Using the modified Wingate test to assess unilateral lower limb muscle power in a healthy and knee injury population: An exploratory pilot study.

Avinash Vazhapandal Nandakumar

19072250

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Primary supervisor: Dr Grant Mawston

Secondary supervisor: Prof. Peter McNair

ABSTRACT

Objective

The primary objective of this study was to explore the use of the modified unilateral Wingate anaerobic cycle test to assess unilateral lower limb power in a healthy population; and to determine if any significant relationship exists with a 30-repetition isokinetic measure of knee extensor power and functional hop and jump tests. A secondary objective was to examine the power profiles of two participants with anterior cruciate ligament (ACL) reconstruction using the unilateral Wingate test.

Study design

An exploratory cross-sectional pilot study, involving assessment of power variables (peak power, mean power, and fatigue index) across limbs during a unilateral version of the Wingate test was undertaken by 11 healthy participants with no previous history of knee ligament injury. Comparison of Wingate power measures were made with knee extensor power produced during a 30-repetition isokinetic knee extension test. Two ACL reconstruction participants were also assessed for descriptive comparison.

Background

Many team sports and recreational activities require significant muscle power. Lack of adequate muscle power might impact a players' performance. Additionally, deficits in unilateral lower limb power may contribute to injury. To improve player performance, a tool to evaluate unilateral lower limb power in a rehabilitation context is required to construct power-focused exercise programmes. The Wingate anaerobic cycle test has been used previously to assess bilateral lower limb muscle power. However, to date, no study has used the Wingate test to assess unilateral lower limb power in recreational young adults and knee injured participants.

Method

Ten men and one women (mean age of 26 years) with no previous history of knee injury, and one man and one woman two years following ACL reconstruction took part in the study. A Watt bike was used for the unilateral Wingate test to assess peak power,

mean power, and fatigue index. A Biodex isokinetic dynamometry was used to assess isokinetic peak and average power of knee extensors over 30 repetitions. Functional performance tests, including the single-leg hop, triple hop for distance, and vertical jump test were also undertaken to evaluate distance reached, and power was calculated from peak height during the single leg vertical jump. Self-reported outcomes were assessed using the Lower Limb Task Questionnaire (LLTQ) and Knee and Osteoarthritis Outcome Score (KOOS). All testing procedures were performed in one session that lasted for 60 minutes (approximately). Statistical analyses were performed using SPSS software. Descriptive statistics were calculated for all measures and for comparisons of the two ACL case studies with healthy subject data. Paired t-tests were used for inter-limb comparison in healthy participants and Pearson correlation coefficients were used to identify significant relationships between functional, isokinetic and Wingate test results. The alpha value was set at <0.05.

Results

No significant difference in muscle power and fatigue index was identified between dominant and non-dominant leg in the healthy participants for the modified Wingate test, isokinetic assessment, and functional performance testing. One ACL reconstruction participant had deficits in lower limb muscle power in the injured side compared with the non-injured side across all tests; whereas no deficits were identified in the other participant across limbs for all tests. There was a significant moderate correlation between the peak power in the Wingate test and peak power in the isokinetic testing ($r=0.57$; $P<0.05$). Further, there was a strong correlation between the peak power in the Wingate test and power calculated from the vertical jump test (left $r=0.84$; right $r=0.86$; $p<0.01$). However, there were low to moderate correlations between the Wingate test and the single leg hop test (left $r=0.2$; right $r=0.5$) and the Wingate test and the triple hop for distance (left $r=0.42$; right $r=0.54$; $P<0.5$). A moderate to poor correlation was identified between the fatigue index of the Wingate test and the isokinetic test (left $r=0.438$; right $r=0.25$; $p>0.05$).

Conclusion

The unilateral Wingate test was able to detect key measures of unilateral lower limb power (peak and average power, and fatigue index) that were typically assessed during the bilateral version of the test with no significant interlimb differences in these measures in uninjured healthy participants. Power profiles during the unilateral Wingate test were similar to that produced during repeated isokinetic knee extension test, further indicating that this test assesses power and targets the anaerobic energy system. The low to moderate correlations between power measures in the unilateral Wingate and traditional hop tests may indicate that these tests measure different constructs of power and place dynamic balance, and neuromuscular co-ordination demands that differ to Wingate test; whereas the high correlation with vertical jump power indicates that both tests measure a similar construct of muscle power and anaerobic capacity. Findings from the two ACL reconstruction case studies indicate the potential of the unilateral Wingate test to detect unilateral lower limb power deficits following ACL reconstruction. However, this remains speculative and a larger study with increased statistical power is required to substantiate these case study findings.

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed: ____________________

Date: 08-12-2021

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The Auckland University of Technology Ethics Committee granted ethical approval for this research on 11 June 2021 (Approval no: 21/13)

1. CHAPTER 1: INTRODUCTION

1.1 Statement of Problem

In recent years, the number of people engaging in sporting activities has increased globally as people find more leisure time (Majewski et al., 2006; Vaisman et al., 2017). Despite muscle strength being an important component for sports performance, many sports activities depend on muscle power to achieve optimal performance (Slimani et al., 2018). Muscle power is described as the amount of work a muscle can produce over a defined period of time; or the ability to exert high levels of force as rapidly as possible (Jafari et al., 2013). Power has been identified as a key component in sporting activities that involve short bursts of high-intensity activities (Morin et al., 2019). Lower limb power is required for high intensity running, jumping, sprinting, kicking, and acceleration all of which are key components of sports like rugby, soccer, football, basketball, and volleyball (Kalinski et al., 2002; Ostojić, 2000; Soslu et al., 2016; Vaisman et al., 2017). These high-intensity activities require instant energy which is fuelled by the creatine phosphate system, and depending upon the time span of the activity, can also involve a glycolytic system contribution (Krishnan et al., 2017).

There is a growing concern about the concomitant increase in various musculoskeletal injuries among players involved in sporting activities. The lower extremity is frequently injured with an average incidence rate ranging between 50 and 66 percent with 30 to 45 percent of these injuries being at the knee (Lam et al., 2017). In New Zealand, a population-based study by Gianotti et al. (2009) has found that 67 percent of knee-related injuries occurred during sports and recreational activities. The most common injuries observed in the knee are ligamentous rupture (anterior and posterior cruciate ligament, medial and lateral collateral ligament), as well as meniscal injury (Logerstedt et al., 2015). In addition, Astur et al. (2016) identified that the incidence of knee injuries was higher during sports where a player performs activities such as cutting, pivoting, and jumping which require high levels of power and generate significant stresses at the knee joint.

Rehabilitation for knee injuries aims to prepare individuals for their return to sport and recreational activities without future complications (Lohmander et al., 2007; Marn-Vukadinovic et al., 2019). The rehabilitation phase for knee injuries lasts between 1 and 18 months based on the injury sustained (De Carlo & Armstrong, 2010; Myer et al., 2006; Shelbourne et al., 1996). Although restoring muscle strength and functional performance following a knee ligament injury has traditionally been the focus of rehabilitation, as mentioned above, many sports require significant muscle power (Popadic Gacesa et al., 2009). Previous research findings on knee injured populations have shown deficits in muscle power of 10 to 25 percent at the time of return to sport and recreational activities (Ageberg et al., 2009; Castanharo et al., 2011; Nagai et al., 2020; Neeter et al., 2006; Thomeé et al., 2012). Due to inadequate muscle power, athletes returning to sports activities are thought to be at greater risk of re-injury when compared to non-injured population (Trigsted et al., 2018). Players with deficits in lower limb power following a knee injury can also experience long-term complications including chronic pain, decreased mobility, and performance, with greater risk of developing osteoarthritis of knee compared to those with no deficits in power (Lam et al., 2017; Logerstedt et al., 2015). Therefore, it would be beneficial to assess lower extremity muscle power during early stages of rehabilitation as results can be used to develop exercise protocols to enhance muscle power earlier in rehabilitation.

Current measures of lower limb power include isokinetic power profiles and equations that calculate power through the measurement of force and linear velocity during jumping manoeuvres (Choukou et al., 2014). The development of isokinetic devices has allowed relatively quick and accurate measurement of muscle performance utilising variables such as torque, acceleration energy, power, and total work (Whinton et al., 2018). Isokinetic devices maintain a constant velocity of movement, allowing the muscle to engage in concentric and/or eccentric activity while controlling the angular velocity of a certain body segment (de Carvalho Froufe et al., 2013). However, isokinetic test values may be limited due to the single-joint testing routine that is normally utilised. Many team sports require multidirectional and simultaneous coordination of multiple joints in different planes (Knezevic et al., 2014; O'Malley et al., 2018). Furthermore, maintaining a constant angular velocity does not reflect sporting activities where joint angular velocity may vary over the range of motion (Knezevic et al., 2014; O'Malley et al., 2018).

Functional performance tests, like hop tests and the vertical jump test, are clinical assessments used by many researchers to evaluate knee function, and are designed to mimic explosive actions evident in team sports (Atabek & Sönmez, 2009; Chamari et al., 2008; Lee et al., 2018; Manske & Reiman, 2013; Thomeé et al., 2012). One of the disadvantages of these clinical measures of power is that they place high forces through the knee (McNair & Marshall, 1994; McNitt-Gray, 1991). An alternative assessment of lower limb power is the Wingate anaerobic cycle test (WAnT) which can assess peak and mean power, as well as fatigue using a cycle ergometer (Bar-Or, 1987). The WAnT is a 30-second test that requires the participant to pedal as fast as possible against a relatively low load based on their body weight (Zupan et al., 2009). This form of testing assesses lower limb power without placing high loads through the knee (Jaafar et al., 2014); thus, has the potential to be used in the early to mid-stages of knee injury rehabilitation. Furthermore, if the test was undertaken unilaterally, comparisons could be made across involved and uninvolved limbs in injured individuals. Before this test might be used in the clinical population, it would be appropriate to undertake initial testing utilising subjects without knee injuries. In doing so, one would get an initial impression of the symmetry across limbs in such tests.

1.2 Purpose of the Study

The purpose of this study is to determine the utility of the protocols in an uninjured population which might then be modified where appropriate for testing power in an injured population. Of particular interest was whether similar power levels were observed across legs in uninjured subjects. The current study also made comparisons of Wingate unilateral power measures with those derived from isokinetic knee extension and functional testing.

The primary research questions were:

1. Is there significant difference in peak power, mean power, and the fatigue index across limbs in uninjured healthy subjects?
2. Is there a similar power profile within the unilateral Wingate test compared to those observed in the isokinetic testing at 180 degrees per second over 30 repetitions?
3. Are there significant correlations between the modified unilateral WAnT variables mentioned above, with knee extensor isokinetic peak and mean power, fatigue index generated at 180 degree per second, single leg hop, triple leg hop for distance and power predicted from vertical jump height?

A secondary analysis examined power profiles in the above-mentioned tests in a male and female participant who had reconstruction of their anterior cruciate ligament (ACL) approximately two years prior to testing.

1.3 Significance of Problem

Knee injuries are common among sports and recreational activities. Although rehabilitation of knee injuries targets power, it does so only late in rehabilitation. It would be advantageous if clinicians could utilise a test to assess and develop exercise programmes focused upon power that can be put in place earlier in rehabilitation. The current study provides initial evidence to assess the feasibility of the unilateral WAnT. Further research might lead to the test being used in clinical practice.

2. CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter has four sections. The first section describes the search strategy used for the literature review. The second section defines power, the energy system involved, and neuromuscular contribution to power generation; together with its relationship to strength, force, velocity (cadence), and the cycling action. The third section covers the WAnT and traditional isokinetic and functional performance tests for power in a rehabilitation setting. The third section reviews the literature assessing relationships between the Wingate test, isokinetic test and functional performance tests. Thereafter a summary is provided.

Section 1:

2.2 Literature Search

2.2.1 Introduction

There were two areas of interest in the literature search. The initial goal was to identify peak power, mean power, and the fatigue index between dominant and non-dominant leg utilising the unilateral WAnT in a healthy population. It was also important to determine if there is any relationship between the modified Wingate test and traditional isokinetic and functional performance tests for power used in rehabilitation context.

2.2.2 Search strategy

2.2.2.1 Inclusion and exclusion criteria

The inclusion criteria were focused upon papers that assessed issues related to muscle power in the lower limb; utilised the WAnT to assess lower extremity muscle power; assessed traditional functional tests that involved power development (e.g., maximal effort hop tests, vertical jump test, and isokinetic strength testing); and involved healthy participants with no previous lower limb injury and those with a significant knee ligament injury/reconstruction (anterior and posterior cruciate ligament injury, meniscal injury, and collateral ligament injury.

The exclusion criteria were studies that did not assess lower limb muscle power using the WAnT; did not use traditional functional tests (hop-tests, vertical jump test and isokinetic strength testing) to assess power in healthy populations and knee injury populations; and were published in languages other than English.

2.2.2.2 Databases and resources used

The electronic databases utilised for the literature search were,

- Medline
- Scopus
- Auckland University of Technology library
- EBSCO health database
- CINAHL
- PEDro (Physiotherapy Evidence Database)
- Google Scholar
- Google search
- AHED (Allied Health Evidence Database)

Additionally, articles were identified from the reference list of articles found through the above databases.

2.2.2.3 Search terms

Search terms were shortened and modified according to the requirements of each database. Search terms were used along with Boolean operators like ‘AND’ and ‘OR’. Articles were searched using generic terms and the author field was used for specific authors. The search terminologies used are listed in Table 2.1.

