 0.14 Nm/kg, $P = 0.046$) compared to the neutral footwear (0.42 ± 0.12 Nm/kg, Table 5.3). There was no significant difference for ankle and hip moments ($p > 0.05$). There was also no significant main effect comparing the meniscectomy leg to the contralateral leg ($P > 0.05$). There was a significant medial shift in the centre of pressure excursion between the stability footwear (0.97 ± 0.31 mm, $p < .001$) compared to the neutral footwear (0.67 ± 0.21 mm).

Table 5.3: Peak ankle, knee and hip moments during walking comparing cushioning, stability and lateral wedge trainers to a neutral trainer (* indicated significance, large effect size indicated by bold and underlined value)

	The kinetic variables (Nm/kg) during stance phase	**Neutral**		**Cushioning**			**Lateral Wedge**			**Stability**		
		Mean, SD		*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
Early stance phase (loading)	Ankle flexion moment	0.52 ± 0.15		0.53 ± 0.14	.431	0.07	0.55 ± 0.15	.055	0.20	0.54 ± 0.13	.080	0.14
	Knee flexion moment	0.36 ± 0.26		0.38 ± 0.31	.471	0.07	0.39 ± 0.26	.101	0.12	0.36 ± 0.30	.733	0.00
	Knee adduction moment	0.42 ± 0.12		0.43 ± 0.12	.128	0.08	0.38 ± 0.14	**.046***	0.31	0.41 ± 0.12	.840	0.08
	Hip flexion moment	0.84 ± 0.29		0.81 ± 0.29	.266	0.10	0.87 ± 0.29	.433	0.10	0.79 ± 0.23	.082	0.19
	Hip adduction moment	0.92 ± 0.18		0.91 ± 0.20	.542	0.05	0.93 ± 0.18	.871	0.06	0.92 ± 0.17	.865	0.00
Late Stance phase	Ankle flexion moment	1.44 ± 0.13		1.44 ± 0.12	.726	0.00	1.48 ± 0.11	.078	0.33	1.48 ± 0.11	.200	0.33
	Knee flexion moment	-0.41 ± 0.17		-0.42 ± 0.16	.756	0.06	-0.44 ± 0.18	.105	0.17	-0.42 ± 0.17	.621	0.06
	Knee adduction moment	0.29 ± 0.09		0.30 ± 0.08	.325	0.12	0.25 ± 0.12	.080	0.38	0.30 ± 0.10	.351	0.11
	Hip flexion moment	-0.94 ± 0.45		-0.91 ± 0.46	.962	0.07	-0.89 ± 0.41	.314	0.12	-0.94 ± 0.43	.947	0.00
	Hip adduction moment	0.82 ± 0.17		0.78 ± 0.15	.118	0.25	0.82 ± 0.20	1.00	0.00	0.80 ± 0.18	.442	0.11
	Vertical GRF (BW)	1.17 ± 0.07		1.16 ± 0.08	.117	0.13	1.16 ± 0.07	.364	0.14	1.16 ± 0.07	.147	0.14
	Centre of pressure position at touchdown (mm)	0.67 ± 0.21		0.74 ± 0.29	.203	0.28	0.71 ± 0.25	.279	0.17	0.97 ± 0.31	**.000***	**1.13**

5.4.2 Running

During running there were no statistically significant changes between footwear conditions for ankle plantarflexion, knee adduction, hip flexion and hip adduction angles (p > 0.05; Table 5.4). There was a statistically significant change in knee flexion angle during late stance phase between the footwear conditions ($F_{3,54}$ = 58.745, p = 0.002). The knee was significantly less flexed in the lateral wedge footwear (31.79 ± 7.10°, p = 0.002) compared to the neutral footwear during late stance (34.55 ± 6.82°; Figure 5.4). There was no significant difference in knee flexion between the stability and cushioning footwear compared to the neutral footwear (p > 0.05). There was no statistically significant change for ankle eversion angle between all footwear conditions during early and stance phase (p > 0.05), however, there was a significant difference between the lateral wedge footwear compared to the neutral footwear. The ankle was significantly more everted in the lateral wedge footwear (-1.77 ± 4.72°, p = 0.021) compared to the neutral footwear in early stance (-0.54 ± 5.43°) and the ankle was also significantly less inverted in the lateral wedge footwear (9.10 ± 5.64°, p = 0.003) compared to the neutral footwear during late stance (10.74 ± 6.51°).

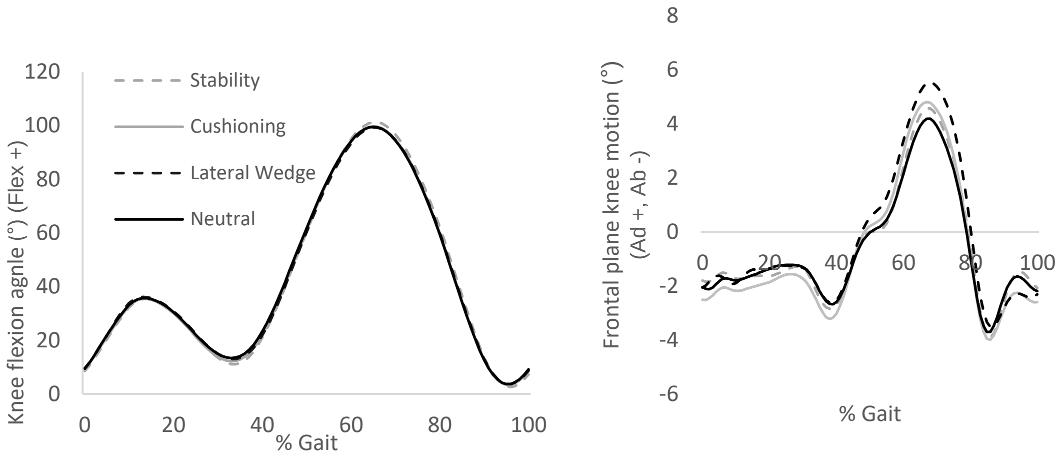


Figure 5.4:Ensemble average sagittal and frontal plane knee motion during running comparing four different footwear conditions (n = 20)

Table 5.4: Peak ankle, knee and hip motion in early and late stance during running comparing cushioning, stability and lateral wedge trainers to a neutral trainer (* demonstrated significance and a bold underlined effect size showed large effect)

	The kinematic variables (º) during stance phase	**Neutral**	**Cushioning**			**Lateral Wedge**			**Stability**		
		Mean, SD	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
	Speed (m/s)	3.34 ± 0.09									
Early Stance phase	Ankle flexion angle	22.48 ± 3.95	20.03 ± 3.42	.195	0.66	23.14 ± 2.90	.092	0.19	21.33 ± 4.46	.647	0.27
	Ankle inversion angle	-0.54 ± 5.43	-1.68 ± 5.74	.231	0.20	-1.77 ± 4.72	**.021***	0.24	-0.60 ± 5.12	.936	0.01
	Knee flexion angle	34.58 ± 5.06	36.15 ± 3.14	.596	0.37	33.70 ± 3.73	.477	0.20	36.16 ± 4.01	.516	0.35
	Knee adduction angle	0.54 ± 3.63	0.42 ± 4.44	.827	0.03	0.67 ± 3.74	.713	0.04	0.56 ± 3.74	.976	0.01
	Hip flexion angle	38.93 ± 9.27	38.63 ± 8.59	.638	0.03	38.71 ± 9.72	.760	0.02	37.88 ± 8.72	.166	0.12
	Hip adduction angle	12.59 ± 3.88	12.44 ± 3.98	.748	0.04	12.87 ± 3.66	.465	0.07	12.41 ± 3.62	.671	0.05
Late Stance phase	Ankle flexion angle	-28.31 ± 7.18	-29.66 ± 6.77	.930	0.19	-27.92 ± 7.00	.330	0.06	-29.81 ± 7.28	.847	0.21
	Ankle inversion angle	10.74 ± 6.51	9.93 ± 7.25	.488	0.12	9.10 ± 5.64	**.003***	0.27	10.48 ± 5.92	.785	0.04
	Knee flexion angle	34.55 ± 6.82	34.07 ± 4.85	.642	0.08	31.79 ± 7.10	**.002***	0.40	32.97 ± 6.31	.057	0.24
	Knee adduction angle	0.68 ± 3.69	0.39 ± 4.11	.501	0.07	0.62 ± 3.90	.841	0.02	0.43 ± 3.82	.558	0.07
	Hip flexion angle	-4.16 ± 8.39	-4.75 ± 8.49	.403	0.07	-4.06 ± 9.16	.896	0.01	-5.62 ± 8.42	.056	0.17
	Hip adduction angle	7.00 ± 3.86	7.13 ± 4.29	.773	0.03	7.53 ± 3.89	.111	0.14	6.99 ± 3.68	.987	0.00

There was a significant main effect for footwear in knee flexion moment ($F_{1,38}$ = 5.265, P = 0.027). The lateral wedge footwear showed significantly lower knee flexion moments (1.94 ± 0.82 Nm/kg, P = 0.017) compared to the neutral footwear (2.04 ± 0.83 Nm/kg, Table 5.5). There was a significant main effect for footwear in knee adduction moment ($F_{1,38}$ = 4.907, P = 0.033). The lateral wedge footwear showed significantly lower knee adduction moment (0.51 ± 0.22 Nm/kg, P = 0.010) compared to the neutral footwear (0.59 ± 0.23 Nm/kg; Figure 5.5). There was however, only a small effect size when comparing the lateral wedge footwear to the neutral footwear (ES = 0.36), which also aligns with the difference not being greater than that seen in the repeatability study showing no clinical meaningful difference. There was no significant main effect between any of the footwear for ankle and hip moments (P > 0.05). There was a significant medial shift in the centre of pressure excursion between the lateral wedge footwear (0.93 ± 0.23 mm, P < .001) compared to the neutral footwear (0.66 ± 0.22 mm).

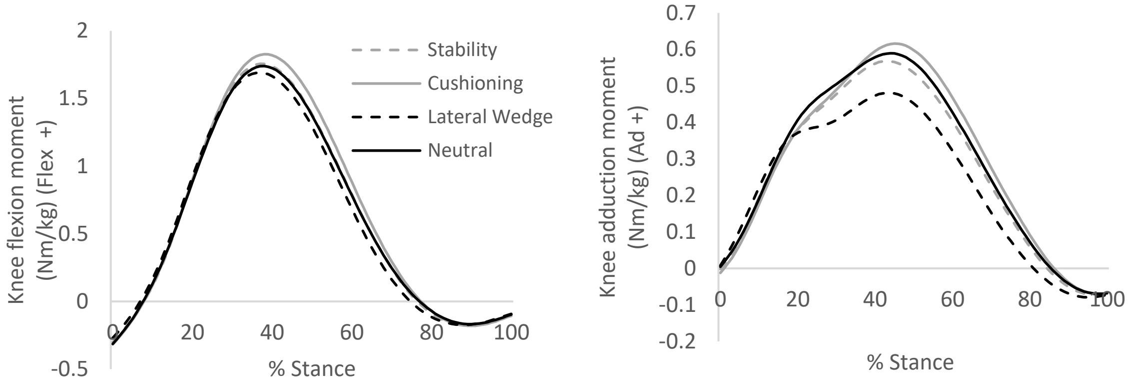


Figure 5.5: Ensemble average sagittal and frontal plane knee moments during running comparing four different footwear conditions (n = 20)

Table 5.5: Peak ankle, knee and hip moments, vertical GRF and medial/lateral COP during running comparing cushioning, stability and lateral wedge trainers to a neutral trainer. (* demonstrated significance. Large effect size was shown by bold and underlined value).

The kinetic variables (Nm/kg) during stance phase	**Neutral**		**Cushioning**			**Lateral Wedge**			**Stability**		
	Mean, SD		*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
Ankle flexion moment	2.24 ± 0.37		2.28 ± 0.37	.578	0.11	2.28 ± 0.29	.998	0.12	2.30 ± 0.37	.549	0.16
Knee flexion moment	2.04 ± 0.83		2.10 ± 0.85	.104	0.07	1.94 ± 0.82	**.017***	0.12	2.08 ± 0.82	.179	0.05
Knee adduction moment	0.59 ± 0.23		0.58 ± 0.26	.837	0.05	0.51 ± 0.22	**.010***	0.36	0.55 ± 0.24	.186	0.17
Hip flexion moment	1.27 ± 0.62		1.22 ± 0.53	.107	0.09	1.25 ± 0.57	.780	0.03	1.19 ± 0.54	.163	0.14
Hip adduction moment	1.71 ± 0.32		1.78 ± 0.35	.076	0.21	1.67 ± 0.36	.528	0.12	1.74 ± 0.35	.355	0.09
Vertical GRF (BW)	2.40 ± 0.29		2.43 ± 0.27	.110	0.11	2.36 ± 0.28	.143	0.14	2.38 ± 0.30	.552	0.07
Medial/lateral centre of pressure position at touchdown (mm)	0.66 ± 0.22		0.81 ± 0.22	.215	0.68	0.93 ± 0.23	**.000***	**<u>1.20</u>**	0.75 ± 0.28	**.027***	0.36

5.4.3 Change of direction

During the change of direction, there were no statistically significant main effects for knee flexion or adduction angle (p > 0.05; Figure 5.6). There were no significance for ankle plantarflexion angle, hip flexion and hip adduction angle (p > 0.05; Table 5.6), however, there was a significant difference between the cushioning footwear hip flexion angle and the neutral footwear. There was a significantly lower hip flexion angle in the cushioning footwear (37.05 ± 11.69°, P = 0.019) compared to the neutral footwear (39.16 ± 11.94°).

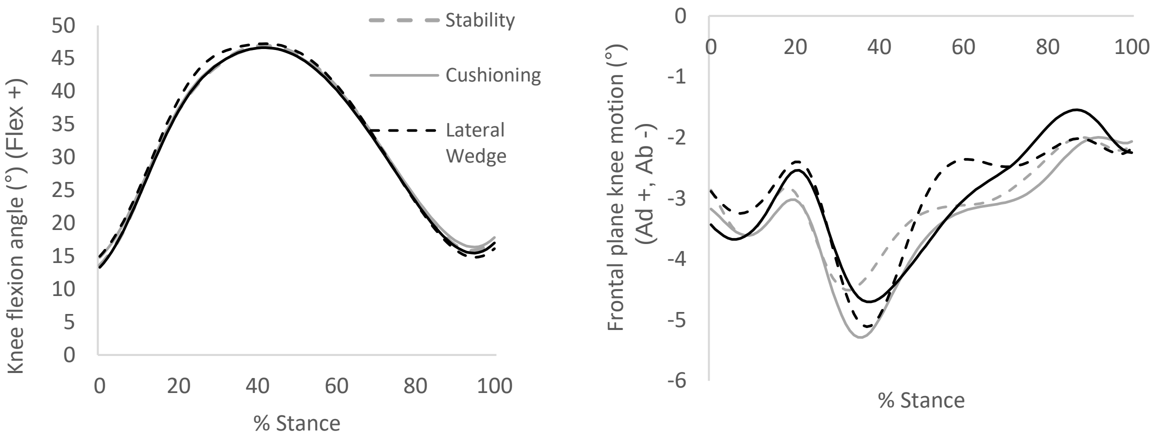


Figure 5.6: Ensemble average sagittal and frontal plane knee motion during change of direction comparing four different footwear conditions (n = 20)

Table 5.6: Average approach and exit velocity, peak ankle, knee and hip motion during change of direction comparing cushioning, stability and lateral wedge trainers to a neutral trainer

The kinematic variables (°) during stance phase	**Neutral**		**Cushioning**			**Lateral Wedge**			**Stability**		
	Mean, SD		*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
Average approach velocity(m/s)	4.04 ± 0.63										
Average exit velocity (m/s)	2.43 ± 0.32										
Ankle flexion angle	12.94 ± 9.46		13.00 ± 10.25	.948	0.01	13.37 ± 8.51	.536	0.05	13.05 ± 11.11	.911	0.01
Ankle inversion angle	5.62 ± 10.96		9.98 ± 13.21	.158	0.36	7.05 ± 10.37	.444	0.13	7.93 ± 9.05	.158	0.23
Knee flexion angle	45.98 ± 7.69		45.63 ± 6.68	.644	0.05	46.35 ± 6.52	.660	0.05	45.31 ± 7.96	.412	0.09
Knee adduction angle	1.77 ± 4.89		1.54 ± 4.65	.651	0.05	1.33 ± 4.89	.291	0.09	1.43 ± 4.59	.349	0.07
Hip flexion angle	39.16 ± 11.94		37.05 ± 11.69	**.019***	0.18	38.83 ± 11.54	.720	0.03	37.95 ± 11.89	.252	0.10
Hip adduction angle	-6.89 ± 7.30		-8.08 ± 6.89	.067	0.17	-7.77 ± 7.24	.344	0.12	-7.69 ± 7.06	.262	0.11

There was a significant main effect for footwear in knee adduction moment ($F_{1,36} = 16.073$, $p < .001$). The lateral wedge footwear showed a significantly greater knee abduction moment (-0.64 ± 0.67 Nm/kg, $p < .001$; Figure 5.7) compared to the neutral footwear (-0.47 ± 0.49 Nm/kg, Table 5.7). There was no significant knee flexion moment or ankle and hip moments between any of the footwear conditions in comparison to the neutral footwear during the change of direction task.

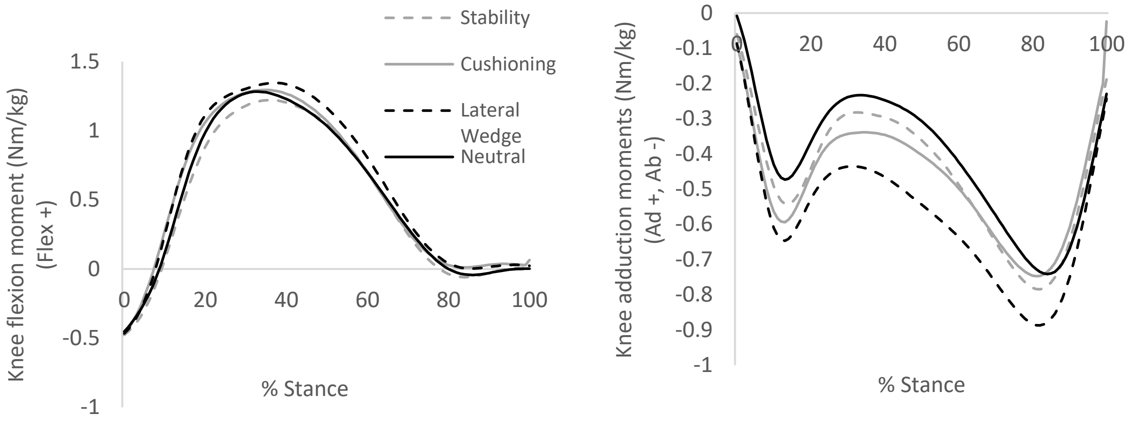


Figure 5.7: Ensemble average sagittal and frontal plane knee moments during change of direction comparing four different footwear conditions

Table 5.7: Peak ankle, knee and hip moments and vertical GRF during change of direction comparing cushioning, stability and lateral wedge trainers to a neutral trainer

The kinetic variables (Nm/kg) during stance phase	**Neutral**	**Cushioning**				**Lateral Wedge**			**Stability**		
	Mean, SD		*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*	*Mean, SD*	*P value*	*ES*
Ankle flexion moment	2.02 ± 0.49		2.02 ± 0.46	.864	0.00	2.10 ± 0.52	.092	0.16	2.02 ± 0.46	.934	0.00
Knee flexion moment	1.64 ± 0.81		1.65 ± 0.79	.647	0.01	1.68 ± 0.84	.472	0.05	1.59 ± 0.71	.476	0.07
Knee adduction moment	-0.47 ± 0.49		-0.60 ± 0.56	.117	0.14	-0.64 ± 0.67	**.000***	0.26	-0.57 ± 0.59	.144	0.04
Hip flexion moment	1.73 ± 0.93		1.64 ± 0.90	.290	0.10	1.78 ± 1.00	.571	0.05	1.65 ± 0.81	.463	0.09
Hip adduction moment	-1.62 ± 1.24		-1.63 ± 1.26	.978	0.11	-1.78 ± 1.31	.067	0.14	-1.65 ± 1.36	.744	0.06
Vertical GRF (BW)	1.04 ± 0.20		1.04 ± 0.33	.990	0.00	1.05 ± 0.21	.833	0.05	0.98 ± 0.23	.174	0.28

5.4.4 Medial and lateral comparison

There was no significant difference between the footwear conditions when comparing the individuals following medial and lateral meniscectomy during walking and change of direction ($p > 0.05$; Table 5.8). There was significantly reduced EKAM in the lateral wedge footwear during running in individuals following lateral meniscectomy (0.51 ± 0.27 Nm/kg, $p = 0.008$) when compared to the individuals following medial meniscectomy (0.57 ± 0.11 Nm/kg). In the change of direction task there was a moderate effect size in the stability shoe (ES = 0.75) and a large effect size in the neutral, cushioning, and lateral wedge footwear (ES > 0.8), showing greater KFM in individuals following lateral meniscectomy compared to individuals following medial meniscectomy.

Table 5.8: EKAM when comparing medial vs lateral meniscectomy in all four footwear conditions

Moments (Nm/kg)	Task	Footwear Type	Medial	Lateral	*P value*	*ES*
EKAM	Walking	Neutral	0.40 ± 0.10	0.43 ± 0.14	.607	0.25
		Stability	0.41 ± 0.09	0.41 ± 0.14	.274	0.00
		Cushioning	0.43 ± 0.10	0.43 ± 0.15	.260	0.00
		Lateral Wedge	0.38 ± 0.10	0.37 ± 0.18	.099	0.07
	Running	Neutral	0.62 ± 0.20	0.64 ± 0.26	.452	0.09
		Stability	0.63 ± 0.22	0.57 ± 0.32	.358	0.22
		Cushioning	0.68 ± 0.17	0.61 ± 0.30	.148	0.29
		Lateral Wedge	0.57 ± 0.11	0.51 ± 0.27	**.008***	0.29
	Change of Direction	Neutral	-0.83 ± 0.89	-1.00 ± 0.46	.176	0.24
		Stability	-0.79 ± 0.81	-1.26 ± 0.62	.483	0.65
		Cushioning	-0.81 ± 0.76	-1.09 ± 0.59	.737	0.41
		Lateral Wedge	-1.00 ± 0.89	-1.13 ± 0.64	.516	0.17

5.4.5 Perception of comfort

The neutral trainers were perceived the most comfortable when scored on a visual analogue scale (Figure 5.8). There was a significant main effect for footwear conditions for the comfort score ($F_{3,57}$ = 20.824, $p < 0.001$). Comfort was rated significantly lower for the cushioning footwear (61.50 ± 20.90 mm, p = 0.002) compared to the neutral footwear (76.50 ± 11.19 mm). The lateral wedge scored the lowest for comfort with a significantly reduced score (39.00 ± 19.63 mm $p < 0.001$) compared to the neutral footwear.

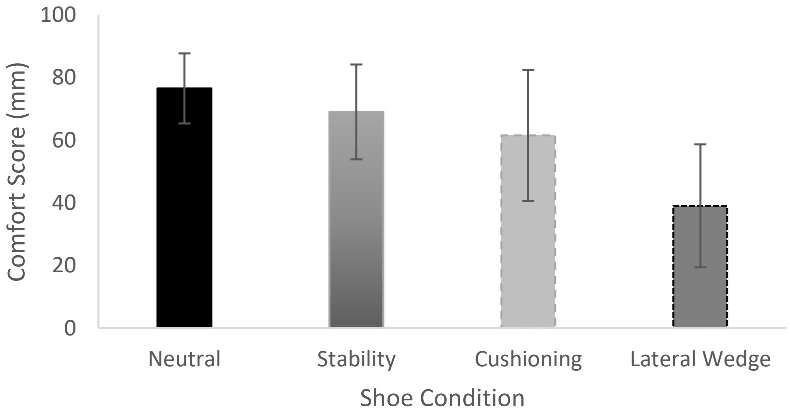


Figure 5.8: Comfort score rated on a visual analogue scale (VAS) for all four footwear

5.5 Discussion

Understanding the loads and compressive forces that go through the knee is essential when choosing your footwear, particularly following knee injury or surgery (Wang et al., 2018). Footwear has been seen to alter foot knee pathology in individuals with OA and is a comfortable and cost-effective way to reduce symptomatic pain and possibly slow OA progression (Bennell et al., 2009).

5.5.1 Cushioning

Several conflicting studies show that cushioning footwear can either reduce knee loading or increase knee loading (Chambon et al., 2014; Kulmala et al., 2018; Day and Hahn., 2019). Footwear with an increased pitch (raised heel in relation to the forefoot), specifically with a soft cushioned heel, have been used to aid in firstly reducing knee loading during impact tasks and secondly to aid in propulsion during running to enhance running economy with an added bounce from the increased soft pitch on the heel (Day and Hahn., 2019). In the current study, on average seven months following meniscectomy, there were no significant changes during running in the frontal plane knee joint loading whilst wearing cushioning footwear ($p > 0.05$; 0.58 ± 0.26 Nm/kg) compared to neutral footwear (0.59 ± 0.23 Nm/kg).

In the current study, there were no significant differences between the neutral trainer and the cushioning trainer, however, there was a moderate effect size (0.66) seen in the ankle dorsiflexion angle in the first stance phase of running, showing a (11%) reduction in the cushioning footwear which was supported by a greater knee flexion angle (6%) as previous research with increased pitch. Kulmala et al., (2018) looked at a neutral running trainer compared to a highly cushioned footwear at 10 km/hr and 14 km/hr and found that there was a 6.4% and 10.7% increase in knee loading. The greater knee loading was attributed to a stiffer leg mechanism being used at heel strike in early stance which is also seen in the current study. In the current study, individuals ran at 3.34 m/s (12.02 km/hr) and found that the vertical GRF results (2.42 BW) were similar to those found in Kulmala et al., (2018) study at 10 km/hr (2.55 BW), however, the vertical GRF increased significantly at 14 km/hr (2.91 BW). Therefore, the increase in vertical GRF at 14 km/hr highlights that knee loading should be analysed during a faster running speed as seen during competitive sports where meniscal injuries are most common. A greater GRF shows greater force applied to the body is shown to increase joint loading (Logan et al., 2010). In the current study, only self-selected running speed was looked at to make sure that the individuals would feel comfortable and to assess their normal running, rather than strained running, particularly as the individuals had to repeat dynamic task movements four times.

On the contrary to cushioning footwear, research has shown that running barefoot or in minimalist footwear may be associated with a reduced incidence of running injuries (Liebermann et al., 2010), and therefore, there has been an increased number of runners that are choosing to run barefoot or with minimalist footwear (Sinclair et al., 2013). Hollander et al., (2015) analysed the effect of cushioning on footwear as they looked at footwear with and without cushioning and found that the ankle dorsiflexion angle was 6.90° without cushioning, however with added cushioning this increased to 11.66° which was closer to what was seen in the current study where the ankle dorsiflexion angle was 20.03°. The reduced dorsiflexion angle was associated with a reduced EKAM (Sinclair et al., 2013) and therefore, highlights that minimalist footwear should be considered for individuals following meniscectomy.

Sacco et al., (2011) found that individuals with knee OA had a lower EKAM whilst wearing minimalist footwear compared to standard footwear. The lower EKAM whilst wearing minimalist footwear in individuals with OA could be due to due to greater sensitivity in the foot with less cushioning and therefore increased sensitivity to the ground, which is often reduced in older individuals, additionally the minimalist footwear would be lighter and therefore may allow greater lower limb movement in older individuals, with muscle weakness and pain as seen in OA individuals (Hurley et al., 1997; Rossignol et al., 2006). In the current study, there was no change in EKAM whilst wearing cushioning footwear during walking, running and change of direction which may be due to the difference of the footwear not being great enough to the neutral footwear or, that with the increased cushioning there is lack of sensory awareness to the floor and therefore, individuals land with greater force. Jellema et al., (2019) literature review reported that footwear sole hardness affects sensorial awareness, which is the sensitivity of the foot, and with greater cushioning in the sole, instability in the elderly was caused, which can be related to a compromised joint. This was demonstrated in this study by the greater difference in ankle inversion/eversion in the cushioning footwear compared to the neutral footwear. Hamacher et al., (2016) showed a greater variability in ankle inversion/eversion angle in individuals with chronic ankle instability, which supports the findings in the current study with the cushioning footwear causing a greater instability.

Bohne et al., (2017) analysed cushioning footwear to minimalist footwear and standard footwear and found similar results to the current study with no significant differences between cushioning footwear and standard footwear, however in Bohne et al., (2017) study there was a significant difference in vertical ground reaction forces, ankle dorsiflexion and knee flexion angles compared to the minimalist footwear. The change of direction task in the current study demonstrated no significant differences in KFM, nor did it show a significant difference in the knee abduction moment. In previous research, knee abduction moments tended to be smaller during 60° change of direction manoeuvres performed with an apparent forefoot strike pattern in healthy adults (Kristianslund et al., 2014; Yoshida et al., 2016). This was not evident in the current study, however, there was a greater knee abduction moment during landing between the cushioning footwear and the neutral footwear. The compromised joint seen following meniscectomy may play a part in greater loading during change of direction tasks; however, this needs to be researched further. Footwear with additional cushioning has demonstrated few differences when compared to a neutral control footwear in individuals following meniscectomy, which suggests that it may not reduce knee loading during dynamic tasks, however with increased speed, loading may increase more drastically and with a compromised joint, the knee may not be able to deal with the extra propulsion as stated by Kulmala et al., (2018).