Table 2.1

Key search terms

Search terminologies		
power	peak power	mean power
anaerobic power	Wingate	fatigue
isokinetic	peak torque	strength
single leg jump	hop-test	knee injury
knee ligament injury	vertical jump	muscle power
lower limb	functional measures	single-leg hop

Section 2:

2.3 Muscle Power

2.3.1 Definition of muscle power

Power is defined as the product of force and velocity (Degens et al., 2019). In a sports and rehabilitation context, force refers to that measured as a result of muscle activation; while velocity can be assessed across single or multiple joint motion and, hence, can be either angular velocity or linear displacement respectively (Cormie et al., 2011; Kraemer & Newton, 2000). The maximum level of power attained during muscle activation and its associated movement is referred to as maximal power. During physical activities that include a take-off, release of an object, or an impact, maximal power has been related to velocity reached at these time-points in the activity (Carvalho et al., 2011; Giroux et al., 2015). Previous research has demonstrated that increasing capacity to generate maximum power generally resulted in improved athletic performance (Aoki et al., 2015). The current work is focused upon lower limb activities that require short-term maximal effort. Short term is defined as 10 to 30 seconds.

2.3.2 Energy system contribution to muscle power

It is well established that the phosphocreatine system and short-term anaerobic glycolysis are the major energy contributors to activities that require muscle power

(Serresse et al., 1988). The energy required for these short-burst and high intensity activities rely on three important closely integrated processes that work together to fulfil the energy demands of the muscle (Baker et al., 2010).

During the initial 0-10 seconds of short-burst, intense, and explosive activities, Adenosine Triphosphate (ATP) stored in the muscle cell is generated via breakdown of phosphocreatine that provides the energy for the muscle work (Gastin, 2001). During this period there is greatest turnover of ATP and muscle power tends to reach its peak (Beneke et al., 2002; Smith & Hill, 1991). Between 10 and 30 seconds, anaerobic glycolysis tends to become more dominant. This involves anaerobic catabolism of carbohydrate that produces ATP and bi-products such as pyruvate and hydrogen that combine to form lactic acid. During this period, ATP turnover begins to decline, and power tends to decline in a curvilinear manner (Smith & Hill, 1991). Figure 2.1 illustrates the ATP turnover provided by the energy systems over time periods up to 100 seconds.

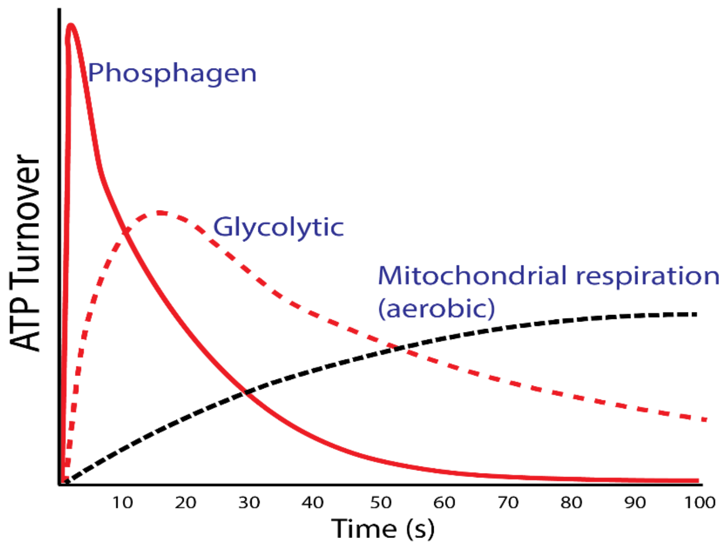

Figure 2.1: *Energy system contribution to ATP turnover over time.*

Compared to anaerobic metabolism, aerobic metabolism has lower rates of ATP turnover resulting in lower power output than anaerobic glycolysis (Baker et al., 2010; Gastin, 2001; Green, 1994; Serresse et al., 1988). In contrast to the phosphocreatine and anaerobic glycolysis, aerobic glycolysis has a relatively small contribution to explosive activities. However, it has been shown that the aerobic system can contribute up to 20 percent of the total energy expenditure within the first 10 seconds in 200 metre sprinting activities and during the performance (Spencer & Gastin, 2001).

2.3.3 Neuromuscular contribution to power

Researchers have reported that maximal power production depends upon several neuromuscular factors working optimally (Mendez-Villanueva et al., 2008). Firstly, maximum power is produced when high threshold motor units containing type II muscle fibres have been recruited. These motor units are recruited methodically through voluntary activation of muscles with increasing force based on the size principle explained by Henneman et al. (1974) and Cormie et al. (2011). Smaller motor neurons that innervate aerobic (type I) fibres are recruited first at low force, whereas larger motor neurons that innervate more anaerobic (type II) fibres are recruited at high force levels (Altenburg et al., 2007). These high threshold motor units are capable of generating high force during muscle activation because they innervate large numbers of muscle fibres with greater rates of cross-bridge interaction (Enoka & Fuglevand, 2001). In maximal cycling, these fast twitch fibres are capable of generating peak power with greater force at high shortening velocity (Hautier et al., 1996).

The second neural factor contributing to high muscle power is often given the term “rate coding” which refers to the firing rates of motor units. Higher motor unit firing frequency is associated with greater force generation. These motor units are recruited when high levels of force are required (Cormie et al., 2011; Haff et al., 2001; Kawamori & Haff, 2004; Moritani, 2003). Previous research has used electromyography (EMG) to detect relationships between neural factors and power during the tests such as WAnT. For example, Stewart et al. (2011) found that muscle fibre conduction velocity and power peaked during the first six seconds of the WAnT and declined in a linear manner throughout the remainder of the test. They suggested that the linear decline in muscle fibre conduction velocity was related to decrease in recruitment of high threshold motor units (type II muscle fibres), whereas the maintenance of normalised EMG, despite a decrease in power during a WAnT, reflected a decline in motor unit discharge rate (Stewart et al., 2011).

2.3.4 Force and power velocity relationship

The force-velocity (F-V) relationship reflects the ability of the skeletal muscle to generate force and maximum rate of movement (Cross et al., 2017). According to this relationship, when velocity increases, the force produced by the neuromuscular system decreases at a given constant degree of muscle activation (Jaric, 2015; Peterson et al., 2006). The FV relationship was first studied by Hill in 1922 who showed a hyperbolic relationship and explained that during single joint movement, skeletal muscles functioned similarly to mechanical devices, where an increase in velocity resulted in less force production (Cross et al., 2017; Yoshihuku & Herzog, 1990, 1996). However, for loaded multi-joint movements, the FV relationship is linear and this relationship is exemplified by a product of complex interactions between muscular coordination characteristics, activation patterns, the anatomy of joints and the orientation of moments (Cross et al., 2017). For instance, Bozic and Bacvarevic (2018) reported a linear F-V relationship where less force was produced at greater velocities using a cycle ergometer in elite athletes. In cycling, FV relationship is calculated by the net force produced during a revolution with simultaneous activation of both lower limb muscles on both pedals (Dorel et al., 2010). The FV relationship is widely used to determine muscle force, velocity, and power producing capabilities; bilateral power deficits; and to optimise load for peak power output (Bozic & Bacvarevic, 2018; Jaric, 2015).

In sports, performance is influenced by the ability to generate large amounts of force in a short period of time (rate of force development), which is directly related to maximal power production (Suchomel et al., 2018; Turner et al., 2020). Because muscle power is the product of force and velocity, the FV relationship has a significant impact on the power-velocity relationship in loaded multi-joint movements (Jaric, 2015). Therefore, a polynomial power velocity relationship represents peak power production during high-intensity exercises like maximal cycling (Dorel et al., 2003; Samozino et al., 2007).

In cycling, the relationship between pedalling rate and crank length influences pedal speed which, in turn, determines the shortening velocity of uni-articular muscles that span the hip, knee, and ankle (Martin et al., 2007; Yoshihuku & Herzog, 1990). It is generally stated that shortening velocity impacts muscular power (Martin et al., 2007). The power-velocity relationship during maximal cycling is exemplified by the relation between power produced during muscle activation and pedalling rate/cadence (shortening velocity) (Ravier et al., 2004). For example, during cycling, power tends to increase with increase in shortening velocities; and when power reaches its maximum, it declines in a linear manner with increase in shortening velocity (Martin et al., 2007). However, the power-velocity relationship is non-linear and may be affected by factors like cadence (i.e., angular velocity). During cycling, the force applied to the pedals is imposed by the setting of load on the bike. For example, Rudsits et al. (2018) suggested that variation in torque and power generation were linked to voluntary activation of lower limb muscles and variability in pedalling rate.

2.3.5 The cycling action

Cycling is a motor task that necessitates the simultaneous coordination of lower limb joints and muscles (hip flexors and extensors, knee flexors and extensors, ankle plantar flexors) in a cyclic action of shortening and lengthening to move the pedal in a circular trajectory at a specific movement speed or pedalling rate, while providing necessary force to the pedal to generate power (Dorel, 2018; Douglas et al., 2021). Power can be measured in different ways; however, the most reported measure is the average power generated by both legs throughout a half pedal cycle or a whole pedal cycle (Hautier et al., 1996; Martin et al., 2007). Previous research on joint-specific power using inverse dynamic analysis techniques have shown that the hip extensors contributed to most power followed by the knee extensors, plantar flexors, and knee flexors; with knee flexion power being nearly equivalent to the contribution of knee extension power in the initial three seconds of maximal cycling (Douglas et al., 2021; Elmer et al., 2010; Martin & Brown, 2009). Approximately, 80-85 percent of total power generated over a revolution is due to leg extension or the downstroke phase, while the remaining 15-20 percent is generated during the leg flexion or upstroke phase (Martin & Brown, 2009). The upper body muscles contribute a minor amount to total power during maximal cycling by transferring power via the hip joint (Martin & Brown, 2009).

The power transfer between the hip and knee joints is enabled by the coactivation of monoarticular knee extensors (the quadriceps) and biarticular hip extensor-knee flexor muscles (the hamstrings) (Driss & Vandewalle, 2013). Electromyographic studies on maximum cycling with the foot taped on pedals with toe clips revealed an increase in knee flexor contribution during the upstroke at high velocity pedalling (>200 revolutions per minute - RPM) (Vandewalle et al., 1991). In a review, Driss and Vandewalle (2013) reported that, the plantar flexors must be able to create high force levels at high shortening velocities to contract concentrically and develop power during knee extension in maximal cycling.

2.3.6 Relationship between strength (force) and power

It is generally agreed in the literature that there is strong link between maximum strength (force) and maximum power production (Taber et al., 2016). Strength is described as the capacity to produce force, which is influenced by several factors including the type of contraction, the rate of motor unit activation, and the degree of muscle activation (Stone et al., 2003). In cycling, muscle power is calculated as the product of the torque applied to the pedals produced by the activation of muscles and its relation to cadence/pedal velocity or pedalling rate (Douglas et al., 2021; Martin et al., 2007).

Stone et al. (2004) found that athletes with a higher peak force and peak rate of force development capacity were able to produce greater maximum forces at high crank velocities, resulting in higher power output than those athletes with lower force production. During sprint cycling, Vercoe and R. McGuigan (2018) observed a strong correlation between peak force and maximal torque, and stated that the capacity to produce high force reflected maximal power output. Further, Arslan (2005) identified that peak and mean power in the Wingate test significantly correlated to isometric leg strength and explosive leg strength of multiple joints, and suggested that participants who partook in regular exercise had a greater maximal power compared to sedentary participants. Rannama et al. (2013) identified a strong relationship between hip extensor strength and peak power in maximal sprint cycling. Similarly, Kordi et al. (2017) identified a strong relationship between isometric knee extensor strength and peak power in isokinetic sprint cycling test, and suggested that knee extensor peak torque was the strongest predictor of peak power in sprint cycling. The relationships identified between peak force and maximum torque appear to indicate that if an athlete can develop muscular strength, it will result in higher torque output throughout a variety of pedalling velocities resulting in increases in maximal power. Altogether, these findings indicate that ability to generate high force resulted in maximal power output.

Section 3:

2.4 Common Measures of Lower Limb Power

2.4.1 Wingate anaerobic cycle test (WAnT) for power

The WAnT is a 30-second cycling test commonly used by researchers and clinicians to assess anaerobic peak power in a variety of sports players (Galán-Rioja et al., 2020; Jakovljević et al., 2018; Lunn & Axtell, 2019; Magal et al., 2009; Meckel et al., 2009). The WAnT was named after the Wingate Institute in Israel and evolved from a friction braked cycle ergometer test (Bar-Or, 1987). Power is generally established from the high-resolution pedalling speed sensors and the force sensors on the pedal of the cycle (Castañeda-Babarro, 2021). In the Wingate test, the participants are instructed to pedal as fast as possible for 30-seconds (Bar-Or, 1987). A typical power profile of a Wingate power test for a healthy adult is shown in Figure 2.2. It shows that power reaches a maximum over five to seven seconds. Thereafter, a curvilinear decline is observed for the remaining duration of the test.

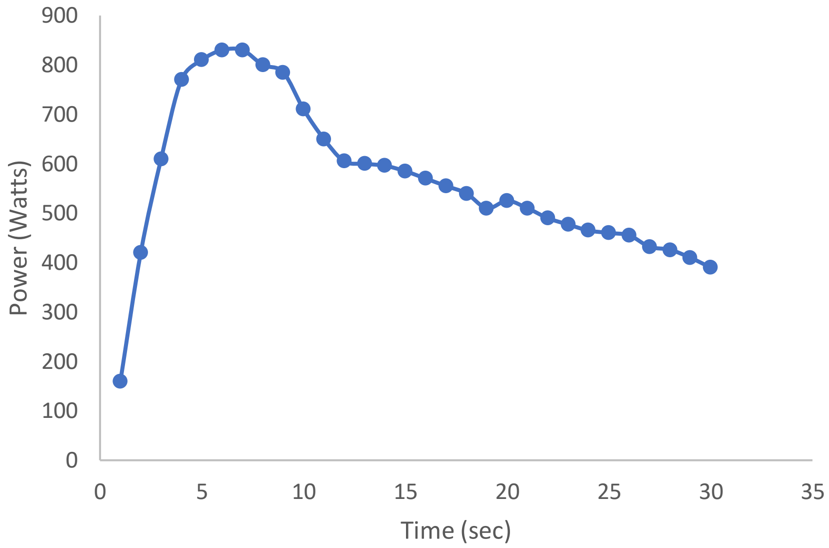

Figure 2.2: *Typical power profile of the Wingate test using a stationary start for a healthy adult,* modified from Stewart et al. (2011).