5.5.2 Stability Footwear

As seen in cushioning footwear, high-supportive footwear generally classed as stability footwear, showed similar results with no great reductions in knee loading, which may be linked to the minimalist score showing a similar score (stability footwear scored 12% and the neutral footwear scored 20%), which includes a greater pitch compared to the neutral footwear. In the current study, the findings for the stability footwear showed similar results as for the cushioning footwear with a reduced ankle dorsiflexion angle, greater knee flexion angle, and greater knee flexor moment during running. The findings for knee joint loading whilst wearing the stability footwear in comparison to the neutral footwear was not significantly different and therefore, do not support the hypothesis H_1 as knee loading was similar between the stability trainer and neutral trainer. The lack of significance could also be due to the Minimalist Index being close between footwear conditions. Therefore, a minimalist shoe could be looked at in future studies.

Stability footwear uses mechanisms to reduce excessive movement of the rearfoot, particularly during dynamic tasks which is classed as motion control (Cheung et al., 2006). Unfortunately, there is conflicting research showing whether stability footwear has beneficial effect for both performance and injury prevention (Butler et al., 2007; Davis., 2014; Langley et al., 2019). The lack of significance in the current study highlights that stability footwear may not be beneficial to help offload the knee in individuals following meniscectomy, however there were no significant detriments to wearing stability footwear during dynamic tasks. Previous studies have found biomechanical changes during change of direction tasks in ACL individuals that may influence knee injuries (Besier et al., 2001; Sun et al., 2017). During a 45° change of direction task, decreased knee flexion angles whilst wearing high-supportive footwear compared to neutral footwear reduced the ability of impact absorption on landing, putting the knee at risk of injury (Derrick et al., 2002). In the current study, although the knee flexion angle during the change of direction task was slightly reduced, there was no significant difference in the stability footwear compared to the neutral footwear, highlighting that there may not be an increased risk of re-injury with the stability footwear. On contrary, it has been stated that excessive foot pronation also plays a part in greater knee loading as foot pronation transfers the load up the kinetic chain, contributing to greater knee abduction moments during landing or change of direction tasks (Sayer et al., 2018; Shin et al., 2011). To neutralise the greater knee loading during these dynamic tasks, high-supportive shoes with appropriate anti-pronation features such as the medial arch support have been suggested to help reduce knee abduction moments (Barton et al., 2009). Morio et al., (2014) agreed to the findings in the current study and stated that there were no significant differences in the ankle joint kinematics and knee loading during change of direction when wearing footwear with increased support and hardness. The lack of differences when comparing stability footwear to neutral footwear illustrates that extra stability and stiffness of the footwear, does not have any negative effects in individuals following meniscectomy when considering return to play, however, was also seen not to be beneficial in offloading the knee and therefore, does not reduce the risk of knee degeneration.

5.5.3 Lateral Wedge

Footwear with a lateral wedge can be used to offload the knee due to greater ankle eversion in early stance and less ankle inversion in late stance, shifting the ground reaction force laterally and therefore reducing EKAM (Kakihana et al., 2005). As the footwear in the current study is a variable stiffness footwear with a lateral wedge, the stiffer lateral midsole results in a medial shift in centre of pressure (COP), which lowers the knee adduction moment arm during stance. In the current study, the lateral wedge footwear with a medial arch support was found to have 15% reduction in EKAM compared to neutral footwear during running. This could be explained by the greater eversion angle (69%) and the medially shifted COP (41%). This accepts the H_1 Hypothesis stating that knee loading was reduced with lateral wedge footwear. Previous studies showed that EKAM is associated with cartilage thickness loss and joint degeneration in the knee over 12 months (Bennell et al., 2011) and 24 months (Chang et al., 2015). Therefore, the reduction in EKAM in the current study with the lateral wedge footwear use may reduce or delay the progression of the knee OA which has been shown to be inevitable following meniscectomy (Hall et al., 2014).

Previous studies have highlighted that a lateral wedge of at least 5° produces reductions in the first peak EKAM similar to those in the current study during walking: 12% (Hinman et al., 2008a), 13.7% (Fu et al., 2015), 10% (Butler et al., 2009), and 12% (Jones et al., 2013). Jones et al. (2015) highlighted that both the typical lateral wedge (5.21%) and medial supported lateral wedge (6.29%) reduced the medial knee loading, showing a more significant reduction with medial support. During walking there was a 11% reduction in EKAM in individuals following meniscectomy whilst wearing lateral wedge footwear which supported the general consensus of studies mentioned above. Steiner (2019) found a considerable variation in response to their variable stiffness footwear and demonstrated a range from an 11% reduction in EKAM to a 19% increase in EKAM when compared to a neutral control footwear. This variation in response to the footwear is supported in part by the literature, where around 15-20% of individuals experience an increase in EKAM (Bennell et al., 2013; Erhart-Hledik et al., 2012; Erhart et al., 2008; Fisher et al., 2007). Chapman et al., (2015) found that when wearing a lateral wedge in individuals with OA, there were 30% of individuals which were non-responders. When comparing to the current study, the lack of significant results may be due to there being some non-responders, specifically when comparing the individuals following medial and lateral meniscectomy.

The change of direction task in the current study, shows a greater knee abduction moment with a significant increase of 17% whilst wearing the lateral wedge footwear compared to the neutral. A greater knee abduction moment has been seen as an indicator for greater risk of injury due to the added strain on the meniscus (Kristianslund et al., 2012; Myer et al., 2014), and therefore may mean that a lateral wedge footwear is not appropriate for dynamic sporting tasks seen in competitive sports, particularly following a meniscectomy. The knee abduction moment was greater compared to all three footwear conditions which supports that adding the lateral wedge may only be beneficial during walking and running. Whilst changes were seen in the footwear, ultimately comfort is an important attribute of footwear selection and thus must be understood to gain the full perspective of the results.

5.5.4 Medial and lateral meniscectomy comparison in footwear

It has been previously stated that the medial and lateral menisci deal with different amounts of loads (Dudhia et al., 2004). In the BOOM study, it was found that although there were no significant differences between following medial and lateral meniscectomy, it was stated that over a longer period, differences may become more apparent. Therefore, analysing the effect of footwear in individuals with both a medial and lateral meniscectomy was important.

Footwear has not been researched following meniscectomy, whereas, it has been widely investigated in joint degeneration such as OA in the knee to try and offload the affected compartment, however this compartment is generally solely the medial compartment (Voloshin, Wosk, & Brull, 1981; Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). Sabbag et al., (2019) found that at 8 years post-lateral meniscectomy approximately 50% of individuals develop lateral knee OA. In the current study, during running, there was a considerable change of knee loading in the lateral wedge footwear. The lateral wedge footwear showed a significant reduction in the EKAM during running (12%) in the individuals following lateral meniscectomy compared to the individuals following medial meniscectomy. This accepted the H_3 Hypothesis stating that there was a difference in knee loading between individuals following medial and lateral meniscectomy. This could be due to the medial arch support helping prevent medial collapse, and with the compromised lateral compartment of the knee.

No significant main effects in the knee loading were seen during walking and change of direction between all four footwear, however, this could be due to all footwear conditions having a slight medial arch support which means there is a slight lateral shift in the GRF in both individuals following medial and lateral meniscectomy. There was also a moderate to large effect sizes in the walking and the change of direction task, which states that there could be a significant result if more participants would have been included when splitting the individuals following medial and lateral meniscectomy. In the current study, it has been observed that the lateral wedge with medial arch support was the most beneficial as it prevented the foot from collapsing inwards and added greater stability which had a more significant effect (Steiner., 2019). In individuals with medial knee OA, it has been widely stated that lateral wedge footwear (Shaw et al., 2018) or footwear with midsoles that are stiffer laterally than medially where the knee load is redistributed away from the medial tibiofemoral compartment towards the lateral tibiofemoral compartment and can be beneficial for individuals with medial knee OA (Bennell et al., 2013; Jones et al., 2015). Likewise, footwear with midsoles that are stiffer medially compared to laterally, such as those with medial arch support seen in stability footwear (Shakoor et al., 2010), shift load toward the medial compartment which may allow a reduction in lateral tibiofemoral knee loading, however this has not been widely researched (Patterson et al., 2020).

Although the lateral meniscectomy shows a more significant reduction in EKAM when wearing the lateral wedge, this may cause more issues for this population. The lateral wedge footwear shifts the GRF laterally to the compromised joint in the lateral meniscus individuals, which reduces medial knee joint loading. This loading is then additionally increased with exercise and could cause further damage or joint degeneration in the knee. Patterson et al., (2020) found that in a healthy population, footwear with medial arch support shifted the GRF medially (Schmalz et al., 2006), reducing loading on the lateral tibiofemoral compartment and therefore may be feasible for offloading individuals following lateral meniscectomy. Whether individuals following lateral meniscectomy develop lateral OA has not previously been researched. Sayer et al., (2018) highlighted that laterally wedged footwear provides a lateral shift of the centre of pressure and increasing the knee abduction moment. On the contrary, medially wedged footwear, create foot inversion, shifting the centre of pressure medially and lowering the knee abduction moment (Franz et al., 2008). This may be applicable for the purpose of offloading the medial and lateral compartment of the knee depending which side had a meniscectomy.

Looking at footwear for both individuals following medial and lateral meniscectomy, therefore, was of interest to investigate whether there was a significant difference between meniscectomies when comparing the four different types of footwear. Sabbag et al., (2019) found that at 8 years post-lateral meniscectomy approximately 50% of individuals develop lateral knee OA. As for medial OA and medial meniscectomy, the intent is to offload the medial compartment of the joint, which is why the lateral wedge footwear may be of benefit for these individuals, however in the individuals following lateral meniscectomy, the aim is to offload the lateral compartment of the knee which is more challenging as the lateral compartment deals with more loads in general. The neutral footwear, which had only a slight medial arch support and has the smallest pitch, seems to be the only footwear that may cause slightly greater medial knee loading, particularly during running and change of direction. With only ten individuals in each group, the results for this study may not have a significant clinical implication. Further research needs to be done with a larger population group comparing individuals following medial and lateral meniscectomy when looking and the lateral wedge and a medial support footwear. The individuals following medial and lateral meniscectomy were grouped together for the comfort analysis as there were no significant differences in kinematic and kinetic outcomes and therefore, comfort was not deemed necessary to be analysed separately.

5.5.5 Comfort Score

Comfort is an important aspect of athletic footwear since it has been associated with health and performance benefits (Hoerzer et al., 2016). Footwear comfort is highly important in clinical populations, as when you have an injury or treatment you do not want discomfort elsewhere (Hurst et al., 2017). Nigg et al., (2015) highlighted that footwear comfort plays an important role in enhancing running performance and in reducing movement-related injuries. Footwear comfort, along with aesthetics are some of the most important aspects to consider when looking at footwear as generally, aesthetics is the deciding factor whether a pair of footwear is chosen followed in priority by its comfort, as seen in high heeled footwear where aesthetics outweigh comfort (Ko and Lee., 2013). Herbaut et al., (2016) stated that comfort for athletic shoes, specifically for individuals who compete in sports is the most important deciding factor when choosing a shoe. In this study, there was a difference in all footwear comfort scores, supporting the hypothesis H_4. The lateral wedge footwear was perceived to be the least comfortable footwear and therefore, it can be assumed that they may not be chosen freely by an individual when purchasing footwear in a retail environment. Ramsey et al., (2019) analysed choice of footwear for 12 runners and identified the complexity of this choice as it includes, the type of running, whether it improves running economy, fit, comfort, performance. The choice of footwear is extremely individualised.

Although lateral wedge footwear may have the most significant benefit in reducing knee loading following meniscectomy during running, due to the low comfort perceived when worn, they would most likely not be worn regularly, and therefore would not have the desired remedial effect expected (Farndon et al., 2016). The comfort in the footwear may also improve as the individuals get used to the footwear, particularly during dynamic tasks and therefore, may still be a solution to offload the knee. Hurst et al., (2017) stated that a more flexible mesh fabric top part of the footwear is thought to reduce pressure on the forefoot and reduce discomfort which is necessary when considering clinical footwear. In the current study, the stability, cushioning and neutral footwear all had a mesh fabric top part, whereas the lateral wedge footwear was a hard leather top, which may have influenced the comfort score. Additionally, with lateral wedge footwear there will be an increased discomfort during athletic tasks. Jones et al., (2014) highlighted that in individuals with knee OA, the pain ratings were correlated with the comfort score of wearing lateral wedge footwear, indicating an increased pain response with reduced footwear comfort. In the current study, the lateral wedge footwear rated the lowest in comfort with a 49% reduction when compared to the neutral trainer. The cushioning footwear also revealed that comfort decreased by 24% compared to the neutral footwear. The reduction of comfort in the cushioning footwear could be explained as the cushioning trainer did have a wider fit around the metatarsals which allowed the foot to slide around particularly during the dynamic tasks and therefore could be the reason for the discomfort of these footwear, whereas the neutral and stability footwear had a more narrow fit. McRitchie et al., (2018) found that 60% of individuals both in an older and younger age group wear the wrong shoe size by around half a size, with around 86% of individuals wearing footwear that was narrower than their actual feet. McRitchie et al., (2018) also showed that narrower shoes are preferred, which is why the cushioning footwear in the current study may have been classes as uncomfortable as it was a wider fit. Mei et al., (2017) highlighted that reduced foot volume in the footwear would lead to footwear support instability, combined with poor motion control from muscle fatigue after long-distance running. Therefore, fit plays a large role in comfort scoring and should be assessed in future work.

5.6 Limitation/Future direction

There were some limitations concerning the findings of the study. Firstly, it is important to note that the individuals in this study were fitted with standard training footwear to minimise the influence of footwear on the results. It is recommended that participant's own footwear be used as control conditions to ensure they do not experience a substantial biomechanical change (Lewinson et al., 2016). However, individuals generally would wear very different footwear and as seen in the current footwear study including variations in pitch, stiffness and including wedges. Implementing different types of footwear has an effect on the data and therefore interpretation of the data would have been harder whilst wearing their own footwear as it would have been unclear if the differences in findings were due to actual changes following meniscectomy or due to different footwear that was worn. However, the standard footwear might have limited comfort during running and thereby might have influenced the running performance. Future studies should be conducted in the participants own footwear or at least include this condition, specifically for the footwear study.

Secondly, the investigator and participants were not blinded to the footwear conditions in the laboratory. However, being blinded to such treatments is difficult due to the footwear conditions looking and feeling different. However, to reduce the bias, the participants were told that all types of treatment are effective following meniscectomy. Future studies should try to have the same outer shell of the footwear with an attractive mesh upper and just adjusting the insoles on the inside and different types of heels such as the increased pitch. The questionnaires for the study were collected without comment to the participants and were analysed at the end of the study without knowledge of the biomechanical data. A cushioning footwear should be used that has a narrower for forefoot to make sure this is not one of the determining factors for the comfort. As these were commercially available footwear provided by Asics, there was no input on footwear in the current study. Additionally, a minimalist shoe should be looked at to identify if there is an greater benefit with an even more reduced pitch. Lastly, not including a control group in the Meni-Foot study with the four footwear conditions is a limitation to the current study as to would have made it clearer what effect these specific types of footwear have following a meniscectomy compared to healthy controls.

In future studies, a lateral wedge footwear should be included with a soft mesh top and more flexible sole to account for aesthetics and comfort. In addition, a more pronounced medial arch support footwear should be included to look at the offload on individuals following lateral meniscectomy.

5.7 Summary

Non-invasive interventions, such as footwear and insoles, have been found to reduce knee loading during running (Lewinson *et al.*, 2013). When participating in sports, it can be assumed that generally, post-meniscectomy the same trainers are worn as before the injury occurred. However, having specific trainers to help offload the affected compartment of the knee could be hugely beneficial in slowing joint degeneration. Lateral wedge insoles have shown promising results in reducing medial knee loading. This does not seem however to be the best method for offloading the lateral tibiofemoral compartment of the knee in individuals following lateral meniscectomy. When considering the comfort of the footwear, the lateral wedge footwear also showed the lowest comfort score compared to the neutral footwear. Further research needs to be undertaken in footwear with a lateral wedge including medial arch support, however including a softer cushioning layer for individuals following medial meniscectomy as well as a footwear with a stiff medial arch support to help reduce lateral knee loading for individuals following lateral meniscectomy. This would then help to create practical based solutions for individuals following a meniscectomy and advice on footwear given.

Chapter 6 - **Final Discussion**

This chapter aims to discuss and summarise the findings of this thesis, to contextualise these findings and their implications and highlight future directions this work should take.

The thesis was created to further understand the effect a meniscectomy has on young active individuals who want to return to sport and perform dynamic tasks and how this could link to an increased risk of joint degeneration in the affected compartment of the knee. This thesis started with a literature review, which identified the gaps in the existing literature. The main gaps identified were the lack of literature looking at the comparison between individuals with a medial and lateral meniscectomy and a lack of literature on dynamic tasks following meniscectomy. A repeatability study was performed to show that the data collected by the researcher was repeatable for the investigation of lower limb kinematics, kinetics and isometric quadriceps strength which were used in this study.

The developed protocol was firstly applied in the BOOM study which investigated the biomechanical outcomes following meniscectomy surgery in comparison to healthy controls and to risk factors associated with knee OA. There was a comparison between individuals with medial and lateral meniscectomies with a focus on dynamic tasks. Lastly, the Meni-Foot study looked at the use of three different types of footwear including a cushioning shoe, stability shoe and lateral wedge shoe in comparison to a neutral shoe, to examine whether footwear offloaded the affected compartment of the knee and slow the risk of OA progression, specifically in a young active population.

The first aim of this thesis was to analyse knee loading in individuals following meniscectomy. The first objective was to compare knee loading and offloading strategies between individuals following medial meniscectomy and individuals following lateral meniscectomy. The second objective was to analyse knee loading during functional and sport-specific tasks and the third objective was looking at outcomes that influence knee loading following meniscectomy such as balance, muscle weakness, activity, kinesiophobia, and quality of life. The second aim of this thesis was to look at footwear as an offloading mechanism for the knee following meniscectomy. The first objective was to identify the difference in knee loading wearing a stability, cushioning and lateral wedge footwear in comparison to neutral footwear. The second objective was to look at knee loading in the three different types of footwear during dynamic tasks and the third objective was to analyse the comfort of these different types of footwear following meniscectomy.

Throughout the thesis there were some hypotheses that showed to be accurate, however there were also several where the null hypothesis had to be accepted instead. H_1 for instance did not show a significant difference in knee loading between individuals following medial and lateral meniscectomy. There were also no significant increases in the EKAM following meniscectomy during all the tasks, however there was still an increase in knee loads which were shown by the increased muscle co-contractions and net activation and therefore H_2, H_3 and H_6 were accepted. H_4 and H_5 were also accepted showing that there were lower self-reported outcomes and isometric muscle strength following meniscectomy compared to healthy controls. There was also a significant difference in knee loads between stability, cushioning and lateral wedge footwear in comparison to the neutral footwear following meniscectomy. This showed a reduction in knee loading whilst wearing the lateral wedge footwear, however the other footwear did not reduce knee loads so H_7 and H_8 can only be partly accepted. Lastly, there was a significant difference in comfort ratings between lateral wedge footwear and cushioning footwear compared to the neutral footwear and therefore H_9 could also be accepted.

The novelty of this thesis was threefold; (i) the changes in biomechanical knee loading following medial meniscectomy were compared to lateral meniscectomy; (ii) a combination of sport-specific tasks in a single sample of individuals following meniscectomy were analysed; (iii) the use of footwear to aid offloading the knee following meniscectomy was investigated.

6.1 Medial compared to lateral meniscectomy

Despite the consideration that medial and lateral menisci properties of the knee deal with different amounts of loads and have different functions (Dudhia et al., 2004), there have been no previous biomechanical studies analysing the comparison between individuals following medial and lateral meniscectomy. The lateral meniscus has been seen to play a more vital part in dynamic movements (Fox et al., 2015), therefore looking at the individuals following medial and lateral meniscectomy in isolation was highly important, specifically in relation to knee joint loading during dynamic tasks. The results in the thesis, however, show no significant differences for both walking and dynamic tasks when comparing individuals following a medial meniscectomy and individuals following a lateral meniscectomy. Therefore, the data was able to be analysed as a whole meniscectomy group following this initial analysis isolating each separate meniscectomy group.

There were no significant differences in kinetic or kinematics for walking, running, landing and change of direction between individuals following medial and lateral meniscectomy. The lack of significant differences could be due to compensatory strategies being used to offload the compartments, such as trunk lean. If an increased lateral trunk lean is implemented, this could help shift the moment arm away from the medial compartment and therefore reduce loads (Jamison et al., 2012). In the current study, it can be seen that lateral trunk lean was greater in the individuals following lateral meniscectomy compared to the individuals following medial meniscectomy during all tasks which aligns with the greater EKAM seen in the individuals following lateral meniscectomy. Fox et al., (2018) highlighted that proximal motion at the trunk appears to have a large effect in managing the loads experienced at the knee following ACL reconstruction. With pain, individuals often walk with an altered gait and may use trunk lean to help reduce the loading on the compromised leg. Although not significant, it could be seen that there was greater knee pain and symptoms present in the individuals following lateral meniscectomy, which showed that they compensate more than the individuals following medial meniscectomy, which is a major contributing factor as to why they were analysed as a sub-group in the Meni-Foot study. Additionally, the differences between meniscectomy groups might become clearer as time progresses when individuals following meniscectomy return back to sport and are no longer in the early stages of rehabilitation.

Footwear had not previously been researched in individuals following a meniscectomy, whereas, it has been widely investigated in joint degeneration (Voloshin, Wosk, & Brull, 1981; Paterson et al., 2017; Shakoor et al., 2010; Paterson et al., 2018). To offload the affected compartment of the knee lateral wedge footwear has been seen to reduce medial knee loading, however this is generally solely looking at medial knee OA (Bennell et al., 2013; Jones et al., 2015; Shaw et al., 2018). Implementing lateral wedge footwear on individuals following medial meniscectomy showed beneficial results as the EKAM was reduced, however, this was indicated to not be the best method for reducing lateral compartment loading for individuals following lateral meniscectomy. Using a greater medial arch support or a medial wedge may be more beneficial for individuals following lateral meniscectomy to offload the lateral compartment and reduce the risk of lateral OA development. The neutral footwear, which had only a slight medial arch support and has the smallest pitch, seems to be the only footwear that may cause slightly greater medial knee loading, particularly during running and change of direction and therefore may be the most beneficial for individuals following lateral meniscectomy.

6.2 Knee loading following meniscectomy in physically active individuals

In this thesis the aim was to investigate the changes in knee loading following meniscectomy surgery compared to healthy controls. Once a meniscal tear occurs and partial meniscectomy is performed, the cartilage is left exposed and loading changes through the whole tibiofemoral joint (Englund et al., 2003). Although tibiofemoral knee loading has been previously analysed following meniscectomy, this has generally been done during walking, with only few studies looking at running (Willy et al., 2016; Hall et al., 2017). Additionally, the running studies were seen not to be ecologically valid, and with a traumatic meniscal tear generally occurring in the young active population (Mitchell et al., 2016), it was important to identify the loads that occur in other non-linear sporting tasks such as landing and change of directions. Joint moments have been identified to be one of the key indicators of joint loading, therefore, understanding these moments is vital for analysing joint health (Sturnieks et al., 2008). The thesis has demonstrated that there were no differences in knee adduction moments (EKAM) and knee adduction angular impulse (KAAI) during walking which contradicts previous studies following meniscectomy (Hall et al., 2015; Sturnieks et al., 2008; Thorlund et al., 2016). The lack of significant differences in the EKAM was hypothesised to be due to the length of time following surgery which aligns with Hall et al., (2014). The previous studies, which have investigated increases in EKAM, were either doing a comparison between early stages of injury/surgery and post-meniscectomy which generally looked at the surgery at least 12 months following meniscectomy, or they were longer term studies of 5-20 years (Sturnieks et al., 2008; Hall et al., 2014; Thorlund et al., 2016). In the current study, EKAM was greater in the individuals following meniscectomy compared to the healthy controls, however, these results were not significant, nor did they have a large effect size. Previous studies suggest that greater EKAM may progress further over time which could show a link to the risk of OA progression and is a future research area for investigation.

The knee flexion moments (KFM) were reduced in the meniscectomy leg compared to healthy controls for walking (29%), running (25%), landing (32%) and change of direction (29%). The reduced KFM was partly caused by changes in the movement patterns such as the significantly greater ankle dorsiflexion angle, greater hip flexion angle and a reduced knee flexion angle during all tasks. These altered movement patterns indicate compensatory mechanisms often seen with quadriceps avoidance that are being used bringing the leg into a stiffer stance which may be due to muscle weakness (Steele et al., 2012) and is often implemented to help ground clearance with a stiffer knee which has been found to increase knee anterior loading (Yavuzer et al., 2011). In the current thesis, it was found that just because the EKAM was not significantly reduced, this did not mean that knee loading did not increase at all as anterior knee loading was greater following the stiffer motion and reduced knee flexion moment. Equally, a stiffer stance has been linked to fear of moving in previous studies, shown by the Tampa scale of kinesiophobia (Molyneux et al., 2017; de Oliveira Silva et a., 2019).

Fear of movement due to surgery and re-injury following ACL reconstruction have been highly reported as negative psychological readiness to return-to-sport outcome (Ageberg & Roos, 2016; Everhart et al., 2020; Hart et al., 2020). Therefore, it was advised that kinesiophobia is brought into standard clinical discharge criteria from physiotherapy and treatment. Several studies which have investigated individuals with knee OA have reported that kinesiophobia has a negative impact on daily activities (Özmen et al., 2017; Alaca 2019; Molyneux et al., 2019). In the current study, there was a significant increase in the Tampa score of Kinesiophobia showing that there was an increase in fear of movement following meniscectomy. The kinematics during running also showed a greater ankle dorsiflexion angle in late stance, with a reduced hip extension angle which are used to increase the push off momentum whilst trying to guard the knee joint following meniscectomy. Changes in knee mechanics and loading were seen to be due to quadriceps avoidance strategies being employed with kinesiophobia and muscle weakness being present which may have been enhanced with the lack of rehabilitation during the current study. When considering the increase of fear of movement at six months post-meniscectomy it is clear that strength and confidence in the movement needs to be implemented earlier in the rehabilitation programme, particularly when considering returning to sport. Rehabilitation criteria and specific programmes have not previously been researched following meniscectomy, however, are crucial for the young active population who wish to return to sport.

Muscle strength is essential to control movement, including movements such as change of direction and landing, which are common in many sports (Rudolph and Snyder-Mackler., 2004). Following meniscectomy quadriceps muscle weakness is often present (Becker et al., 2004; Sturnieks et al., 2011). In the current study, the strength difference between the meniscectomy leg and the healthy controls was 29%, which is a clinically relevant amount as it is more than 10% (Vaidya et al., 2018). Muscle strength recovery is considered important for young individuals after arthroscopic surgery to regain the capacity to participate in sports (Ericsson et al., 2006; Pietrosimone et al., 2016). The muscle net activity was also greater following meniscectomy in the current study, which can be associated with compensatory mechanisms with muscle weakness (Özmen et al., 2017). These changes in strength and muscle activity strongly support the kinesiophobia outcomes and changes in kinematics at early stages of rehabilitation which in turn reduce the physical ability to participate in sport and the quality of life in individuals following meniscectomy.

Activation of the muscles was hypothesised to be lower with greater muscle weakness (Williams et al., 2005). In the current study, however, muscle activation was greater in the knee extensors in both the meniscectomy leg and the contralateral leg compared to the healthy controls in early stance, which was shown in aid to help brace the knee at impact, however the greater knee extensor activation also contributes to increased stiffness around the knee and could increase loading overall. The knee flexors showed significantly greater net activation in the individuals following meniscectomy and the contralateral leg compared to the healthy controls in late stance to aid in knee flexion in preparation for swing. There was a large effect size in the knee extensor and flexor net muscle activation which aligned with the statistical significance highlighting the gravity of change in individuals following meniscectomy compared to the healthy controls. Greater muscle activation has been shown to be linked to pain and kinesiophobia, therefore trying to support the knee joint by keeping it stiff, the individuals keep the muscles actively contracted (Lamoth et al., 2004; Starkey et al., 2020).