The three power variables of most interest are the maximum power which typically occurs during the first five seconds of the test; the mean power across the 30-seconds; and the difference between the highest to lowest power output which is calculated as fatigue index (Zupan et al., 2009). The most common method used to assess fatigue index is calculating the percentage difference between peak power in initial five seconds and the lowest power in the last five seconds (Baker et al., 2011; Naharudin & Yusof, 2013). Other researchers have used slope methods to calculate fatigue rate which is the rate of power decline over 30 seconds (Baltzopoulos et al., 1988; Micklewright et al., 2006). Previous research on the WAnT has established the validity and reliability for assessing peak power, mean power, and the fatigue index in healthy participants (Ayalon et al., 1974; Bar-Or, 1978; Tharp et al., 1985).

Researchers have proposed that power output at different time periods of the 30 second WAnT represents the different energy system utilised. In a study involving amateur athletes, Zajac et al. (1999) suggested that the phosphagen system was the primary energy source for peak power achieved within the first 10 seconds of the WAnT, while glycolysis accounted for 50-60 percent of total energy required for power output throughout the test. Recently, Julio et al. (2019) compared the energy system contribution in the upper and lower body WAnT in high level elite judo athletes using oxygen consumption (VO2) obtained during the tests, lactate delta, and the fast period of excess VO2 following WAnT. The researchers identified that the phosphagen system was responsible for lower extremity peak anaerobic power, and concluded that the phosphocreatine system contributed up to 32 percent, the glycolytic system contributed up to 45 percent, and the oxidative system contributed up to 23 percent of total energy during the 30 second lower limb bilateral WAnT.

Peak power in the Wingate test is generated during optimal breaking force, which is set prior to the test (Vandewalle et al., 1987). Inbar and Ayalon (1974) proposed an optimal breaking force of 7.5 percent of body mass for peak power output. Later research on optimal breaking force found that higher resistance (8.4, 9.5, 10.5% of body mass) was suitable for peak power output in both athletes and non-athletes (Bediz et al., 1998; Bradley & Ball, 1992; Linossier et al., 1996). Similarly, Jaafar et al. (2016) studied optimal resistance during the Wingate test in recreational and trained athletes and reported a load of 10 percent of body mass is recommended for optimal power output in recreational athletes. Recently, a review by Castañeda-Babarro (2021) reported that the optimal load in the Wingate test must be altered according to patient demographics.

During the bilateral Wingate test, power output is a combination of that generated during the downstroke phase of one side and the upstroke phase of the contralateral lower limb. The downstroke (leg extension) phase produces between 80-85 percent of total power during a single pedal revolution, whereas only 10-15 percent of power is generated during the upstroke phase (Douglas et al., 2021). The downstroke phase engages the monoarticular muscles which include the hip (gluteus maximus) and knee (vastus medialis oblique), leg extensors and the tibial muscles (tibialis anterior and soleus) (Driss & Vandewalle, 2013). The upstroke or transition phase involves more biarticular muscles that include rectus femoris, semimembranosus, semitendinosus, biceps femoris, and gastrocnemius (Driss & Vandewalle, 2013; Hug et al., 2004; Hug & Dorel, 2009; Okano et al., 2017; Raasch et al., 1997)

Cadence, an indirect measure of velocity, is also an important measure that has been shown to influence power throughout the Wingate test. The literature has shown that peak power during the bilateral Wingate test tends to be achieved at a cadence range between 120 and 130 revolutions per minute (RPM) (Hautier et al., 1996; Hintzy et al., 1999; Martin et al., 2007). Figure 2.3 shows a typical profile of cadence/pedal velocity throughout a bilateral Wingate test. It shows that a maximum cadence (velocity) of between 130 and 140 RPM is achieved at 5-10 seconds. Thereafter, a gradual decrease in cadence occurs (Stewart et al., 2011). Cadence has also been shown to influence power production during maximal cycling. McDaniel et al. (2014) revealed that hip extension power doubled as pedalling rate increased from 120 RPM, peaking at a pedalling rate of 150 RPM. Knee extension power also increased at higher cadence, peaking at 120 RPM. In contrast, hip flexion power (8-24%) and plantar flexion power (8-25%) decreased as pedal rate was elevated from 120 RPM (McDaniel et al., 2014).

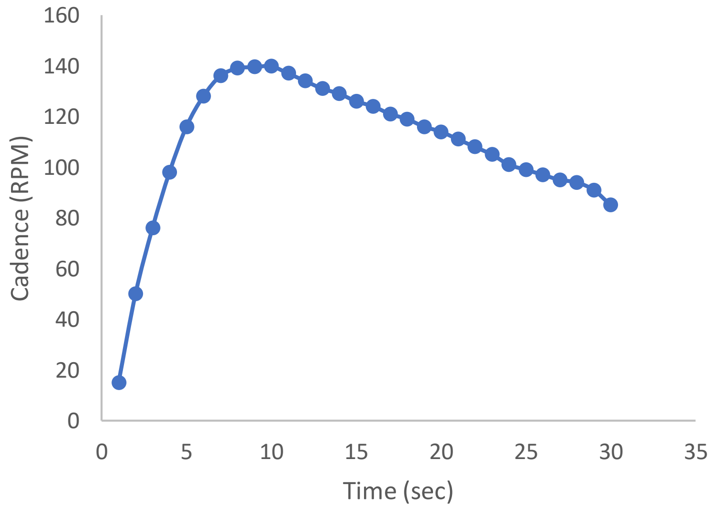

Figure 2.3: *Typical cadence/ pedalling rate profile of the Wingate test for a healthy adult,* modified from Stewart et al. (2011).

Researchers have measured the decline in lower limb joint power throughout the Wingate test. This rate of decline in peak power throughout the 30 seconds is calculated as fatigue index (Noehren et al., 2016). Previous studies have shown that fatigue index varies from 37 to 53 percent in physically active adults and competitive athletes (Baker et al., 2011; Maud & Shultz, 1989; Zupan et al., 2009). Typically, in 30 second maximum sprint cycling at a pedalling rate of 120 RPM, Martin and Brown (2009) observed a 41 percent decrease in knee extension power, 55 percent decline in hip extension power, 47 percent decrease in knee flexion power, and 37 percent decrease in ankle joint power compared to initial power in the last three seconds of the maximal sprint cycling.

Most research has focused on the bilateral Wingate test for assessment of lower limb muscle power. While this provides important information, the bilateral Wingate test is unable to clearly make comparisons of power between the right and left lower limb. Interlimb comparisons are important for establishing whether limb dominance influences power output in healthy populations, and would be an important tool for establishing unilateral deficits in power during rehabilitation from knee injury. To the author's knowledge, there is only one study that has used a unilateral Wingate test for interlimb comparisons of power and this was used on a paediatric population. Hebestreit et al. (1999) used the single leg WAnT to assess unilateral lower extremity muscle power and total mechanical work in pre-pubertal and mid-pubertal children and young adults. The peak power calculated from the single leg WAnT was identified to be highly reliable with intraclass coefficient correlation of 0.89–0.93. Furthermore, Hebestreit et al. (1999) suggested the single leg WAnT to be a useful measure to identify unilateral lower limb muscle power and leg dominance.

In summary, the WAnT involves activation of major muscle groups of the lower limbs working in a coordinated pattern to generate power. The advantage of using the WAnT is that it requires simple equipment and places relatively low loads on the lower limb compared to jumping and hopping assessments of power (Bar-Or, 1987; Jaafar et al., 2014). Though there is limited research on the unilateral Wingate test, it has the potential to provide the assessor with a reliable measure of overall maximal limb power. Furthermore, compared to traditional measures of power, it has the potential to be used earlier in rehabilitation scenarios and to identify deficits in power between limbs.

2.4.2 Functional performance tests for power

The most common functional tests utilised to assess power in the lower limb are hopping and jump tests, with the time and the distance covered being the outcomes of interest. The vertical jump test uses height as a surrogate for the power generated vertically, and predictive equations for lower limb power have been established (Harry et al., 2021; Pérez-Castilla et al., 2019). The popularity of these activities probably reflects the ease at which these variables can be measured (Bandy et al., 1994; Barber et al., 1990; Bolgla & Keskula, 1997; Clark et al., 2002; Cordova & Armstrong, 1996; Hopper et al., 2002; Maulder & Cronin, 2005; Paterno & Greenberger, 1996; Risberg et al., 1995). A number of studies have provided information concerning the validity and reliability of these tests. For instance, previous researchers indicated that the single leg hop test has shown excellent test-retest reliability (Booher et al., 1993; Reid et al., 2007; Ross et al., 2002). Similarly, prior studies have shown that the vertical jump test is an accurate and effective way to measure lower limb muscle power (Aragón, 2000; Liebermann & Katz, 2003; Ravier et al., 2004).

These tests are commonly employed in clinical settings and the results are interpreted with a comparison across the injured and non-injured limb (Barber et al., 1990; Noyes et al., 1991; Ross et al., 2002). During the end stage of rehabilitation, these functional tests (single leg hop and vertical jump test) have been thought to be useful as a part of a series of tests to assess participants' readiness to engage in sports and physical activity (Manske & Reiman, 2013). Previous studies have examined the level of muscle activity observed during the hop test and the vertical jump test. They show that the primarily muscle groups active are the hip and knee extensors, and ankle plantar flexors (Charoenpanicha et al., 2013). The contribution of hip, knee, and ankle joints to the overall power generated during the horizontal single leg hop is 44 percent from the hip joint, 13 percent from the knee joint, and 43 percent from ankle joint during propulsion phase; whereas during landing, the hip joint contributes only 24 percent, the knee joint contributes upto 65 percent, and ankle joint contributes up to 11 percent of total power

(Kotsifaki et al., 2021). Similarly in the vertical jump, the hip, knee, and ankle contributed up to 31, 34, and 35 percent respectively during propulsion phase; whereas during landing the hip, knee, and ankle contributed to 29, 34, and 37 percent respectively of total power (Kotsifaki et al., 2021; Vanezis & Lees, 2005).

A key concern of jump and hop tests is that the forces and loads upon muscles and joints are considerably high during landings (McNitt-Gray, 1991; Prapavessis & McNair, 1999). For instance, previous studies based on kinematics of jump landings have shown that subjects produce ground reaction forces of up to 9.1 to 11.0 times their body weight (McNitt-Gray, 1991; Mizrahi & Susak, 1982; Prapavessis & McNair, 1999). Similarly, ground reaction forces exerted on the body during landing from a vertical jump are high (McNair et al., 2000; Nigg & Segesser, 1988). Further, McNair and Marshall (1994) showed a positive relationship between vertical ground reaction forces and anterior tibial accelerations. It has been suggested that these activities could cause inflammatory episodes and place undue stress on knee structures if undertaken too early in the rehabilitation programme (Mizrahi & Susak, 1982). Hence, these clinical measures of lower limb power are typically performed in the latter stages of rehabilitation.

2.4.3 Isokinetic testing for power

Isokinetic dynamometry is thought to be valuable method for assessing isolated joint torque, power, and muscle activity in the field of rehabilitation (Gleeson & Mercer, 1996; Iossifidou et al., 2005). Some authors (Taylor et al., 1991; Thom et al., 2007) have suggested that isokinetic dynamometry is the gold standard method for assessing muscular power and performance under regulated conditions. The parameters that can be evaluated utilising maximum or submaximal isokinetic procedures include peak torque, power, and total work (Alvares et al., 2015; Li et al., 1996; Sole et al., 2007). Isokinetic dynamometers typically control the angular velocity of the joint and measure torque through a joint's range of motion (Alvares et al., 2015; Dirnberger et al., 2012; Thompson et al., 1989). Peak power in isokinetic testing has been calculated as the product of the moment generated and the pre-selected joint angular velocity (Rothstein et al., 1983). However, Iossifidou and Baltzopoulos (2000) found that during high angular velocity movements (greater than 180 degrees per second), constant velocity periods were limited and that pre-selected angular velocities tended to overestimate power at these angular velocities. They suggested that the product of the "actual" constant angular velocity and the highest moment produced during this period was a more accurate measure of power (Iossifidou & Baltzopoulos, 2000). Actual refers to joint angular velocity derived from angular displacement, which is generally different from the pre-selected angular velocity (Iossifidou & Baltzopoulos, 2000).

In earlier studies, Maffiuletti et al. (2007) measured average power using Con-Trex MJ isokinetic dynamometer utilising concentric knee flexion and extension procedures performed at 60, 120, and 180 degrees per second; and eccentric knee flexion and extension at a single angular velocity of 60 degrees per second. These researchers observed no difference in average power between two testing sessions at the angular velocities tested. Maffiuletti et al. (2007) also reported that the results were highly reliable for knee extensors average power ($ICC=0.99$, $P<0.05$) at 180 degrees per second and for knee flexors ($ICC=0.99$, $p<0.05$) at 180 degrees per second.

In summary, isokinetic testing provides the advantages of the accurate assessment of peak torque, power, and work of individual muscle groups over a joint range of motion; and is a safe, valid, and reliable measure. However, it has been questioned whether using controlled joint angular velocity to calculate power in isokinetic dynamometry reflects the variation in muscle and joint function during various physical tasks that generate muscle power (Iossifidou et al., 2005).