The greater lateral co-contraction compared to medial showed a greater offloading strategy occurring to help offload the medial compartment of the knee. There was also a large effect showing an increase in lateral co-contraction of the muscles in individuals following meniscectomy, highlighting the importance of this measure and the gravity of the outcome when looking at all the muscle activity. Sturnieks et al., (2011) reported that greater lateral co-contraction relative to medial is a compensatory mechanism often seen in Individuals with knee OA to try and reduce medial knee loading and lower the EKAM which could support why the EKAM in the current study was not significantly greater. It would be beneficial to look at muscle activation in later stages following meniscectomy and whether the greater activation is an early response to the meniscectomy, or whether this could be a key indicator for risk of knee OA development. These results confirm that there is an increase in knee loading post-meniscectomy with a reduced knee flexion moment for quadriceps avoidance, greater net muscle activation and with greater muscle co-contraction on the lateral side to try and shift the load away from the medial compartment. However, to gain further depth and understand the knee loading response from the muscle activation and co-contractions, it would need to be further examined in an EMG-driven model (Kumar et al., 2012) or a musculoskeletal modelling approach whilst running the EMG data through Opensimm or similar software which was outside the scope of this PhD.

Individuals who sustain a meniscal injury during competitive sport generally aim to return to their pre-injury level of competitive sport as soon as possible (Eberbach et al., 2018). In the current study, 87% of individuals who previously participated in competitive sport were not able to return to their previous sporting level on average six months post-meniscectomy. The low return to sport numbers following meniscectomy in the current study may be linked to lack of rehabilitation with most individuals not starting rehabilitation straight away following the surgery, with significant muscle weakness and kinesiophobia being present. Rehabilitation aids in building confidence in movement while building the strength to participate in sport (Podlog et al., 2015).

In this study, out of the four individuals that went back to participating at a competitive level of their sport, one individual had already suffered a re-injury and has had to be subsequently re-operated. Ekhtiari et al., (2018) stated that out of 244 individuals who had undergone a meniscectomy, 80.4% of them returned to their preoperative level, playing their sport as soon as 4.3 months post-rehabilitation. The individuals playing sport as soon as 4.3 months post-could have been linked to the fact that the individuals had particularly good level of physiotherapy, as Ekhtiari et al., (2018) used elite athletes in their study and they therefore had more physiotherapy contact time. However, in this study, individuals were 3 – 12 months post-surgery and had not returned to sport owing to poor knee function (KOOS), reduced strength, greater fear of movement and poor movement patterns which increases the risk of re-injury (greater KFM and reduced knee flexion angle).

Lack of rehabilitation following ACL reconstruction, specifically including muscle strength, neuromuscular function and range of motion was highlighted by Noyes and Barber-Westin.,

(2019) to lead to reinjury as sport specific tasks are not targeted in general rehabilitation programmes. The reduction in knee flexion moment during all tasks, particularly change of direction has been seen to indicate a reduced ability to absorb loads through the knee (Fox et al., 2018). The knee stays in a more extended position and can therefore influence the re-injury susceptibility on return to their competitive sports (Dos'Santos et al., 2018). The previously stated results such as the stiffer movement strategies, greater muscle co-contraction and greater kinesiophobia have all been linked to bad KOOS outcomes (Hall et al., 2013; Thorlund et al., 2017). The lower perception of the function of the knee following meniscectomy could also be linked to poor rehabilitation and not building strength and confidence in the knee following meniscectomy, to allow the individuals to return to participating in their preferred sport.

6.3 Footwear following meniscectomy compared to healthy controls

Stability, cushioning and lateral wedge footwear were analysed in the Meni-foot study to identify an easy way to help offload the compromised joint following a meniscectomy which can be implemented both in rehabilitation/recovery and when returning to sport and performing dynamic tasks. Footwear has been seen to knee loading in individuals with knee OA and can be a comfortable and cost-effective way to reduce symptomatic pain and possibly slow OA progression (Bennell et al., 2009). There has been previous research which has stated that footwear can be used to help offload individuals who suffer from knee pain and joint degeneration by shifting the GRF and reducing the EKAM (Jones et al., 2015), however, footwear had never been looked at following meniscectomy, which could be employed as an effective and relatively low-cost way to offload the knee and help return back to significant physical activity.

In all the footwear conditions, there were no significant changes during walking in EKAM, which was comparable to the data found in the BOOM study. The values in both sagittal and frontal planes were comparable to those found in the BOOM study which is to be expected as the participants were the same for both studies. Nigg et al., (2017) analysed the difference in running whilst wearing a conventional running shoe, a racing flat shoe and a minimalist shoe and found that there were minimal differences. Similar to the current study, Nigg et al., (2017) only found differences in the sagittal plane, however there were no changes in joint angles more than 2.5° which was stated not to be significant in their study. Nigg et al., (2017) showed the magnitude of differences to be split in thresholds of 2°, 3° and 5°, showing the greatest difference as anything over 5° during running. In the current study all differences in motion was also under 2.5°. Nigg et al., (2017) also looked at wearing footwear and barefoot and found that there was a greater change, which states that the change in movement patterns is dependent on the magnitude of the change introduced by the footwear condition, which supports why there is a greater change in movement seen in the current study whilst wearing the lateral wedge footwear.

When examining knee loading during drop landing, whilst footwear with greater cushioning, EKAM was seen to be slightly greater in healthy controls (Lindenberg et al., 2011). The increase in knee loading is due to the additional imbalance caused by the increased soft heel, which the body needs to compensate for and can be seen by the greater shift in the centre of pressure in the cushioning footwear compared to neutral footwear (Jellema et al., 2019). Bohne et al., (2017) found that there was not a substantial difference in knee loading between extra cushioning in a shoe and a standard normal shoe during running. The current Meni-foot study supported the lack of difference in increased cushioning as seen by Bohne et al., (2017), as there were minimal changes in knee loading in the cushioning footwear compared to neutral footwear in the current study.

Following injury or surgery, knee stability is often reduced (Almekinders et al., 2004), however, the current study shoes that adding more stability or stiffness to shoes may not be the most beneficial intervention for an active clinical population. Previous studies have reported greater peak KFM wearing stability shoes and neutral shoes compared to barefoot in a mixed cohort (Bonacci et al., 2014 and Sinclair et al., 2014), which supports the findings in these individuals following meniscectomy as there was a slight increase in KFM in the stability shoe, however no significant difference compared to the neutral shoe. This was supported by the effect size throughout the study being low in walking, running and change of direction. Sayer et al., (2018) found that the greater KFM was mainly due to the footwear pitch. Similarly, to the cushioning data, the stability shoe results showed a slight reduction in EKAM and increase in KFM. This could be due to the minimalist index being identical at 12% in the stability and cushioning footwear, which leads to minimalist footwear being of greater interest for future research. The similarity in knee loading between the meniscectomy and healthy controls whilst wearing stability footwear shows that although there are no significant differences between the stability and neutral shoe, there is a reduction in knee loading similar to those of the healthy controls. Wearing shoes in general increases the EKAM compared to barefoot walking

(Shakoor et al., 2006). Sinclair et al., (2018) however, emphasised the opposite, and analysed barefoot, minimalist and general running trainers during running and found that there was greater medial compartment knee loading (20-25%) when wearing no or minimalist trainers which puts the runners at increased risk of medial compartment knee OA. Minimalist footwear should be considered in a future study in individuals following meniscectomy as the footwear conditions did not reduce knee loading compared to the neutral shoe which may indicate that a lower pitch leading to minimalist footwear could be beneficial in the compromised knee joint, however caution needs to be taken when analysing more dynamic tasks and minimalist footwear.

Previous studies have highlighted that a lateral wedge of at least 5° produces reductions in the first peak EKAM during walking (Hinman et al., 2008; Fu et al., 2015; Butler et al., 2009; Jones et al., 2013). Jones et al. (2015) highlighted that both the typical lateral wedge (5.21%) and medial supported lateral wedge (6.29%) reduced the medial knee loading during walking, showing a more significant reduction with medial support. On contrary, Starbuck et al., (2017) found that during running whilst wearing lateral wedge footwear knee loading did not differ, which was stated to be associated to different foot strike patterns. However, in most literature with individuals with medial knee OA, it has been widely stated that an lateral wedge footwear, where the knee load is redistributed away from the medial compartment towards the lateral compartment of the knee can be beneficial for reducing knee loading in individuals with medial knee OA (Bennell et al., 2013; Jones et al., 2015; Shaw et al., 2018). Likewise, footwear with midsoles that are raised medially compared to laterally, such as those with medial arch support seen in stability footwear (Shakoor et al., 2010), shift load toward the medial compartment which may allow a reduction in lateral compartment knee loading, however this has not been widely researched (Patterson et al., 2020).

It has been stated that lateral wedge footwear can be used to offload the knee, due to an increase in ankle eversion occurring, shifting the ground reaction force laterally and therefore reducing EKAM (Kakihana et al., 2005). In this study, a medially supported lateral wedge was found to have an 11% reduction in EKAM during walking in meniscectomy which supported the consensus of previous studies (Bennell et al., 2013; Erhart-Hledik et al., 2012; Erhart et al., 2008; Fisher et al., 2007). Although dynamic tasks were not previously considered in footwear, specifically in individuals following meniscectomy, it was found in the Meni-Foot study that knee loading was reduced even more significantly during running with a reduction in the

EKAM of 15% in the lateral wedge footwear compared to neutral footwear and a 17% reduction in knee abduction moment during the change of direction task. In comparison to the BOOM study, it could be seen that the KFM was greater to a similar level in the lateral wedge footwear as the healthy controls during walking, running and change of direction. The EKAM whilst wearing the lateral wedge footwear was reduced to a level that was on average 12% lower than the healthy controls indicating that the knee loading can be reduced using a lateral wedge footwear following meniscectomy.

6.4 Limitations

There were some limitations concerning the overall findings in this thesis. Firstly, it is important to note that the individuals in this study were fitted with standard training shoes to minimise the influence of footwear on the results. Individuals would normally wear different footwear than that worn in this study and therefore it may affect the data as the individuals may need not find the footwear easy to manoeuvre in and they were not given a familiarisation period to get used to the footwear. Standardising footwear allows the exploration of knee loading in individuals following a meniscectomy compared with healthy individuals without the influence of footwear. However, the standard training shoes might have limited the comfort during running and thereby might have influenced the running performance. Future studies should be conducted in the individuals own training shoes or at least include this condition, specifically for the footwear study.

Secondly, although it was seen that knee loading was greater in the current study with a stiffer gait and greater co-contraction of the muscles, the results appearing may be short-term consequences to lack of rehabilitation and muscle weakness. A limitation is that exact rehabilitation was not recorded, but self-reported ones were which may not be as accurate. A longer-term study should be considered to look at both short term outcomes including a group that follows vigorous rehabilitation and a group that does not. The study should include all the related outcome measures that were used in the current study including EMG, KOOS, kinesiophobia, balance and the kinematics and kinetics to establish how rehabilitation and changes following meniscectomy alter over a longer period of time. A longitudinal study would help establish a clearer link to the risk associated with OA, particularly when including dynamic tasks and return to sport criteria. The current study did not look at the exact rehabilitation plan, nor the quality of rehabilitation, which is a limitation, as all the data collected was either verbal feedback or from the rehabilitation questionnaire which due to its length may not have been filled out completely or as detailed as it could potentially have been.

The lack of differences could be due to the size and location of the meniscal tear, however this has not been previously researched as discriminating between size of meniscectomy is quite complex and difficult to accurately determine consistently. The size of the meniscal tear may affect the number of loads managed by the knee and therefore could cause increased risk of knee degeneration. On contrary, some of the significant differences that were found in the current study without a large effect size, may have been due to the number of statistical tests that were run, therefore causing mass significance and creating a false positive result.

Although the sample size in the current study was comparable with previous studies, the outcomes would have had more power to them with a larger sample size. Specifically, when having the individuals following medial and lateral meniscectomy separate, it could be seen that there were no significant differences, however there were moderate effect sizes which highlight that with a greater sample size, there may have been more significances. As the protocol in this study was not complex, the rigour of the study was still high even if the low sample size was not massive.

Lastly, the investigator and participants were not blinded to the footwear conditions in the laboratory. However, being blinded to such treatments is difficult due to the footwear conditions looking and feeling different. The intervention is inserted in the shoes or is wrapped around the knee, however, to reduce the bias, the participants were told that all types of treatment are effective following meniscectomy. The questionnaires for the study were collected without comment to the participants and were analysed at the end of the study without knowledge of the biomechanical data.

6.5 Novelty of study

This study investigated the biomechanical outcomes post-meniscectomy during functional and sport specific tasks compared to healthy individuals. Meniscal injuries are one of the most common knee injuries in competitive sport which include running, change of direction and landing movements, with meniscectomy being the most common treatment. To the authors knowledge, only a very few studies have investigated the effect of high impact activities as seen in competitive sports on individuals following meniscectomy including two studies looking at non-ecologically valid running (Willy et al., 2016, Hall et al., 20140, one study looking at landing (Ford et al., 2011) and one study looking at a single leg hop (Hsu et al., 2016). As a traumatic meniscal tear generally occurs in a sporting environment, looking at dynamic tasks such as running, landing and change of direction where the knee is at greater risk is much more beneficial, specifically to understand what happens to the knee following meniscectomy in an active population.

There has never been a study looking at balance nor muscle activation combined with links relating to strength, KOOS and kinesiophobia in individuals following meniscectomy. This could have a major implication for individuals following meniscectomy as this could identify issues post-surgery and give strategies and modalities to help slow if not offset degeneration in the joint, allowing these athletic individuals to carry on with competitive sport. This is the first study to look at the entire gamut of everything that occurs biomechanically, clinically and psychologically in a sporting population post-meniscectomy. For example, EKAM is the most reported outcomes in meniscectomy literature to look at knee loading, as previous studies have shown that EKAM is correlated with loading and is a valid and reliable measurement (Kutzner et al., 2013; Schipplein & Andriacchi, 1991). Furthermore, muscle co-contraction has recently been found to correlate with knee joint loading (Brandon et al., 2014; Sritharan et al., 2017; Winby et al., 2013) and may cause higher loading even if EKAM remains the same (Lu et al., 1997; Trepczynski et al., 2014). Moreover, Walter et al. (2010) highlighted that a reduction in EKAM may not guarantee a reduction in loading due to the increase in the knee flexion moment. This highlights the importance of combining several outcomes in the same study as EKAM, muscle co-contraction and the knee flexion moment, as it is important that a reduction in one outcome that reflects knee joint loading is not offset by an increase in another one. This was then supported by looking at the strength, balance and psychological aspects to support any other findings in knee loading and to fully understand why these changes may be present. In this thesis the most important outcome six month following meniscectomy was the knee flexion moments as this showed quadriceps avoidance and greater knee loading in the early stages of rehabilitation. This highlights the strength of the current thesis for gaining a full picture and a better view of what is going on following meniscectomy.

To date, there has only ever been one study that looked at the biomechanical outcomes following lateral meniscectomy (Ford et al., 2011), however, there have been no biomechanical studies that compare both individuals following medial and lateral meniscectomy. Both the medial and lateral menisci load differently and aid in different aspects of movement. Therefore, looking at both medial and lateral meniscectomies, specifically when looking at sport is of high value.

Footwear interventions have been used in individuals with knee OA to reduce knee loading and pain (Butler et al., 2007; Chapman et al., 2013; Erhart et al., 2008). This conservative strategy could be used to help offload the affected knee following meniscectomy and possibly help slow joint degeneration by alleviating the affected compartment of the knee. Looking at several different types of footwear allowed this study to determine the biomechanical changes in knee loading mechanisms whilst wearing different commercially available footwear and possibly use these as an offloading mechanism post-meniscectomy. Footwear interventions have never been looked at in individuals following meniscectomy, however, could be used as way to help slow or reduce the risk of knee OA development. Looking at both the medial and lateral meniscectomy also helps identify different strategies to help offload both compartments of the knee.

6.6 Implications of study to clinical practice

In the current thesis, although results were not significant, compensatory mechanisms were seen in individuals following lateral meniscectomy more than in individuals following medial meniscectomy. Due to its role in dynamic tasks, it is essential to look at the lateral meniscus when individuals return to sport and analyse the knee loading capabilities over a longer period of time, with a minimum follow-up period of 12 month. Although the differences were not significant in the early stages following rehabilitation, literature has suggested that gait adaptations may become more evident longer term (Thorlund et al., 2016).

Following the results found in this thesis, knee loading increases and changes over time following meniscectomy. Rehabilitation is key in the early stages of recovery influencing an individual’s muscle activation and weakness, gait adaptations, kinesiophobia, and perception of knee function and may have played a part in the current study results, however accurate correlations between these outcomes cannot be made. In the UK, for the sample of individuals appearing in this thesis, it was demonstrated that NHS rehabilitation was insufficient for individuals with the aim of returning to sport. When stating that rehabilitation was insufficient, it refers to the time taken to start rehabilitation, in addition to muscle weakness still being significantly reduced six-months following meniscectomy compared to healthy controls.

Lateral wedge footwear has been seen to help offload the medial compartment of the knee and therefore can be recommended for individuals following medial meniscectomy when participating in dynamic tasks. Greater pitch has been seen to increase knee loading slightly and therefore is not as advisable for individuals following meniscectomy, however this may not be as evident in the longer term when stability in the knee is improved with muscle strength. Footwear to offload the lateral compartment of the knee, needs to be researched further and it is not advisable for individuals following lateral meniscectomy to wear lateral wedge footwear.

6.7 Future directions

In this thesis, although there were no significant differences in the outcomes compared to medial and lateral meniscectomy, there were still indications that there might be differences longer term as knee loading was still greater in individuals following meniscectomy compared to the healthy controls. This needs to be investigated further in a longitudinal study with an increased sample size. Understanding what occurs in the lateral meniscectomy over time could be clinically beneficial to help understand the difference in movement patterns between these injuries and why medial meniscectomies are more likely to end up developing OA. Future studies looking at both medial and lateral meniscectomies and medial compared to lateral OA should include MRI scans.

Future studies should also look at analysing the total knee joint moment which incorporates all planes, as well as using SPM to analyse the whole waveform, rather than solely interpreting the peak values. SPM allows for the comparison of entire movement cycles, reducing the likelihood of errors in the reporting of statistical inferences. SPM removes interpretation bias and focuses solely on the quantitative data. Such an analysis is required to appropriately identify the biomechanical differences between individuals following meniscectomy and healthy controls.

There has been previous research which has stated that footwear can be used to help offload individuals who suffer from knee pain and joint degeneration by shifting the GRF and reducing the EKAM (Jones et al., 2015). The lateral wedge insole with a medial arch support shows the most promising results in offloading the medial compartment for individuals following medial meniscectomy, however due to the comfort of these shoes being low, further research needs to be done to look into a softer insole in a more flexible shoe in order to increase acceptance by the individuals. In addition, a stronger medial arch support shoe should be analysed to help offload the lateral compartment of the knee in individuals following lateral meniscectomy.

Post-meniscectomy research thus far has only concentrated on either walking or non-ecologically valid running, as Willy et al., (2016) looked at treadmill running and Hall et al., (2014) looked at barefoot running. These previous running studies are not translatable to a real life setting where individuals would run over ground wearing shoes and therefore, does not give a full indication of the loads that are applied to the body in competitive sports, particularly in individuals who may have a compromised knee joint. In the current study, it has been demonstrated that loads are greater on the joint following meniscectomy, and with a greater muscle weakness return to sport between 3-12 months post-surgery point is not advisable. Rehabilitation should be started at an earlier stage following meniscectomy and should be managed more than once every two weeks to avoid muscle atrophy and get back to dynamic movement as soon as possible without the psychological trauma of kinesiophobia. Further research should be conducted looking at the effect of different stages of rehabilitation and how this may influence return to sport for the individuals whilst looking at compensatory mechanisms following meniscectomy.

6.8 Summary

To summarise, the comparison between the medial and lateral meniscectomies did not show any significant results, however a greater dysfunction in the individuals following lateral meniscectomy was indicated with greater loading and greater compensatory mechanisms present such as greater trunk lean. When returning to sport between 3-12 months post-meniscectomy, individuals are not generally ready as they still suffer from muscle weakness, lack of motor control, reduced self-perceived function and kinesiophobia, increasing movement inhibition and therefore causing reduced quality of life and potentially increasing the risk of re-injury.

Non-invasive interventions, such as footwear and insoles, have been found to reduce knee loading during running (Lewinson et al., 2013). Lateral wedge insoles have shown promising results in reducing medial knee loading in individuals following meniscectomy. When considering the comfort of the shoes however, the lateral wedge shoe also showed the most significant discomfort. Using the lateral wedge footwear also does not seem however, to be the best method for offloading the lateral tibiofemoral compartment of the knee in individuals following lateral meniscectomy. Shoes with more significant medial arch support may be of greater benefit for individuals following lateral meniscectomy and need to be researched further.

The current thesis has provided substantial knowledge in individuals following meniscectomy in various methodological areas. Increases in knee loading following meniscectomy were shown due to a stiffer movement pattern, greater muscle activation and quadriceps avoidance. Fear of movement was present and self-reported function was low. This is the first study to the authors knowledge that looked at dynamic tasks such as change of direction following meniscectomy although it is a common sporting injury. All the findings highlight the importance of rehabilitation, particularly when returning to sport. Without proper rehabilitation, specifically in the early stages following meniscectomy compensatory factors start developing which may have severe consequences when returning to sport and can increase the risk of OA developments. Footwear can be seen to be a good way to help offload the affected compartments of the knee, however the perfect shoe has not yet been established for both individuals following medial and lateral meniscectomy, but future directions have been made clear.

Chapter 7 - **References**

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Chapter 8 - **Appendices**

Appendix 1: Ethical approval

University of Salford
MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

10 March 2017

Dear Vanessa,

RE: ETHICS APPLICATION–HSR1617-57–'The reliability of lower limb and thoracic kinematics and strength measures in relation to clinical patients.'

Based on the information you provided I am pleased to inform you that application HSR1617-57 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

University of
Salford
MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

21 February 2017

Dear Vanessa,

RE: ETHICS APPLICATION HSR1617-56 – 'Biomechanical Outcomes associated with OA progression in Meniscectomy patients during athletic and functional tasks (BOOM study).'

Based on the information you provided I am pleased to inform you that your application HSR1617-56 has been approved to go forward to NRES.

Once you have received it, please submit a copy of the NRES approval letter to Health-ResearchEthics@salford.ac.uk so that it can be placed on your application file.

If there are any changes to the project and/or its methodology, please inform the Health Research Ethics Support team as soon as possible.

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

University of Salford
MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
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22 June 2017

Dear Vanessa,

RE: ETHICS APPLICATION HSR1617-140 – 'The effect of commercially available footwear interventions on biomechanical outcomes associated with knee osteoarthritis in meniscectomy patients. The MENI-FOOT project.'

Based on the information you provided I am pleased to inform you that your application HSR1617-140 has been approved to go forward to NRES.

Once you have received it, please submit a copy of the NRES approval letter to Health-ResearchEthics@salford.ac.uk so that it can be placed on your application file.

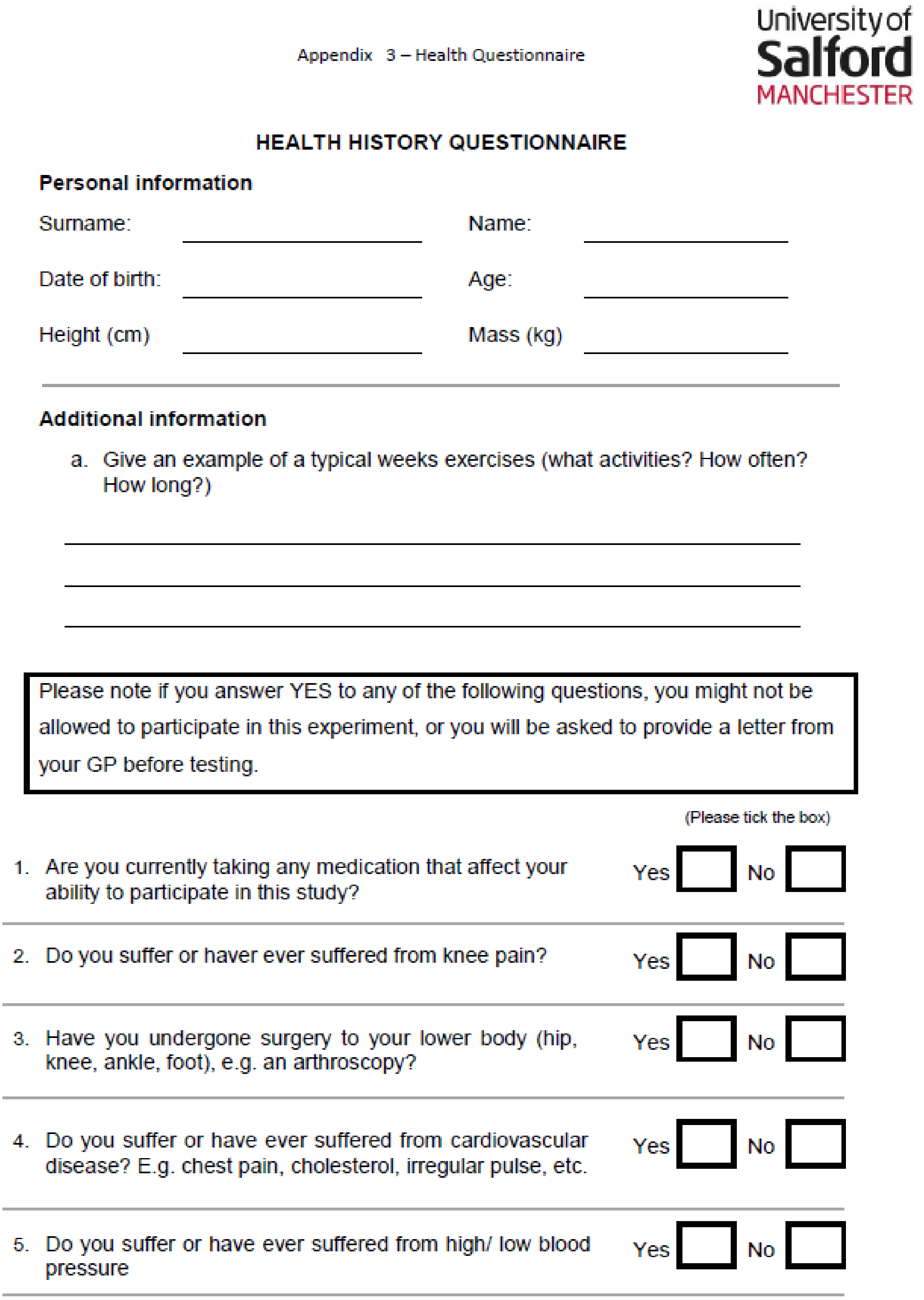
If there are any changes to the project and/or its methodology, please inform the Health Research Ethics Support team as soon as possible.

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

Appendix 2: Questionnaires

Appendix 2.1: Health questionnaire



Appendix 3 – Health Questionnaire

University of Salford
MANCHESTER

HEALTH HISTORY QUESTIONNAIRE

Personal information

Surname: ____________________ Name: ____________________

Date of birth: ____________________ Age: ____________________

Height (cm) ____________________ Mass (kg) ____________________

Additional information

a. Give an example of a typical weeks exercises (what activities? How often? How long?)

____

____

____

Please note if you answer YES to any of the following questions, you might not be allowed to participate in this experiment, or you will be asked to provide a letter from your GP before testing.