2.4.4 Relationships between functional tests and Wingate test

Relationships between the functional tests (hop test and jump test) and unilateral Wingate test have not yet been established. Although a number of studies have investigated associations between the bilateral Wingate test and vertical jump test, there are currently no studies that have assessed the relationships between bilateral Wingate test and hop test performance. Bosco et al. (1983) assessed peak and mean power using the Wingate test and vertical jump test in young male basketball players with mean age of 23 years. The results showed a high significant correlation ($r=0.87$; $p\leq0.001$) between the vertical jump test and peak power during a 15 second Wingate test and high correlation ($r=0.67$; $p\leq0.001$) between the vertical jump test and a 60 second Wingate test. Kasabalis et al. (2005) investigated the association between anaerobic power using the Wingate test and the vertical jump test in youth volleyball players of different ages. Across all age groups, there was a strong correlation ($r=0.82$; $p\leq0.001$) between peak power in the Wingate test and vertical jump height. Furthermore, there was a strong correlation between peak power in Wingate test and vertical jump height irrespective of the study cohort being athletes ($r=0.86$; $p\leq0.001$) or non- athletes ($r=0.84$; $p\leq0.01$).

Others have reported low to moderate correlations between outcomes of the two tests. Hoffman et al. (2000) reported moderate to high ($r=0.59$ and 0.76) but significant correlation ($p\leq0.05$) between peak and mean power in Wingate test and the vertical jump test in basketball players. However, a poor correlation ($r=0.2$ and 0.28; $p>0.05$) was identified between anaerobic jump test and peak and mean power in the Wingate test. Although both the WAnT and the vertical jump test assess lower-body anaerobic power, Hoffman et al. (2000) suggested that the lack of a significant relationship may be explained by variations in exercise mode and differences in power generated by legs operating simultaneously or sequentially, and that the influence of upper body muscles might affect power production. Changela and Bhatt (2012) assessed the relationship between the Wingate anaerobic power test and the vertical jump test in basketball players. They also observed that there was a moderate positive correlation between mean power of vertical jump test and the Wingate test ($r=0.031$; $p>0.05$) and peak power of vertical jump test and the Wingate test ($r=0.044$; $p>0.05$). These researchers suggested that the vertical jump test was a valid test to determine peak power.

Overall, these findings suggest that a moderate to high correlation has been determined between the vertical jump height and Wingate test peak power and mean power. The difference in correlation observed in these studies can be due to variance in sample size, type of protocol utilised, and difference in age and participants' athletic performance.

2.4.5 Relationships between isokinetic testing for power and Wingate test

Few researchers have compared isokinetic dynamometry measures of power to the power results from the WAnT. Baltzopoulos et al. (1988) examined the relationship between the Wingate test and isokinetic testing using knee flexion and extension over six repetitions at a joint angular velocity of 240 degrees per second followed by a 30 second knee flexion and extension endurance test in healthy young adults. The researchers identified a significant correlation between Wingate test peak power and isokinetic knee extension peak power ($r=0.96$; $p<0.01$) and between Wingate test peak power and isokinetic knee flexion peak power ($r=0.95$; $p<0.01$). Furthermore, Baltzopoulos et al. (1988) identified a significant correlation between fatigue index during the Wingate test and isokinetic knee extension and flexion endurance test ($r=0.84$; $p<0.01$). Brown et al. (1994) measured peak and mean power, as well as fatigue slope and fatigue percentage in healthy young adults using Biodex isokinetic dynamometry at a joint angular velocity of 180 degrees per second and the WAnT. The results showed a strong correlation between the two tests for peak power ($r=0.84$; $p<0.05$), a moderate correlation for mean power ($r=0.54$; $p<0.05$), and a low/fair correlation for fatigue percentage ($r=0.37$; $p<0.05$).

More recently, using a Watt bike, Daameche et al. (2021) assessed peak and mean power using a Wingate test and isokinetic testing in male competitive cyclists. The isokinetic testing was performed at a joint angular velocity of 60 degrees per second for five repetitions and 300 degrees per second for 15 repetitions. The researchers identified a fair to moderate positive relationship between peak power in the Wingate test and mean power in the isokinetic knee extension ($r=0.36$-0.37; $p<0.05$) and flexion test

($r=0.41-0.53$; $p<0.05$) at 60 degrees per second, and a similar correlation between peak power in the Wingate and mean power in the isokinetic knee extension ($r=0.55-0.58$; $p<0.05$) and flexion test ($r=0.27-0.43$; $p<0.05$) performed at 300 degrees per second. The researchers suggested that the low correlations were attributed to methods used to assess power. They argued that isokinetic testing is an open kinetic chain test involving only the knee joint, whereas the Wingate test is a closed kinetic chain test that involves multiple joints of both lower limbs working in a cycling action to generate power (Daameche et al., 2021).

In summary, isokinetic measures of power have a poor to moderate correlation with Wingate measures of power. Both tests assess muscular power; however, the isokinetic test is a single joint test, whereas the Wingate test engages numerous joints and requires coordination of these joints to generate power.

2.5 Literature Review Summary

It has been clearly established that the Wingate test is an important and reliable measure of power for both competitive and recreational athletes. The primary contributors to power in the Wingate test are the quadriceps and hamstring muscles with coordination of hip extensors and ankle plantar flexors. During this test (maximal effort up to 30 seconds), the primary energy systems used by these muscles are the phosphocreatine system and short-term anaerobic glycolysis. Maximum power and decline in power output during the test have been shown to be influenced by neuromuscular factors such as high threshold motor unit recruitment and rate coding.

In individuals without injury, relationships have been observed between the WAnT and isokinetic testing and functional performance tests (vertical jump test). Many studies have combined isokinetic testing and functional tests (e.g., hop test and vertical jump test) to assess lower limb muscle power in individuals with knee injuries. Those that do, indicate deficits ranging from 10 to 25 percent in unilateral power at the time of return to sport and recreational activity.

However, such tests are generally undertaken at the end of the rehabilitation programme as the loads associated with such activities might induce inflammatory episodes that could slow down rehabilitation and return to sport. A unilateral Wingate test provides the opportunity to measure peak power, mean power, and fatigue index earlier in the rehabilitation programme. No clinically based studies have utilised the Wingate test to quantify unilateral lower limb power following a knee ligament injury or reconstructions. Before utilising the test in a clinical cohort, it was thought that testing a non-injured group would provide initial evidence of its merits, or otherwise, and highlight any operational matters (attachments, limb postures) and difficulty of performing what is normally a bilateral activity with just one limb.

3. CHAPTER 3: METHODOLOGY

3.1 Introduction

This section is divided into six subsections. The first section covers the study design, while the second section describes the participants. The third and fourth section includes the equipment and questionnaires utilised in the current study, and the fifth portion outlines the techniques and procedures. The final section describes the statistical approaches employed in the analyses.

3.2 Study Design

The study design employed was an exploratory cross-sectional pilot study, inter-limb comparison, which involved assessing relationships and comparing across limbs in healthy participants and two ACL-reconstruction participants 24 months post-surgery. All participants performed functional tests (hop for distance and vertical jump), a unilateral WAnT, and an isokinetic test.

3.3 Participants

3.3.1 Healthy participants and two ACL-reconstructed participants

All participants were recruited via advertisements on Auckland University of Technology (AUT) campus notice boards and word of mouth to physiotherapists. The first 11 healthy participants who responded to the advertisement were recruited for testing. Participants were physically active and recreational athletes with no history of knee injury or low back pain. All participants were aged over 18 years at the time of testing and were fluent in English. Similarly, two participants with history of ACL-reconstruction with post 24 months were recruited for the experimental testing. The key exclusion criteria are explained below.

In the non-injured group, participants with recent history of trauma affecting the lower limb, severe previous traumatic musculoskeletal injuries, and knee ligament injuries or meniscal damage, neurological illness/deficiency, and cardiovascular problems were excluded.

The two ACL-reconstructed participants included one female and one male with history of post-24 months ACL-reconstruction. The female participant was an elite skier who had undergone ACL-reconstruction thrice using both hamstring and patellar tendon graft in the last five years; whereas the male participant was a recreational soccer player who was 24 months post ACL-reconstruction using patellar tendon graft.

The experimental testing procedures were explained to all participants verbally and in written format (Appendix A). Participants were given extra time (one day) to ask questions regarding the experimental testing. Prior to the experimental testing, all participants signed a written consent form (Appendix C). The AUT ethics committee granted approval on 11 June 2021 (reference number: 21/133) (Appendix B).

3.4 Equipment

3.4.1 Watt bike

The unilateral WAnT was performed on a Watt bike (Watt bike Pro, Watt bike Ltd, Nottingham, UK) to evaluate peak power, mean power, and fatigue index. It has been found to be a valid and reliable means for determining anaerobic peak power, mean power, and a fatigue index (Bar-Or, 1987; Herbert et al., 2015; Hopker et al., 2010; Senturk, 2019). Seat height, seat setback, and handlebar height were standardised and documented. Foot straps and toe clips were utilised to keep the feet from sliding off the pedal. During experimental testing, the contralateral limb was supported by a wooden block placed just outside the trajectory of the pedal on that side.

3.4.2 Isokinetic dynamometry

A Biodex isokinetic dynamometer was used to quantify peak power, average power, and fatigue index of knee extensors (Biodex Medical Systems Incorporation, New York, USA). Previous research has shown the validity and reliability of the Biodex (Gapeyeva et al., 2000; Maffiuletti et al., 2007). To guarantee uniformity across evaluations, seat height, seat depth, chair distance, lever arm length, and level arm distance were standardised and recorded. For all participants, the seat angle was fixed at 85 degrees. Fixation straps were secured at the thigh, hips, and chest to minimise compensatory movement.

3.4.3 Jump mat

A Speed Light Sports Timing System (Swift Performance Equipment, PO Box 726, Lismore, NSW 2480, Australia) vertical jump mat was used for the assessment of unilateral vertical jump test. This device use sensors to calculate flight time from which the jump height is calculated. Although the force plate has been recognised as the gold standard method for evaluating force and power, the validity and reliability of the jump mat has been established with the force plate (Lake et al., 2018; Loturco et al., 2017; Rogan et al., 2015).

3.4.4 Inch tape

A standardised measuring tape was used to assess the horizontal distance during the single-leg hop and triple hop for distance, which are commonly used in rehabilitation settings to assess the distance jumped following knee ligament injury, and are used as a criterion for return to play (Davies et al., 2020). Both functional tests (unilateral vertical jump test and hop tests) have shown excellent test-retest reliability, validity, and specificity (Chamari et al., 2008; Fitzgerald et al., 2001; Gustavsson et al., 2006; Keskula et al., 1996; Kockum & Annette, 2015; Lee et al., 2018; Noyes et al., 1991).

3.5 Questionnaires

3.5.1 Demographic questionnaire

A custom designed questionnaire (refer Appendix D) was used to obtain demographic data such as age, gender, height, weight, ethnicity, dominant limb, recreational sports levels, and working status. Furthermore, for the ACL participants, the questionnaire focused on issues such as the type of injury sustained, the side of the lower limb injured, rehabilitation methods, and length of the rehabilitation phase.

3.5.2 Lower Limb Task Questionnaire (LLTQ)

The LLTQ is split into two sections. The first section focuses on activities of daily living, while the second section focuses on recreational activities. Both sections are provided with a grading scale. Each portion of this questionnaire contains 10 questions, and participants must assess their degree of difficulty for the following tasks in the last 24 hours or estimate the level of difficulty if the activity was not completed. The scale is divided into five categories: 4) no difficulty, 3) mild difficulty, 2) moderate difficulty, 1) severe difficulty, and 0) unable to execute. The total of all questions for each part is summed to get a score out of 40 (refer Appendix E). The LLTQ was identified to be valid and reliable tool for evaluating functional activities (McNair et al., 2007).

3.5.3 Knee injury and Osteoarthritis Outcome Score (KOOS)

The Knee Injury and Osteoarthritis Outcome Score (KOOS) is designed for young, middle-aged, and elderly adults with knee injury and/or knee osteoarthritis (Marot et al., 2019), and it may be used to track rehabilitation outcomes after surgical and other therapies (refer Appendix F). The KOOS has five subscales: (1) Pain; (2) Other symptoms; (3) Activities of daily living; (4) Sport and recreation function; and (5) Knee-related quality of life. Each subscale is rated independently, ranging from 0 (severe knee issues) to 100 (no knee problems) (Collins et al., 2016). The KOOS was chosen because it has been shown to be a valid and reliable measure for determining functional performance following a knee injury or osteoarthritis (Roos et al., 1998; Salavati et al., 2011).

3.6 Procedure

All participants attended a single session at AUT biomechanics lab situated at AUT North campus, Auckland. The testing session lasted 60-90 minutes and was conducted by the primary researcher who was knowledgeable with the experimental testing. The testing session included five procedures: 1) familiarisation, 2) standardised warm-up 3) functional performance tests (vertical jump test and hop tests), 4) isokinetic testing, and 5) the WAnT. To minimise excessive fatigue, five minute intervals were provided between assessments.

3.6.1 Familiarisation and Standardised warm-up

Participants were instructed to perform a five-minute warm-up on a cycle ergometer at a submaximal speed. After the generalised warm-up, the testing procedures of the isokinetic dynamometry, unilateral Wingate test, and functional tests (hop test and vertical jump test) were explained to the participants. Participants were given additional time for questions regarding the testing methods.

3.6.2 Functional performance tests

Participants were instructed to perform a single-leg vertical jump test on a Speed Light Sports Timing System (Swift Performance Equipment, PO Box 726, Lismore, NSW 2480, Australia) vertical jump mat after becoming familiar with the testing protocols. The test (hop or jump test) and limb to be assessed first were chosen by tossing a coin. For the vertical jump test, participants were instructed to stand with one leg on the jump mat and perform a squat leading to a jump as high as possible then landing on one leg in a controlled manner as described by Hopper et al. (2002). Participants performed two consecutive jumps with a one-minute rest between jumps. The sensors on the mat measured flight time, which was converted by the jump mat software into jump height.