(Please tick the box)

1. Are you currently taking any medication that affect your ability to participate in this study? Yes ☐ No ☐
2. Do you suffer or haver ever suffered from knee pain? Yes ☐ No ☐
3. Have you undergone surgery to your lower body (hip, knee, ankle, foot), e.g. an arthroscopy? Yes ☐ No ☐
4. Do you suffer or have ever suffered from cardiovascular disease? E.g. chest pain, cholesterol, irregular pulse, etc. Yes ☐ No ☐
5. Do you suffer or have ever suffered from high/ low blood pressure Yes ☐ No ☐

6. Do you suffer or ever suffered from respiratory disease? E.g. asthma, bronchitis, etc. Yes ☐ No ☐

7. Do you suffer or ever suffered from diabetes? Yes ☐ No ☐

8. Do you suffer or ever suffered from epilepsy/ seizures? Yes ☐ No ☐

9. Have you had a cold or feverish illness within the last two weeks Yes ☐ No ☐

10. Do you ever lose balance because of dizziness, or do you ever lose consciousness Yes ☐ No ☐

11. Are you currently receiving treatment or medical advice from a GP or physiotherapist? Yes ☐ No ☐

12. Are there other reasons, not mentioned above, why you should not exercise? E.g. an accident, pregnancy, surgeries, or anything else Yes ☐ No ☐

Name of participant ______________________ **Date** __________

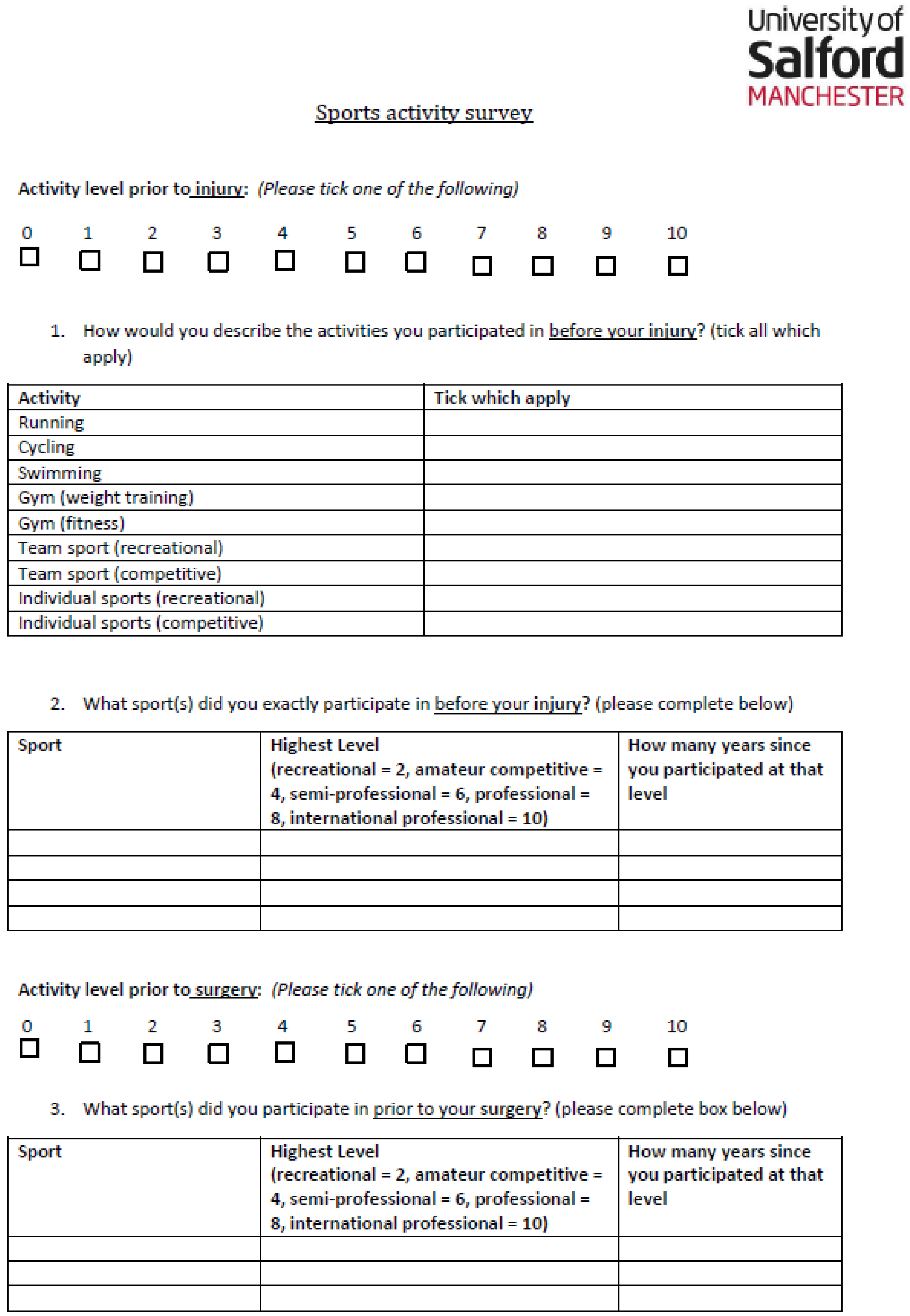
If this questionnaire was not completed and countersigned immediately prior to testing, the participant must complete this section:

I certify that none of the above information has changed since I completed this questionnaire.

Signature of participant ____________________ **Date** ________

Name of researcher ____________ **Signature** ____________ **Date** ________

Appendix 2.2: Sport activity survey



University of Salford MANCHESTER

Sports activity survey

Activity level prior to injury: *(Please tick one of the following)*

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

1. How would you describe the activities you participated in before your injury? (tick all which apply)

Activity	Tick which apply
Running	
Cycling	
Swimming	
Gym (weight training)	
Gym (fitness)	
Team sport (recreational)	
Team sport (competitive)	
Individual sports (recreational)	
Individual sports (competitive)	

2. What sport(s) did you exactly participate in before your injury? (please complete below)

Sport	Highest Level (recreational = 2, amateur competitive = 4, semi-professional = 6, professional = 8, international professional = 10)	How many years since you participated at that level

Activity level prior to surgery: *(Please tick one of the following)*

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. What sport(s) did you participate in prior to your surgery? (please complete box below)

Sport	Highest Level (recreational = 2, amateur competitive = 4, semi-professional = 6, professional = 8, international professional = 10)	How many years since you participated at that level

4. In the 3 months prior to your surgery could you indicate how much time you spent doing the following training activities?

Activity	**Hours per week (0-2, 3-4, 5-6, 7-8, 9-10)**
Gym (weight training)	
Gym (circuit training or classes)	
Gym (cardiovascular training; bikes, cross trainer rowing, running etc)	
Sport specific training	
Competitive matches-events	
Other sport activity	

Activity level NOW: *(Please tick one of the following)*

0	1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

5. Give an example of typical week's exercises at present:

Activity	**How often a week**	**How many hours**	**Level**

Please tick one of the following

6. Compared to before your injury, how would you rate your activity level now?
   - Much better than before injury ☐
   - Somewhat better than before injury ☐
   - About the same as before injury ☐
   - Somewhat worse than before injury ☐
   - Much worse than before injury ☐

Please tick one of the following

7. Compared to before your surgery, how would you rate your activity level now?
   - Much better than before surgery ☐
   - Somewhat better than before surgery ☐
   - About the same as before surgery ☐
   - Somewhat worse than before surgery ☐
   - Much worse than before surgery ☐

Appendix 2.3: Rehabilitation questionnaire

Rehabilitation Questionnaire

Date:

Name: Date of Operation:

Age: Type of operation:

Did you have regular physiotherapy sessions: Yes/No

Rehabilitation period: ____________________

How often did you see physiotherapist: ____________________

Are you back to full physical strength: Yes/No

In your physiotherapy programme did you do any of the following exercises, how often and at what stage of the programme?

1. **Passive knee extension**

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

2. **Heel slide**

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

3. Standing knee to wall

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

4. Hamstring stretch on wall

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

5. Straight leg raise

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

6. Clams

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

7. Glute bridges

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

8. Step up

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

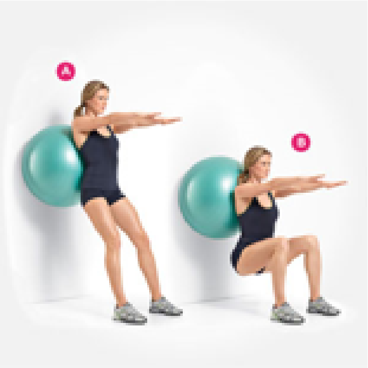
9. Wall squat

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________



10. Crab walks

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

11. Resisted knee extension

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

12. Leg press

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

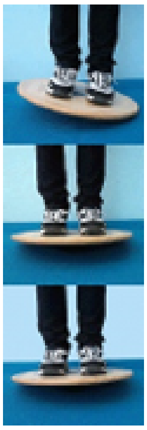
13. Balance board exercises

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________



14. Squats

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

15. Lunges

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

16. Single leg squat

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

17. Plyometric (jumps, hops)

Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

18. Agility (ladders, change direction)

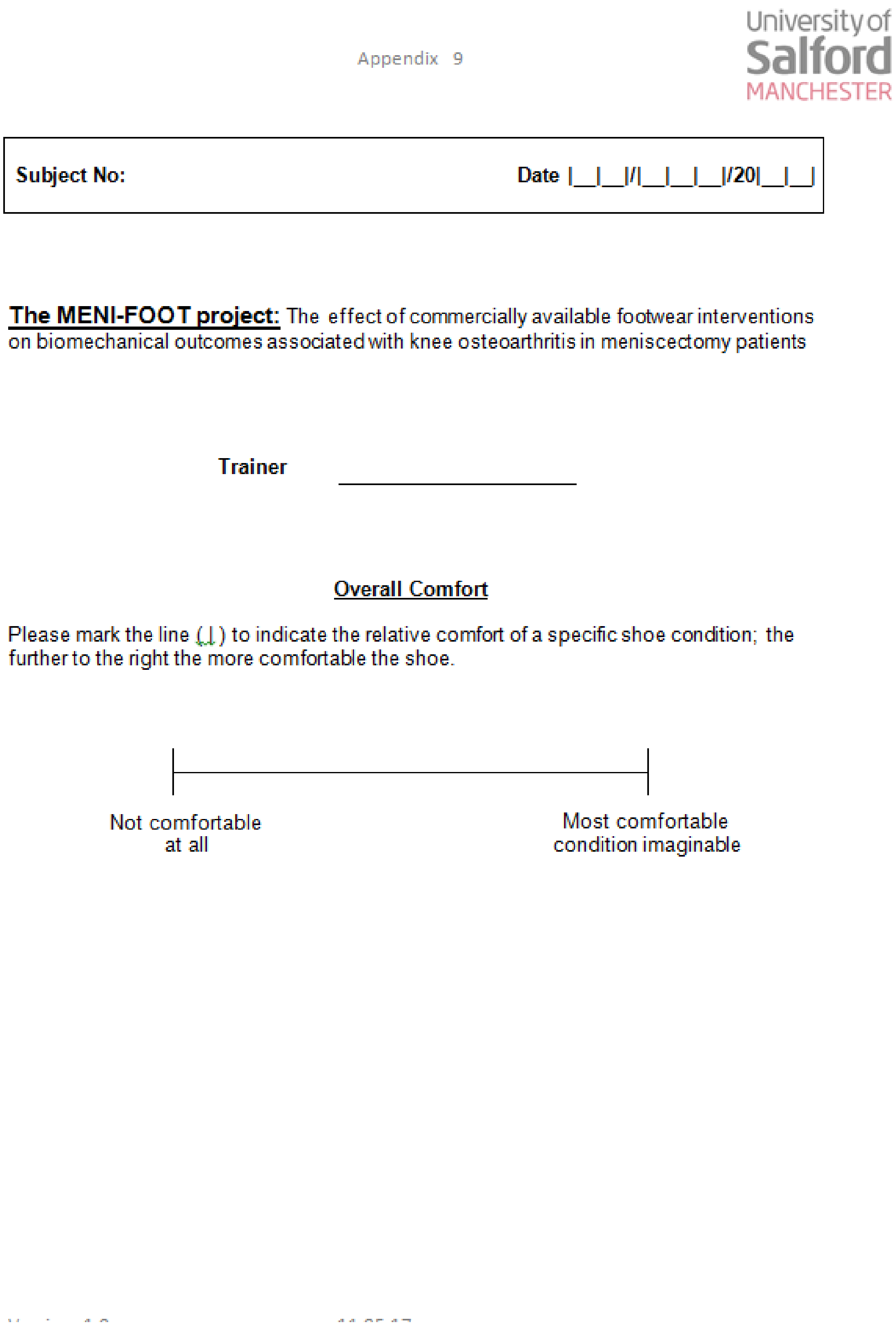
Have you done this in your rehab? Yes/No

At what stage of your program did you do this? ____________________

How often did you do this exercise? ____________________

How long did you carry on doing this exercise? ____________________

Appendix 2.4: VAS Footwear comfort score



Appendix 9

University of Salford MANCHESTER

Subject No: **Date |__|__|/|__|__|__|/20|__|__|**

The MENI-FOOT project: The effect of commercially available footwear interventions on biomechanical outcomes associated with knee osteoarthritis in meniscectomy patients

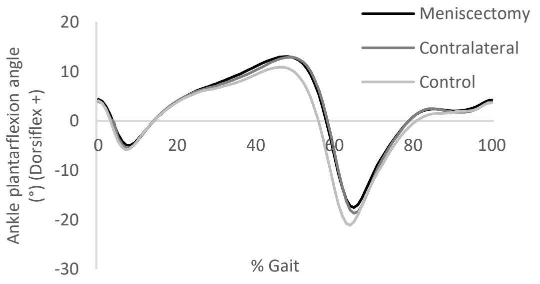
Trainer ____________________

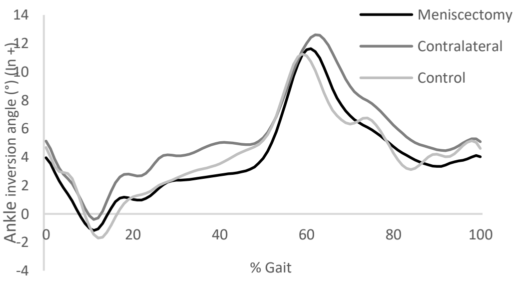
Overall Comfort

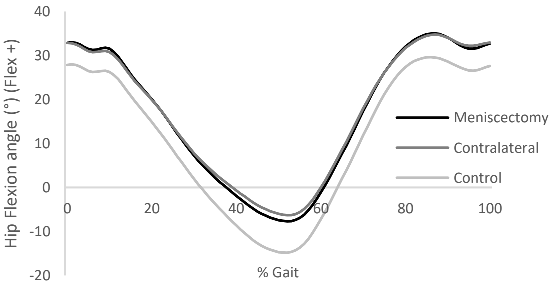
Please mark the line (|) to indicate the relative comfort of a specific shoe condition; the further to the right the more comfortable the shoe.