The mean height of the two jumps was utilised for calculating power. Lower limb muscle power was calculated using the formula developed by Sayers et al. (1999): “PP (W) = 60.7 x jump height (cm) + 45.3 x mass (kg) – 2055”. The test was then performed on the opposite leg and the Limb Symmetry Index (LSI) index was calculated (LSI = weak leg/strong leg x 100). Participants were given 4-5 practice tests prior to commencement of the main test.

Following this, participants performed two hop tests (single-leg hop for distance and triple-hop for distance) as described by Lee et al. (2018) and Noyes et al. (1991). For the single-leg hop for distance, participants were instructed to stand on one leg with arms positioned on the hips, jump as far as possible, and land with one leg in a controlled manner for two times. Similarly, for the triple hop for distance, participants were instructed to stand as above, but to perform three hops for maximum distance and finish in a controlled one legged position. The test was then performed on the opposite leg and mean distance jumped between two tests was used to calculate the LSI. Prior to the start of the main test, four to five submaximal practice tests were performed. Both measures have been found to be highly reliable and valid in assessing functional performance in both healthy and knee-injured populations (Chamari et al., 2008; Fitzgerald et al., 2001; Gustavsson et al., 2006; Keskula et al., 1996; Kockum & Annette, 2015; Lee et al., 2018; Noyes et al., 1991).

3.6.3 Isokinetic testing

Following the functional tests, the unilateral WAnT or the isokinetic dynamometry test was performed. A coin was flipped to randomise the sequence. A Biodex isokinetic dynamometer (Biodex Medical Systems Incorporation, New York, USA) was used to measure quadriceps peak power, average power, and fatigue index. The limb to be assessed first was selected by flipping a coin. The seat back rest was placed at an angle of 85 degrees for all participants. The axis of the dynamometry was positioned close to the lateral femoral condyle of the knee with 90 degrees knee flexion, and the tibial pad was positioned two centimetres above the medial malleolus. Seat height, seat depth, chair distance, lever arm length, and level arm distance were recorded. To reduce compensatory movement, fixation straps were secured over the thigh, hips, and chest. Lower limb weight was assessed using computer software. Participants first underwent a generalised warm-up to become familiar with the testing process. During the warm-up, participants performed 10 concentric knee extension (quadriceps muscular contraction) and flexion (hamstrings muscle contraction) movements against a resistance of 25, 50, 75, and 100 percent of their maximum effort. After a two-minute rest period, participants performed 30 maximal concentric knee extension and flexion movements at a joint angular velocity of 180 degrees per second, ranging from 90 degrees knee flexion to full knee extension. Verbal encouragement was provided throughout the test (McNair et al., 1996). Peak power and average power were recorded from the Biodex software over 30 repetitions and were used to calculate a fatigue index. The test was then performed for the opposite limb and LSI was calculated. A similar methodology has been utilised in the literature with no known adverse effects, and the reliability of the isokinetic test has been demonstrated often (Gapeyeva et al., 2000; Maffiuletti et al., 2007).

3.6.4 The unilateral Wingate anaerobic cycle test

A Watt bike (Watt bike Pro, Watt bike Ltd, Nottingham, UK) was utilised to perform the modified unilateral WAnT. For the measurement of peak power, mean power, and fatigue index, participants were seated on a Watt bike. Randomisation of leg to test was made by flipping a coin. According to the participant’s demographics, the seat height, width, and armrest position were adjusted. Further, participants were positioned with their hips and knees flexed at 90 degrees, and their foot strapped on the pedal with toe clips. The contralateral leg was placed on a box just to the side of the pedal. To avoid compensatory muscle activity, participants were instructed to pedal without rising from the seat. The participants were then instructed to warm-up at submaximal pedalling speed until they became familiar with the unilateral cycling. After warm-up, a resistance load was added to the air brakes and magnetic brakes of the Watt Bike, calculated based on of 7.5 percent of their body weight. The participants were instructed to pedal at submaximal speed and when instructed “ready, set, go”, to pedal as fast as possible for 30 seconds. Verbal encouragement was given throughout the test. Using the Watt bike software (Watt Bike Pro, Watt Bike Ltd, Nottingham, United Kingdom), the data acquired during the 30 seconds of maximal effort pedalling were used to calculate peak power, mean power, and fatigue index. The fatigue index was calculated using the formula as described by Naharudin and Yusof (2013).

$$FI = \left[\frac{(Highest\ 5s\ anaerobic\ power - Lowest\ 5s\ anaerobic\ power)}{Highest\ 5s\ anaerobic\ power}\right] \times 100$$

For comparison, the procedure was performed on the opposite limb and LSI was calculated. This methodology (unilateral) has previously been employed in a paediatric population with no documented side effects, and the reliability of the unilateral WAnT is has been tested in a paediatric population (Hebestreit et al., 1999).

3.7 Statistical Analyses

Statistical analyses were performed using Statistical Package for Social Sciences (SPSS software) version 25 (International Bussiness Machine Corporation, Armonk, Newyork, USA) and Microsoft office excel 2017 (Microsoft corporation, Redmond, Washington,USA). An alpha level of 0.05 was set for statistical significance.

To determine significant difference in peak power, mean power, and the fatigue index across limbs in healthy participants, paired t-tests were utilised.

To determine similarities in key measures of power (power profiles, peak and mean power, and fatigue index) between the modified unilateral WAnT and isokinetic knee extensor power generated at 180 degrees per second over 30 repetitions, descriptive statistics were used qualitatively.

To determine significant relationships between the modified unilateral WAnT variables with knee extensor isokinetic peak and mean power, fatigue index generated at 180 degree per second, single leg hop, triple leg hop for distance, and vertical jump height, Pearson correlation coefficients were calculated.

A secondary analysis examined variables in the above-mentioned tests in two participants who had undertaken rehabilitation after reconstruction of their ACL. The results were compared to the uninjured group means and standard deviations qualitatively.

4. CHAPTER 4: RESULTS

4.1 Introduction

This chapter is divided into four sections. The first section describes participants' demographics and characteristics. The second section explains the self-reported outcome measures assessed using the KOOS and LLTQ. The third section is divided into three parts and describes the key findings of the unilateral Wingate test, isokinetic knee extension test, and functional performance tests. Comparisons were made between dominant and non-dominant legs for the 11 healthy participants. Interlimb comparisons were also performed for the male and female participants two years post ACL reconstruction, and these were compared descriptively with uninjured participant data. The last section describes the relationships between Wingate performance and functional performance tests (hop and jump test) and isokinetic performance.

4.2 Demographics

Thirteen participants volunteered to participate in this pilot study. The healthy group had 11 participants (10 male; 1 female) with mean age of 26 years (Table 4.1). Healthy participants were primarily recreational athletes who were classified as overweight (BMI=27). The two participants with history of ACL-reconstruction had their surgery two years prior to the testing. The 39-year-old male was a recreational soccer player who had a right patellar tendon graft reconstruction, and the 20-year-old female had a hamstring graft reconstruction. The male participant had not partaken in any formal rehabilitation and returned to recreational soccer at the time of testing. The female had not returned to competitive sport but was undertaking strength and conditioning training four times per week at the gymnasium. Participants from both groups were able to complete all the tests in a single session.

Table 4.1

Demographic data for healthy participants and two ACL reconstruction participants.

	Mean	SD	Range
Healthy Participants			
Age (years)	26.3	6.9	20-39
Height (cm)	176.1	12	161-191
Body mass (kg)	84.3	18	64-118.8
ACL-Reconstructed Participants			
Female Participant			
Age (years)	20		
Height (cm)	169.5		
Body mass (kg)	62		
Male Participant			
Age (years)	39		
Height (cm)	174		
Body mass (kg)	78		

SD: Standard Deviation; cm: centimetre; kg: Kilograms.

4.3 Self-Reported Outcome Measures

Functional scores measured using the KOOS and LLTQ questionnaire are displayed below in Table 4.2. The mean total score for the KOOS questionnaire for the uninjured group was 96 percent. Eight of the uninjured group participants scored greater than 98 percent for the KOOS score, with one participant scoring 95 percent and two participants scoring 81 percent and 82 percent respectively. Both participants with ACL reconstruction reported decreased quality of life (75%, female; 69%, male) and sports/recreation scores (85%, female; 80%, male) compared to uninjured group scores that were above 95 percent for both these sections of the KOOS questionnaire. The ACL reconstruction and uninjured participants had similar KOOS scores for pain, symptoms, ADL; and similar scores for LLTQ (Table 4.2).

Table 4.2

KOOS and LLTQ score of knee injured participants and healthy participants.

	Healthy participants	*ACL-reconstruction participants*	
	Mean+SD	Female participant	Male participant
KOOS			
Pain	95.4+9.6	92	94
Symptoms	93.8+8.3	89	89
ADL	97.8+5.5	100	100
Sports/recreation	96.8+6.4	85	80
QoL	95.5+11.3	75	69
LLTQ			
ADL	39.1+1.5	40	40
RA	37+3.5	35	38

SD: Standard Deviation; ADL: Activities of daily living; QoL: Quality of life; RA: Recreational activities.

4.4 Lower Limb Muscle Power and Fatigue Index

4.4.1 Muscle power and fatigue index in the Wingate test

Figure 4.1 shows mean power of uninjured participants recorded every second during the 30-second unilateral WAnT. All participants in the uninjured group showed similar power profiles on the right and left side. Peak power was achieved within the first 5 seconds followed by a relatively linear decline in peak power throughout the remainder of the Wingate test (Figure 4.1). There was no significant difference in peak power between the left (non-dominant) and right (dominant) side (P>0.05). This was reflected by a mean LSI of 89.5+5.3% (Figure 4.4).

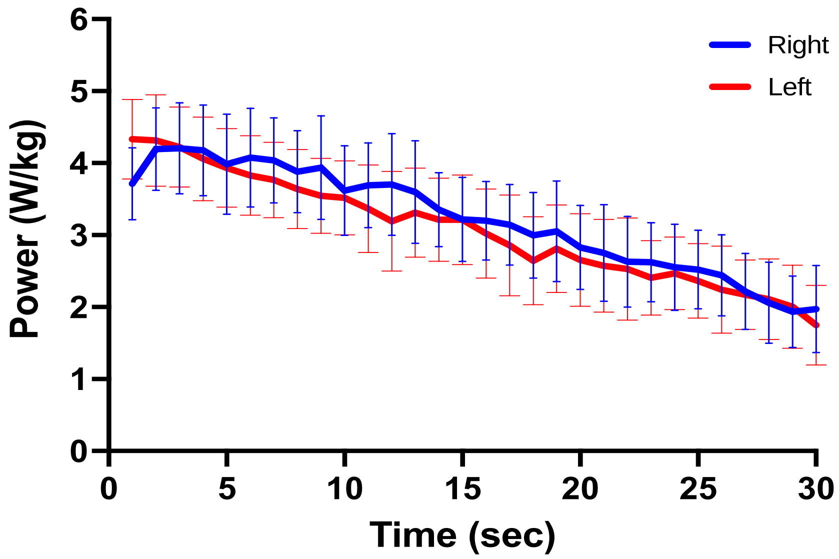

Figure 4.1: *Mean power of uninjured controls in the Wingate test for each second.*

Wingate power profiles for the female and male ACL reconstruction participants are shown in Figure 4.2. The power profiles of the female participant were similar to uninjured group participants and there was no clear difference between the ACL-reconstructed leg and non-injured leg (Figure 4.2). In contrast, the male ACL participant power profiles differed considerably when compared to the uninjured group. In this participant, the reconstructed side displayed consistently lower power measures throughout the test when compared to his non-injured leg and uninjured group power data (Figure 4.2).

Figure 4.3 illustrates the means and standard deviations for peak and average power per kilogram of body mass for the left (non-dominant) and right (dominant) lower limbs of uninjured participants and ACL-reconstructed leg and non-injured leg of two ACL-reconstruction participants during the unilateral Wingate test.

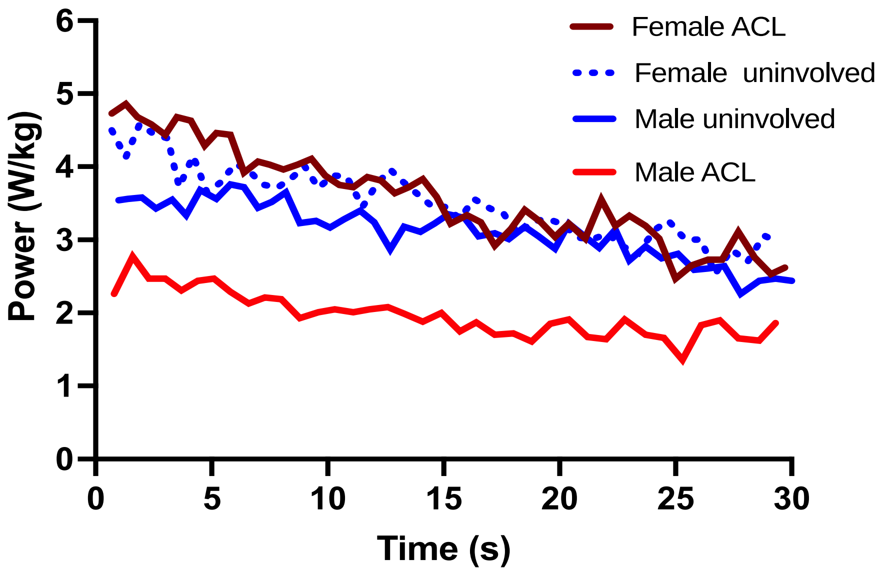

Figure 4.2: *Wingate power profiles of the female and male ACL-reconstructed participants.*

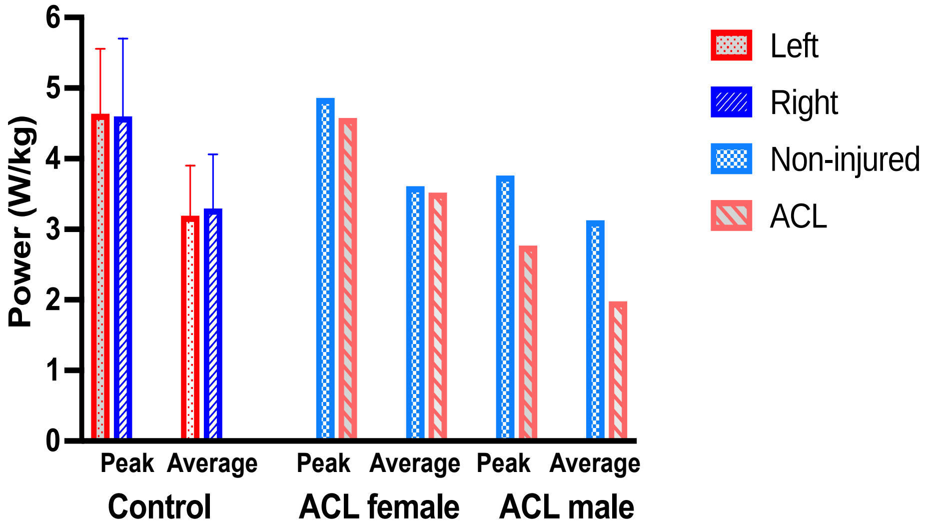

Figure 4.3: *Mean and standard deviation for peak and mean power of uninjured group and two ACL-reconstructed participants in the unilateral Wingate test.*

Peak and average power for the female ACL reconstruction participant was similar to the uninjured group, and no notable deficits in peak and average power were seen in the ACL-reconstructed leg compared to the non-injured leg (Figure 4.3). This was reflected by an LSI of 94 percent for peak power in this participant (Figure 4.4). Deficits in peak and average power were observed in the side of ACL reconstruction in the male participant and the peak power of his non-injured side was also lower than that produce by the uninjured group and the female with an ACL reconstruction. The male participant also scored a lower peak power LSI (73%) than other participants (Figure 4.4).

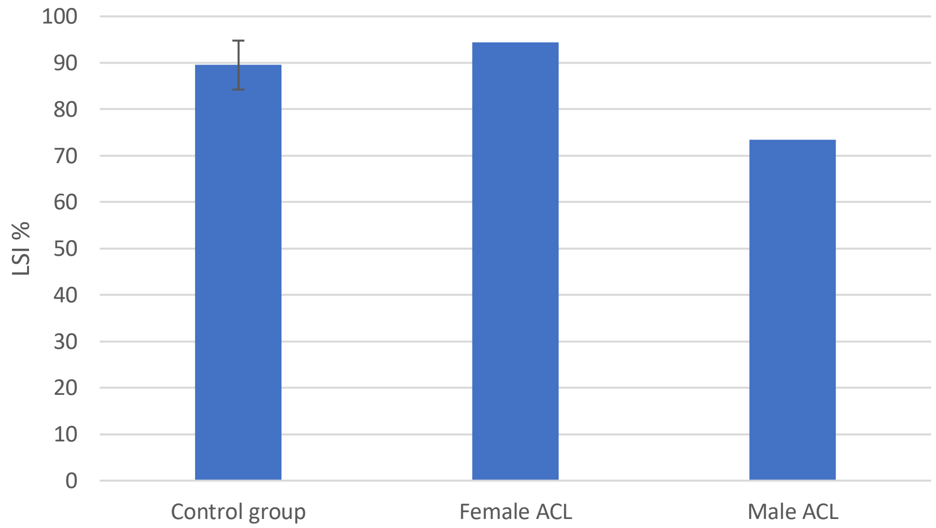

Figure 4.4: *Peak power LSI of uninjured group and two ACL-reconstructed participants during unilateral Wingate test.*

Figure 4.5 illustrates the fatigue index of uninjured group and two ACL reconstructed participants respectively. The fatigue index was used to determine the magnitude of power decline throughout the test. Uninjured group participants had a fatigue index of 60 percent for both limbs (Figure 4.5). Both the female and male ACL-reconstructed participants showed lower fatigue index percent in the ACL-reconstructed leg (female participant, 44%; male participant, 40%) compared to the non-injured leg (female participant, 49%; male participant, 50%).

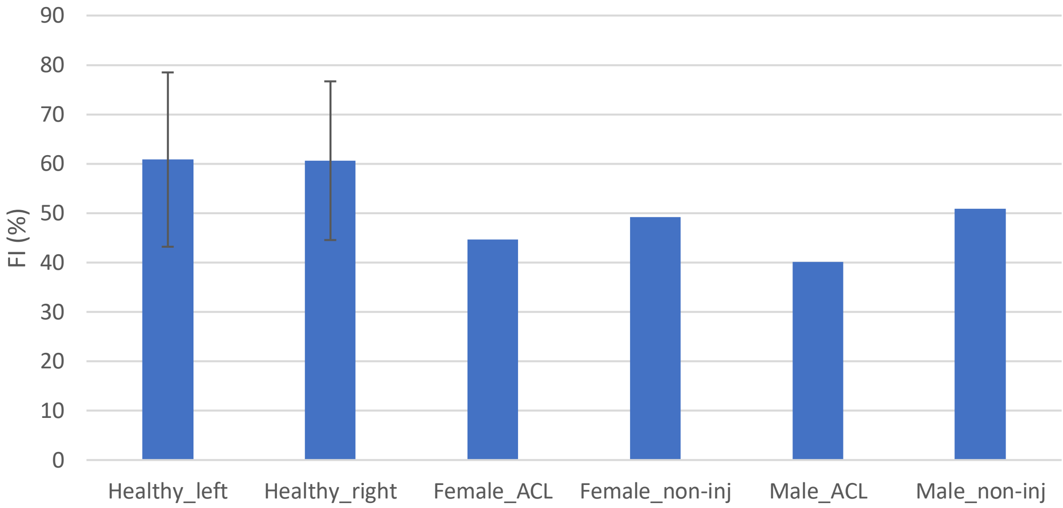

Figure 4.5: *Fatigue index (FI) of uninjured group and two ACL reconstruction participants.*

Figure 4.6 shows the mean cadence/pedalling rate of uninjured participants measured every second during the 30-second unilateral WAnT. All participants in the uninjured group showed similar cadence/pedalling rate on the left and right side where peak cadence was achieved in the first 5 seconds followed by a gradual decline over 30 seconds. There was no significant difference in peak cadence between the dominant and non-dominant leg.

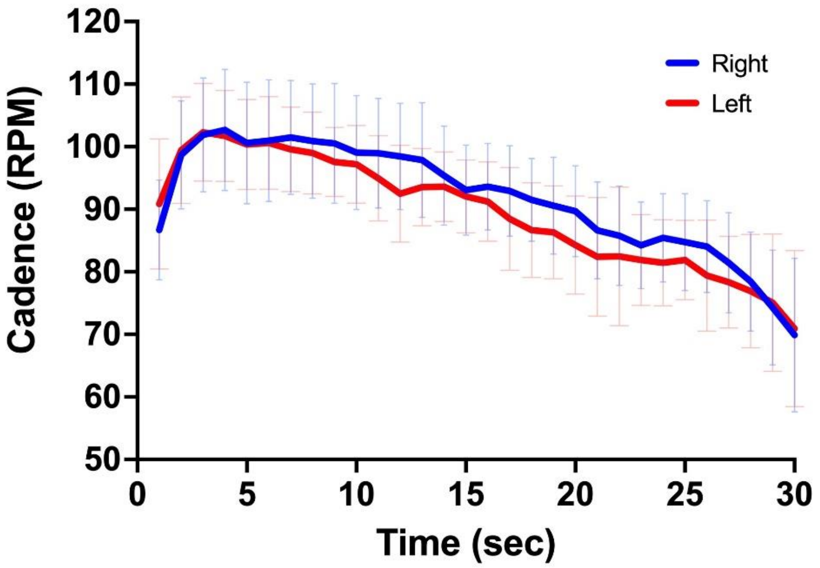

Figure 4.6: *Mean cadence/pedalling rate of uninjured controls in the Wingate test for each second.*

Figure 4.7 shows the mean cadence/pedaling rate of the ACL-reconstructed participants measured every second during the 30-second unilateral WAnT. The cadence profile of the female and male participants differed considerably. The female participant showed a cadence profile similar to uninjured participants and there was no difference between the non-injured and ACL-reconstructed limb. In contrast, the cadence profile of the male ACL participant differed when compared to uninjured participants and the female ACL participant. The male participant showed a lower cadence profile and there was minimal decline in cadence throughout the test in the reconstructed side compared to his uninjured limb and uninjured participants. However, even in the uninjured leg the male participant was unable to achieve similar peak cadence when compared to the female and healthy participants.

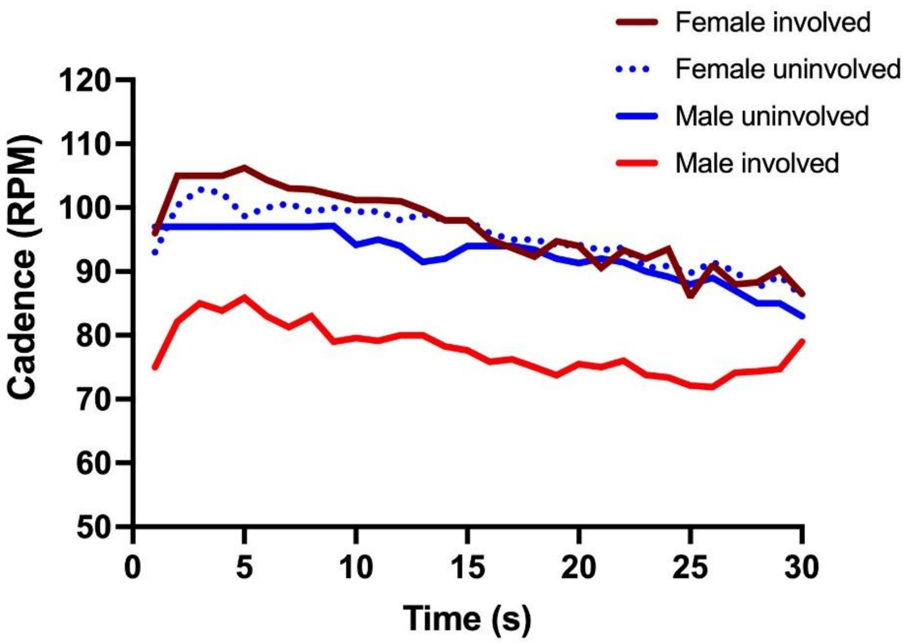

Figure 4.7: *Mean cadence/pedalling rate of the female and male ACL reconstructed participants in the Wingate test for each second.*

4.4.2 Muscle power and fatigue index in the isokinetic test

Figure 4.8 illustrates average knee extensor power calculated for each repetition over the 30 repetitions of the isokinetic testing. During the 30-repetition isokinetic testing, participants in the uninjured group showed similar power profiles for the right and left side, with peak power for extension achieved in first five repetitions and a linear decline in power throughout the remainder of the test. There was no significant difference in peak power between the left and right side (Figure 4.10). Interlimb comparisons revealed a mean LSI of 89.5±6 for peak power (Figure 4.11).

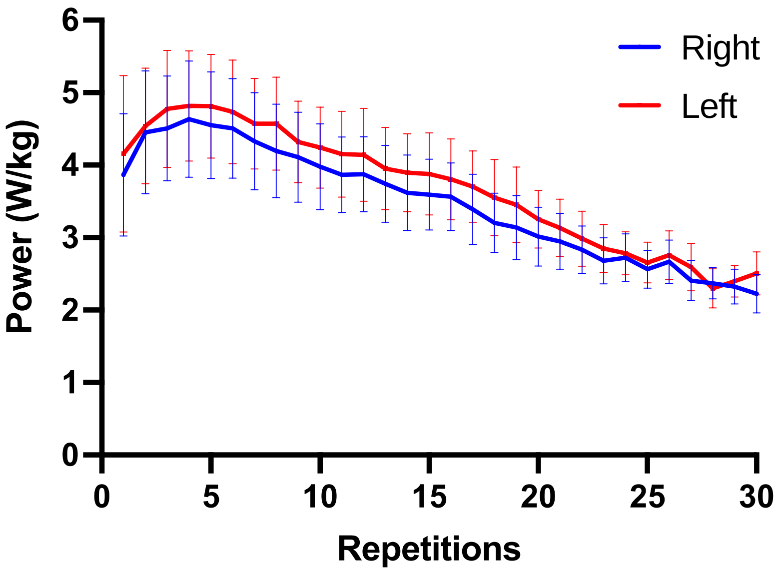

Figure 4.8: *Mean knee extensor power for uninjured group over 30 repetitions during isokinetic testing.*

Isokinetic power profiles of male and female ACL-reconstructed participants over 30 repetitions during the isokinetic testing are displayed in Figure 4.9. The isokinetic profiles of the female participant with ACL-reconstruction were similar to the uninjured group with no notable difference between the injured and non-injured side. The power profile of the involved leg of the male ACL participant differed considerably to the uninjured group and female ACL participant (Figure 4.10). The male participant showed considerably lower average power in the reconstructed side during the first 10-15 repetitions compared to the non-injured side and uninjured group (Figure 4.9). There was also no clear evidence of a reduction in power on the involved side throughout most of the test (Figure 4.9).