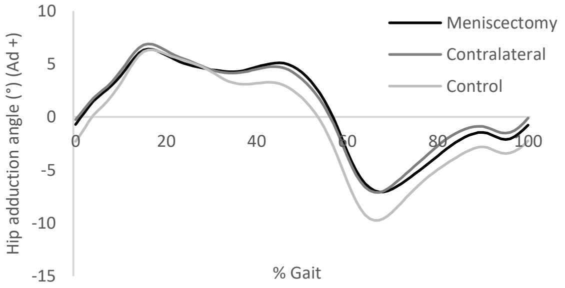
Appendix 3: Graphs

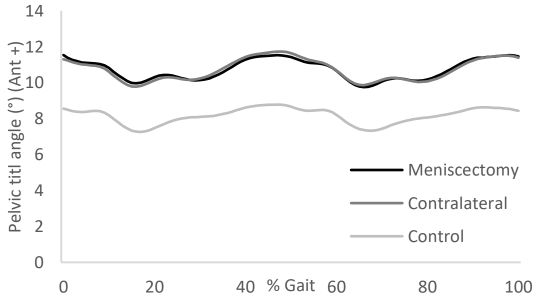
Appendix 3.1: Walking

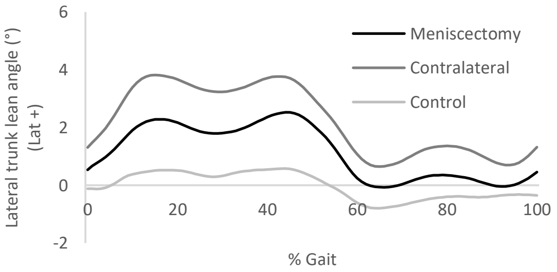


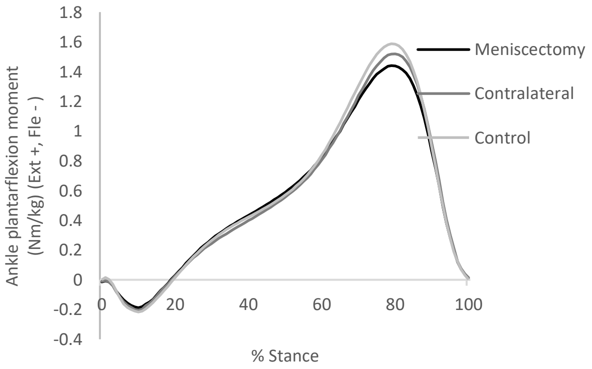


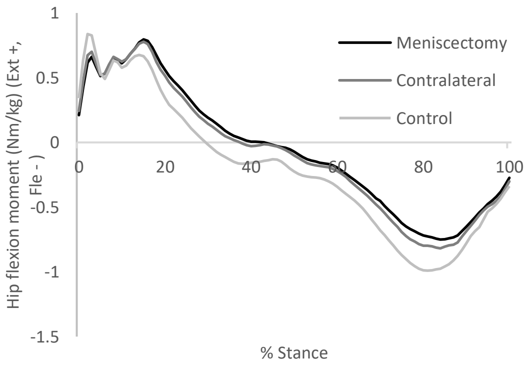


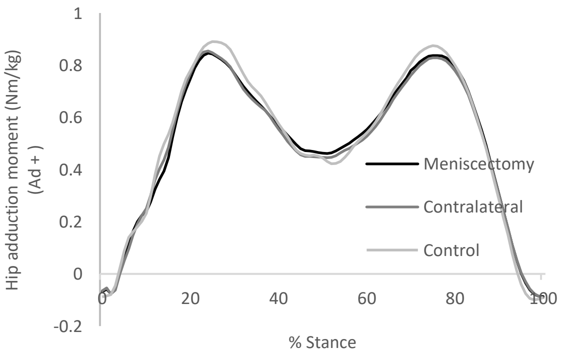


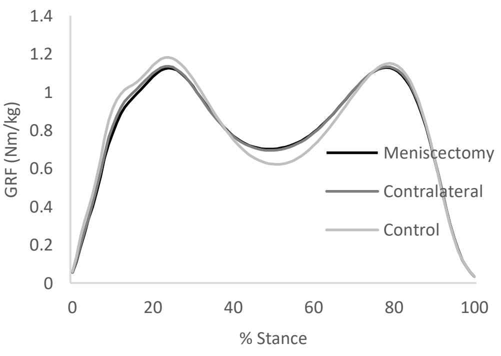




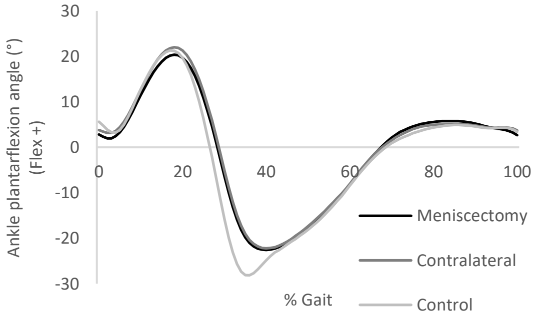


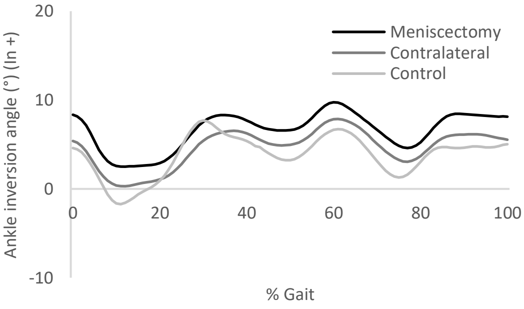


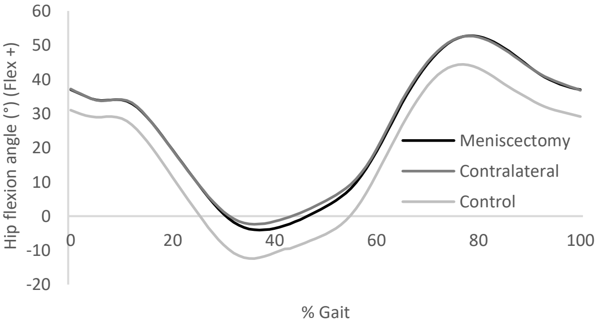


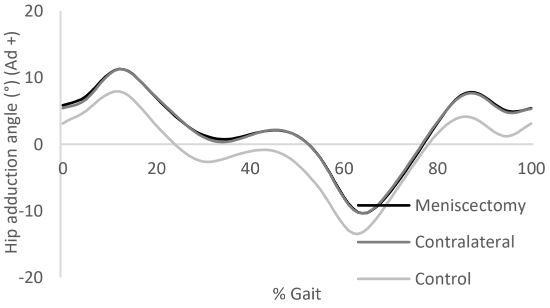


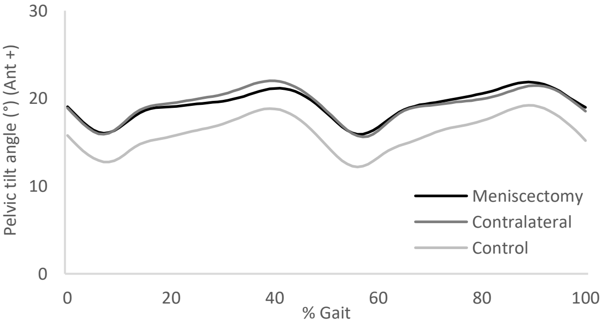
Appendix 3.2: Running

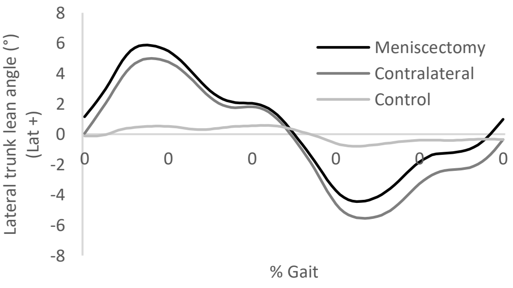


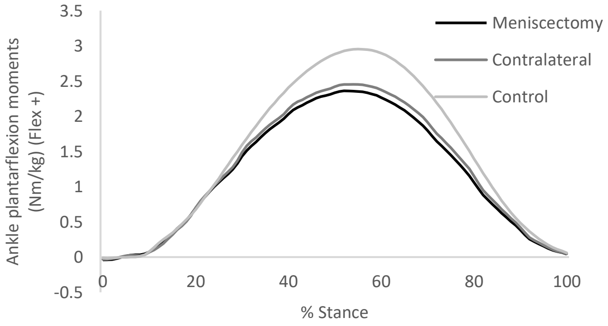


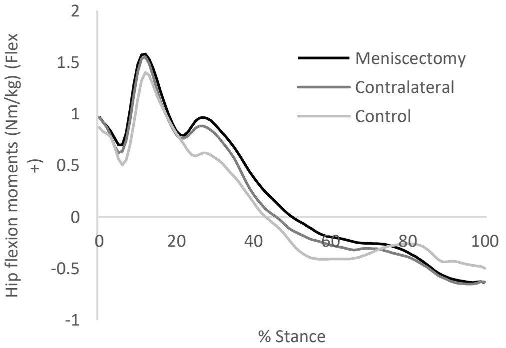


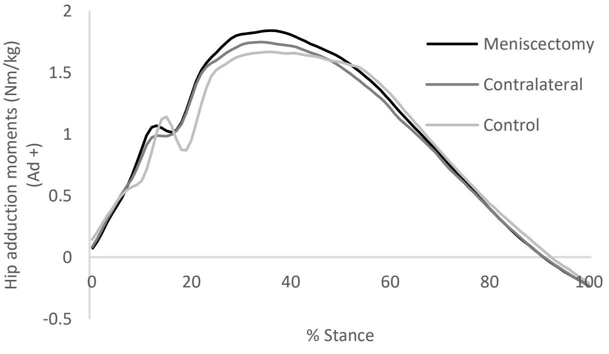


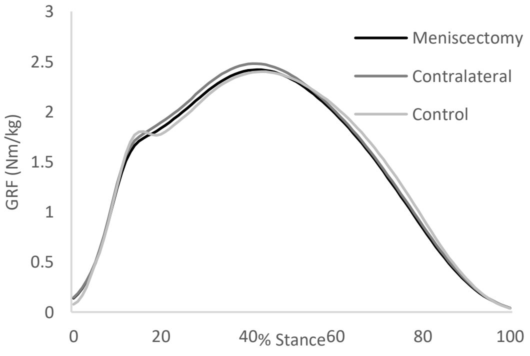




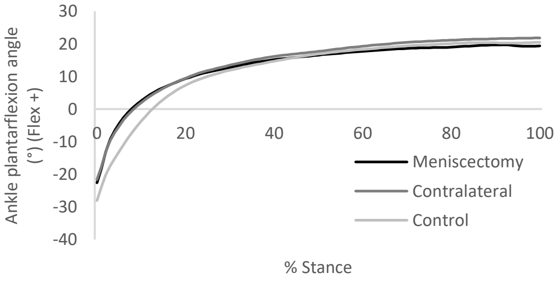


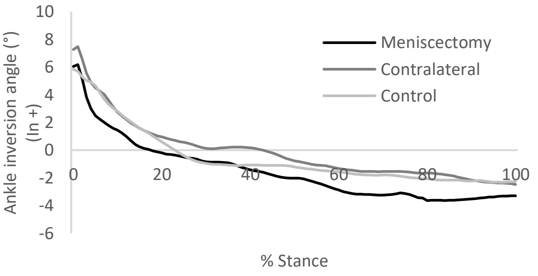


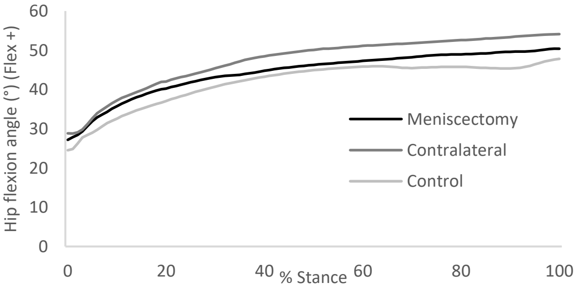


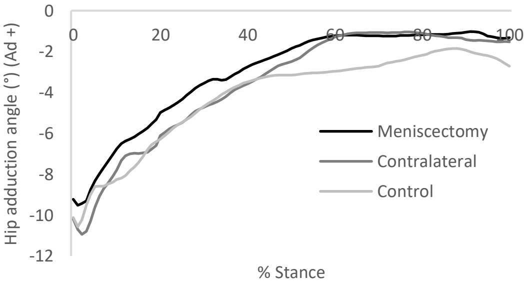


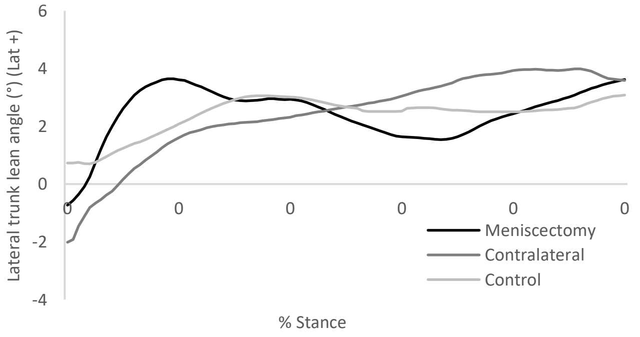
Appendix 3.3: Landing

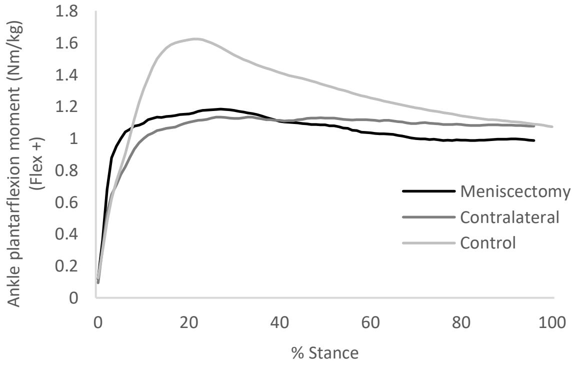


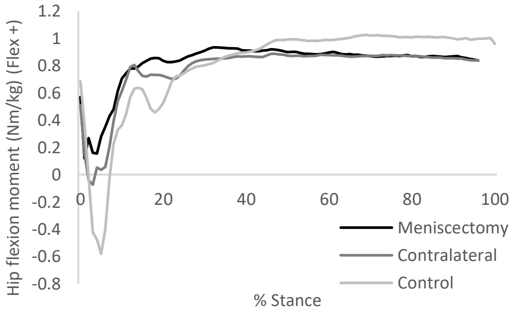


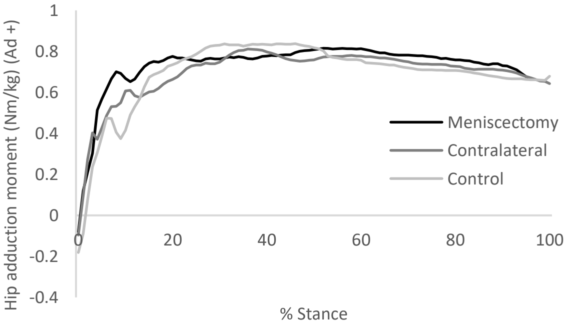


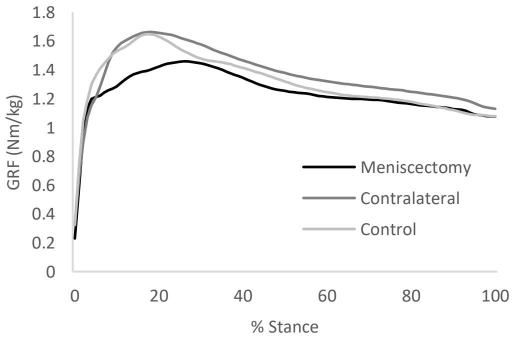












Appendix 3.4: Change of direction