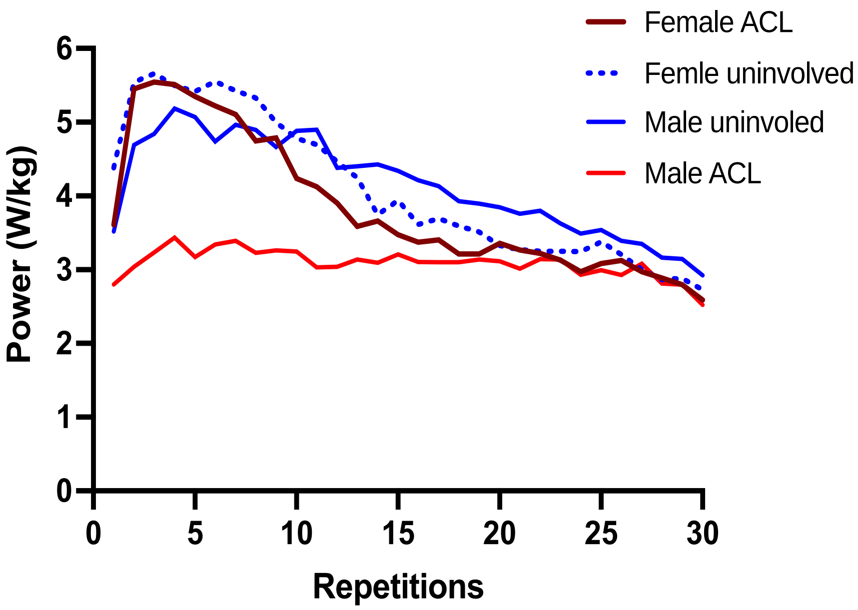

Figure 4.9: *Average knee extensor power of two ACL-reconstructed participants over 30 repetitions during isokinetic testing.*

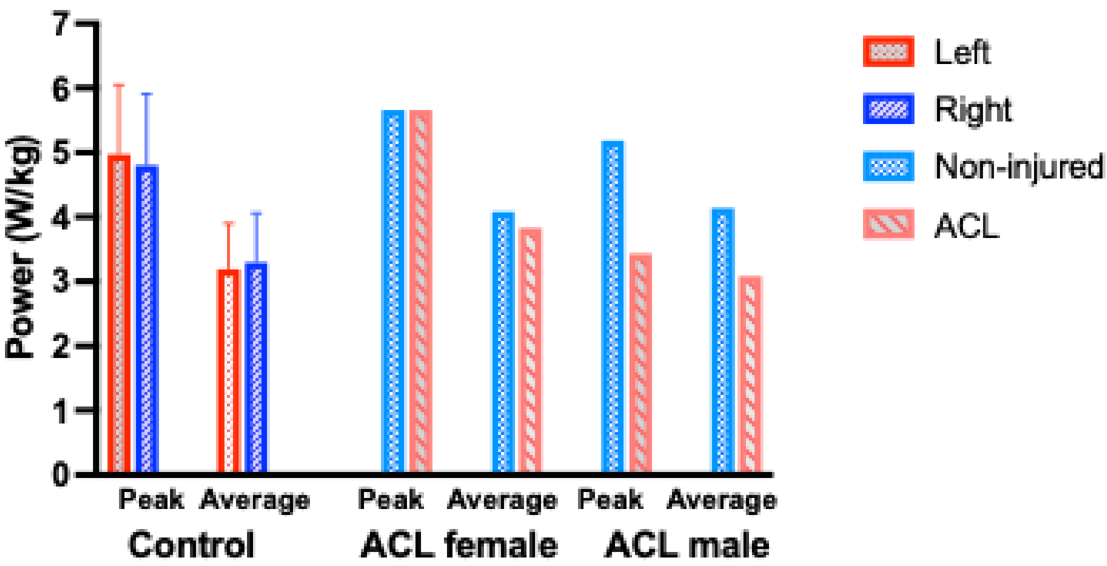

Figure 4.10: *Mean and standard deviation of peak and average power for uninjured group and two ACL-reconstructed participants during isokinetic testing.*

Figure 4.11 illustrates the LSI of peak power of the uninjured group and two ACL-reconstructed participants during isokinetic testing. Analysis of peak and average power of the female participant displayed no deficits between the injured and non-injured side.

The female participant scored a similar LSI of 97 percent for peak power (Figure 4.11). In the male ACL participant, deficits in peak and average power were observed in the injured side with lower LSI score of 66 percent for peak power (Figure 4.11).

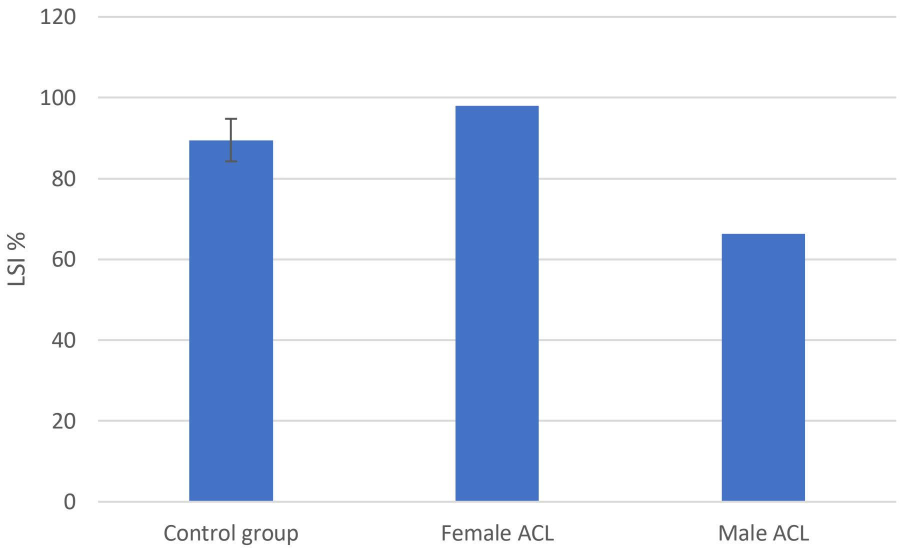

Figure 4.11: *Peak power LSI of uninjured group and two ACL-reconstructed participants during isokinetic testing tests.*

Figure 4.12 shows the fatigue index of the uninjured group and two ACL-reconstructed participants. Fatigue index was calculated using the same formula as mentioned before (peak power in first 5 repetitions subtracted by lowest power in last 5 repetitions, divided by peak power in first 5 repetitions, multiplied by 100). The uninjured group had a fatigue index of 55 percent for both the left and right side. Further, the female ACL participant showed similar fatigue index percent between her reconstructed side (53%) and non-injured side (51%). A large difference in fatigue index was observed in the injured side (26%) compared to non-injured side (43%) in the male ACL-reconstructed participant.

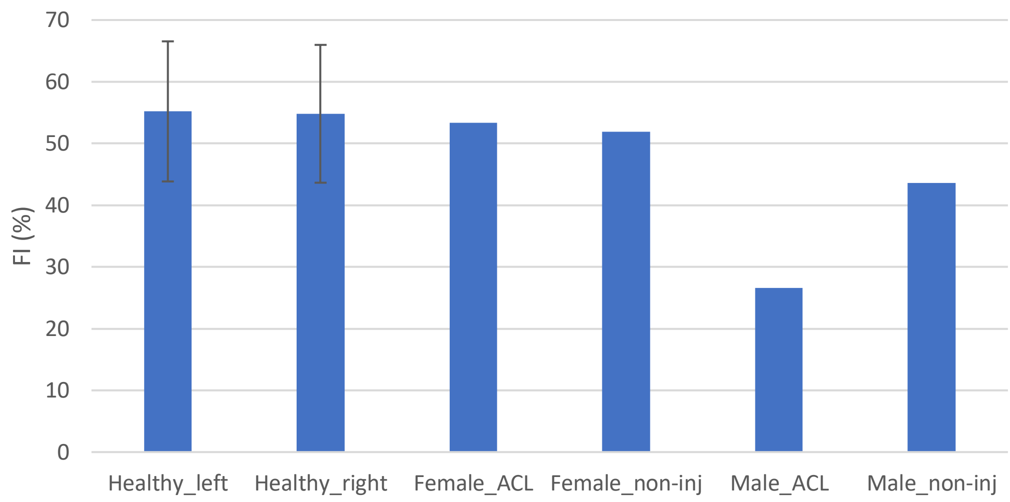

Figure 4.12: *Fatigue index (FI) of uninjured group and two ACL reconstruction participants during isokinetic testing.*

4.4.3 Functional performance test

Figure 4.13 illustrates the LSI of the functional performance tests (single leg hop, triple hop for distance, and vertical jump test). No side-to-side difference (p>0.05) was observed in all three tests for the uninjured group. The mean LSI's of the uninjured group were 95 percent for single-leg hop, 96 percent for triple hop, and 91 percent for vertical jump test. Figure 4.14 shows the LSI of the two ACL-reconstructed participants for all three functional tests. The female ACL-reconstructed participant showed no difference between the injured and non-injured leg for all three tests and achieved an LSI of 97.5 percent for single leg hop, 99 percent for triple hop, and 100 percent for the vertical jump test (Figure 4.14). The male ACL participant showed a large difference in all three tests between the injured side and the non-injured side, and the uninjured group. This participant scored a LSI of 77.2 percent for single leg hop test, 78 percent for triple hop, and 89.6 percent for the vertical jump test (Figure 4.14).

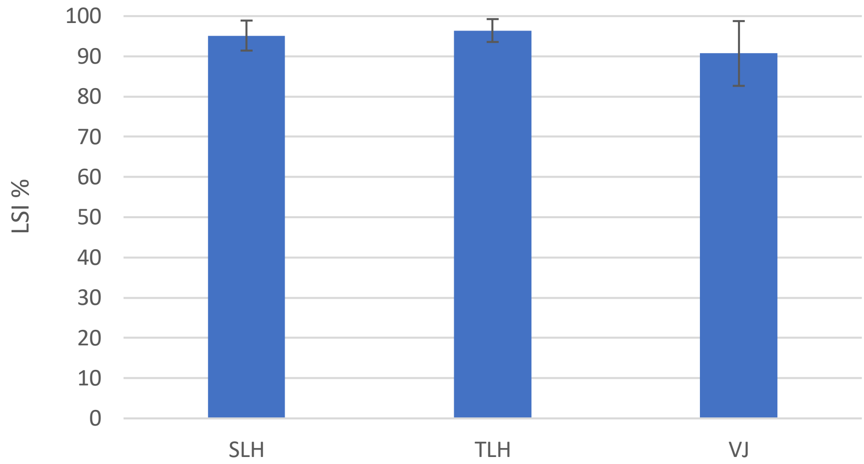

Figure 4.13: *LSI (%) of uninjured group in functional performance tests.*

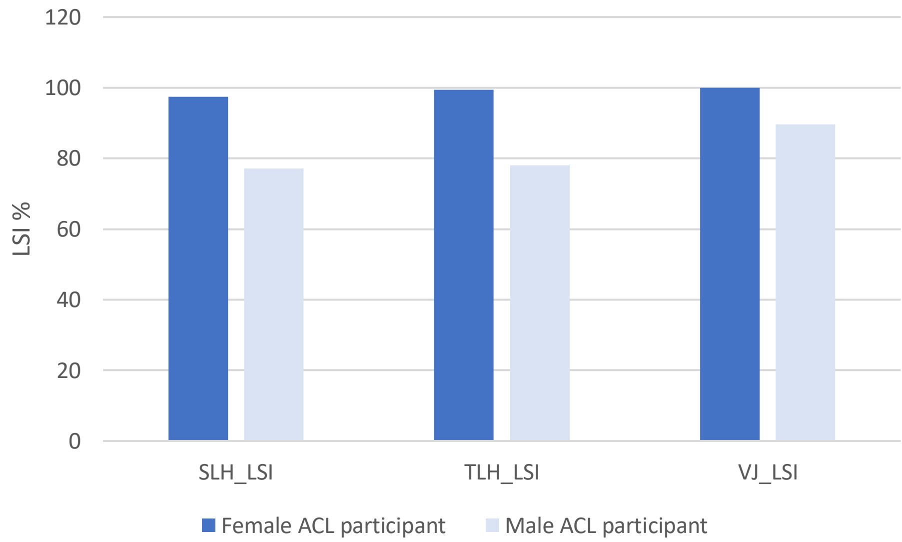

Figure 4.14: *LSI (%) of knee injured participants in functional performance tests.*

4.5 Relationship between Wingate test, Isokinetic test, and Functional Performance tests

Table 4.3 illustrates the correlation between peak power in the Wingate test, isokinetic test, and functional performance tests. From the results, a moderate linear relationship was identified between peak power in the unilateral WAnT and peak power in the isokinetic testing ($r=0.57$; $p<0.05$). A poor positive relationship was identified between the peak power in the unilateral WAnT and single leg hop test (left $r=0.2$; right $r=0.5$). However, a moderate positive relationship between peak power in the unilateral

WAnT and triple hop for distance was identified (left r=0.42; right r= 0.54; p<0.5). Finally, a high positive relationship between peak power in the unilateral WAnT and vertical jump test was also determined (left r=0.84; right r=0.86; p<0.01). The results also showed a moderate to poor positive relationship between fatigue index in the unilateral WAnT and isokinetic testing for power (left r=0.43; right r=0.25; p>0.05).

Table 4.3

Correlation between Wingate test, isokinetic testing, and functional performance tests in healthy participants.

	WAnT PP (ND)	*ISO_ND*	*VJ_PP_ND*	*SLH_ND*	*TH_ND*
WAnT PP (ND)	1				
ISO_ ND	0.57	1			
VJ_PP_ ND	0.84	0.54	1		
SL_ ND	0.18	0.55	0.26	1	
TH_ ND	0.42	0.61	0.36	0.91	1
	WAnT PP (D)	*ISO_ D*	*VJ_PP_ D*	*SLH_ D*	*TH_ D*
WAnT PP (D)	1				
ISO_ D	0.57	1			
VJ_PP_ D	0.86	0.43	1		
SH_ D	0.51	0.47	0.23	1	
TH_ D	0.54	0.51	0.29	0.95	1
	WAnT_FI_ND	*WAnT_FI_ D*			
ISO_FI_ ND	0.43	0.30			
ISO_FI_ D	0.09	0.25			

WAnT – Wingate anaerobic cycle test; PP – Peak Power; ISO – Isokinetic testing; VJ – Vertical Jump; SLH – Single leg hop; TH – Triple hop for distance; FI – Fatigue index; ND – Non-Dominant leg (left); D – Dominant leg.

5. CHAPTER 5: DISCUSSION

5.1 Introduction

This chapter contains four sections. The first section describes the participant characteristics. The second section explains the functional outcome measures assessed using questionnaires. The third section discusses the peak power, mean power, and fatigue index assessment using the modified unilateral Wingate test and the isokinetic test followed by functional performance tests (single leg hop, triple hop for distance, and vertical jump test). The last section explains the relationship between the modified Wingate test and isokinetic testing and functional performance test.

5.2 Participants

Participants in the uninjured group consisted of 10 males and 1 female with a mean age of 25.7±6.2 years, mean height of 175.6±11.5 centimetres, and mean weight of 83.4±17.2 kilograms, which was similar to participant demographics from previous studies on the Wingate test (Coppin et al., 2012; Hachana et al., 2012; Lovell et al., 2013). The cohort in the uninjured group had no history of knee injury, were physically active and involved in recreational sports.

The two ACL-reconstructed participants (1 male and 1 female) included in this study had their reconstruction approximately two years prior to testing. The female participant was a professional skier with a history of ACL injury three times in the last five years. Her first ACL reconstruction was a patellar tendon graft and she returned to competitive skiing within six months of her surgery. She then re-ruptured her ACL for the second time a year after her return to sport. This was followed by a third ACL rupture and a hamstring tendon graft reconstruction two years prior to participating in the current study. Following her last reconstruction, the female participant was no longer skiing and partook in strength and conditioning training four times a week and other recreational physical activities. Her injury history was similar to the 35 percent of young athletes who return to sports less than nine months after an initial ACL reconstruction and are prone to re-injury within 24 months (Webster & Feller, 2016). Paterno et al. (2014) reported that female athletes who return to sport within 24 months after a first ACL reconstruction are five times more likely to get a subsequent ACL injury. The female participant was 20 years old, with height 169.5 centimeters, and weight 62 kilograms.

The male ACL-reconstruction participant was a recreational soccer player who had an ACL injury while playing soccer and underwent reconstructive surgery using patellar tendon graft. The male participant did not undergo any formal rehabilitation following reconstructive surgery and cleared himself to return to recreational activity (soccer) after eight months. The male participant was 38 years old, with height 174 centimeters, and weight 78 kilograms.

5.3 Self-Reported Outcome Measures

The KOOS subscale scores for the uninjured group were within normal range and consistent with prior research (Antosh et al., 2018; Marot et al., 2019). The two ACL-reconstructed individuals had a low KOOS score for quality of life and sports and recreation sections. Similar KOOS score findings in ACL-reconstructed patients have been reported in the literature (Antosh et al., 2018; Muller et al., 2016; Salavati et al., 2011; Tengman et al., 2014). Ithurburn et al. (2019) reported scores of 65.7 percent for sports and recreation and 26.9 percent for quality of life at the time of return to sport following ACL reconstruction. Lower scores for KOOS sports and recreation components (83.6%) and quality of life (71.6%) were evident up to two years after return to sport. The current findings for KOOS pain, symptom, and ADL were comparable to those of the uninjured group. These findings were consistent with prior research findings. Aga et al. (2018) and Antosh et al. (2018) observed similar KOOS scores for pain, symptoms and ADL for ACL reconstruction participants and uninjured subjects between 18 to 40 years of age at two years follow-up, which closely resembles the findings in the current study. Further, the LLTQ scores for ADL and sports and recreation for the uninjured group were normal in the current study. The two ACL reconstruction participants scored less in the sports and recreation section than uninjured participants. According to McNair et al.

(2007), patients with lower limb injuries may suffer minor difficulties while doing high intensity or loading activities, which results in lower LLTQ ratings.

5.4 Muscle Power and Fatigue Index

5.4.1 Peak power, mean power, and fatigue index in the Wingate test

To the author's knowledge, this is the first study to explore power parameters of the unilateral Wingate test in adult recreational athletes. All participants were able to successfully complete the unilateral Wingate test in a single session with no occurrence of any adverse events. In the current study, a flying start protocol was used for all participants to measure peak power, mean power, and fatigue index. It has been suggested that peak power is achieved more consistently in a flying start (Clark et al., 2018) and a similar method to the current study has been shown to be reliable for determining unilateral peak power and total mechanical work in the unilateral Wingate test (Dunstheimer et al., 2001; Hebestreit et al., 1999). Altogether, these findings indicate that the unilateral Wingate test was a feasible and safe method to assess unilateral lower limb muscle power in recreational athletes and the two ACL reconstruction participants in the current study.

The primary finding of this study was that peak and mean power during the modified unilateral WAnT were similar between the dominant and non-dominant leg in the uninjured group. To the author's knowledge, only one study has assessed unilateral power production during the Wingate test, and this study primarily focused on paediatric population (Dunstheimer et al., 2001). However, Dunstheimer et al. (2001) did assess a subgroup of males and females aged between 17 and 21 years. They reported average peak power scores of 6.2 and 5.6 W/kg for the right and left side respectively in the male population, and 4.8 W/kg across legs for the females. In the current study, peak power measures for the right (4.6 W/kg) and left (4.63 W/kg) side during the unilateral Wingate test were less than those documented for males in Dunstheimer et al. (2001)'s study. Reasons for such differences are difficult to determine as participants in both studies were recreational athletes. However, the male participants in Dunstheimer et al. (2001)'s study were younger with a mean age of 19 years and had a lower BMI (22 versus 27 in the current study). Although both studies employed a flying start protocol, Dunstheimer et al. (2001) applied a breaking force of 2.8 $J.Kg^{-1} rev^{-1}$ one second after the start of the test followed by a two-minute warm-up; whereas in the current study, a breaking force of 7.5 percent of body mass was applied at the start of the test with a five to seven minute warm-up before testing.

Although direct comparisons cannot be made with bilateral Wingate testing, the sum of right and left unilateral peak power has been found to be approximately 5-10 percent greater than bilateral Wingate peak power (Dunstheimer et al., 2001). The combined right and left leg peak power of 9.24 W/kg and average power of 6.24 W/kg in the current study was considerably lower than the mean peak power of 12.9 W/kg and mean average power of 9.3 W/kg documented by Coppin et al. (2012). The combined peak power of the left and right side was also slightly lower than bilateral Wingate test values in healthy young males (10.4 W/kg) but higher than the 7.8 W/kg reported in college aged females (Gressick & Borgert-Poepping, 2008). Such a large difference between current findings and those of Coppin et al. (2012) may be attributed to level of sporting performance of the participants. Coppin et al. (2012) assessed highly trained division one power athletes who received vigorous exercise training and participated in American football or power sports; whereas in this study, all participants were involved in recreational sports with no formal power training. The greater peak power values documented in some of these studies may also be explained by difference in muscle coordination between unilateral and bilateral cycling. During the bilateral Wingate test, the pushdown phase is stronger, and can assist the pull-up phase of the opposing limb (Dunstheimer et al., 2001). In the current study, only one leg was utilised to push down and pull up to generate peak power requiring greater coordination of the lower limb muscle groups on the side tested. The current findings are more in line with previous findings of Maud and Shultz (1989) who assessed physically active males and females of a similar age range to the current study (18-28 years) and showed a mean peak power of 9.18w/kg in males and 7.61w/kg in females.

In the current study, there were no significant differences between peak power produced during the right (mean=4.6 W/kg) and left (mean=4.63 W/kg) unilateral Wingate test. Further, individual interlimb comparison revealed the peak power of the weakest side tested to be within 90 percent of the strongest side. These findings are similar to Dunstheimer et al. (2001) who, based on average values for males, found peak power of the left side to be within 90 percent of the right. Another study reported a higher LSI of 96.7 percent using maximal isokinetic cycling in healthy young male adults between 18 and 30 years of age (Baron et al., 1999). The difference in LSI observed in the current study and Baron et al. (1999) study can be due to testing method utilised. Baron et al. (1999) used a 10 second bilateral maximal isokinetic cycling at speeds ranging from 50 to 140 RPM and peak power between left and right leg was determined using measures from each leg; whereas in the current study, participants pedalled unilaterally as fast as possible for 30 seconds at maximal effort to generate power whilst the non-tested leg remained stationary.

The unilateral power profiles of the uninjured group were similar to those previously documented in bilateral Wingate testing where, irrespective of side, participants reached their peak power in 0-5 seconds during the unilateral Wingate test, which was similar to previous studies using the bilateral Wingate tests (Beneke et al., 2002; Julio et al., 2019; Smith & Hill, 1991). It has been suggested that the high levels of power within 5-10 seconds of the Wingate test are generated via recruitment of high threshold motor units and utilisation of the phosphocreatine system to rapidly generate adenosine triphosphate (Smith & Hill, 1991; Stewart et al., 2011; Zajac et al., 1999). For example, Stewart et al. (2011) found that peak power during the bilateral Wingate test occurred at a similar time (5-7 seconds) to peak mean muscle fibre conduction velocity (MFCV) and peak mean frequency of the vastus lateralis muscle. They argued that because MFCV is positively correlated to the diameter of muscle fibres (Farina et al., 2004), the peak MFCV achieved in first 5-7 seconds of the Wingate test represented the recruitment of high threshold motor units mainly consisting of type II fibres.

In the current study, peak power during the Wingate test was followed by a relatively linear decline in power throughout the remainder of the test, and was similar for both sides. These patterns were similar to previous research findings using a bilateral Wingate test (Bar-Or, 1987; Beneke et al., 2002; Bradley & Ball, 1992; Coppin et al., 2012; Julio et al., 2019; Zajac et al., 1999; Zupan et al., 2009). Stewart et al. (2011) stated that this linear decline in power is best explained by the reduction of high threshold motor unit (fast twitch type II fibres) contribution over the 30 seconds. Using EMG techniques, Stewart et al. (2011) found that a decrease in MFCV of vastus lateralis muscle had a significant correlation with reduction in power output throughout the test; yet, there was a little change in normalised muscle EMG throughout the test. Stewart et al. (2011) suggested that the linear decline in MFCV reflected the reduction in recruitment of high threshold type II motor units; whereas the maintenance of normalised EMG reflected a decrease in motor unit discharge rate. Similar findings were also reported by Hunter et al. (2003) and Wang et al. (2015) who observed no change in EMG amplitude of vastus lateralis muscle but substantial change in the mean frequency towards lower levels during the 30-second sprint cycling and the first 30 seconds of a three minute all out maximal cycling. Hunter et al. (2003) suggested that the decrease in power throughout the Wingate test is accompanied by reduction in muscle pH with metabolite accumulation in the periphery and inefficient afferent signals to the central nervous system, which influences neuronal recruitment strategies resulting in low power production.

The rate of peak power decline during the unilateral Wingate test in the current study was substantially greater than that previously reported in bilateral Wingate test studies. For instance, the fatigue index in the current study was 60 percent for both right and left side, which was almost double when compared to bilateral Wingate test values in the literature (Baker et al., 2011; Maud & Shultz, 1989; Zupan et al., 2009). There is no previous study which has established a unilateral fatigue index using the Wingate test in recreational young adults. However, using a bilateral Wingate test, Maud and Shultz (1989) reported a mean fatigue index of 37.6 percent in males and 35 percent in females using a resistance of 7.5 percent of body mass in physically active young adults of similar age group to the current study. Similarly, Zupan et al. (2009) identified a mean fatigue index of 47 percent in males and 42 percent in female athletes of similar age group to the current study (18-25 years) using a resistance of 7.5 percent of body mass in bilateral Wingate test. The current fatigue index findings were also slightly higher than findings by Baker et al. (2011) who performed the bilateral Wingate test on female competitive athletes of similar age (18-30 years). Baker et al. (2011) reported a mean fatigue index of 53 percent using a resistance of 8.5 percent of body mass.

The higher fatigue index observed in the current study may be attributed to increased lower limb muscle work in unilateral Wingate test compared to bilateral Wingate test. For example, Dunstheimer et al. (2001) assessed total mechanical work (TMW) between unilateral and bilateral Wingate test in young recreational adults with a mean age of 19 years. These authors reported that the sum of left and right TMW during unilateral Wingate test was comparatively greater than that produced during the bilateral Wingate test, and argued that lower limb muscles were more activated in the unilateral test when compared to the bilateral test. Given that higher levels of muscle recruitment are associated with greater rates of muscle fatigue (Bodkin et al., 2021), it is not unexpected that decreases in muscle power would occur at a greater rate in the unilateral Wingate when compared to the bilateral Wingate test.

In the current study, the cadence profile measured over the 30 second period of the unilateral Wingate test was similar between the left and right leg, with a peak cadence of 104 RPM. Interestingly, peak power and peak cadence/pedalling rate was achieved in initial five seconds indicating that optimal cadence of 104 RPM was required for development of peak power in the unilateral Wingate test. To the author’s knowledge, this is the first study to measure unilateral cadence/pedalling rate using the modified Wingate test in recreational athletes. However, previous research findings have showed that an optimal cadence/pedalling rate for developing maximal power in the bilateral

Wingate test is 120-130 RPM. For instance, Stewart et al. (2011) assessed peak power and cadence using the 30 second bilateral Wingate test and showed that peak power was achieved in five to seven seconds at an optimal cadence of 120 to 140 RPM. The researchers also showed a gradual decline in peak cadence of 39 percent after attaining peak power, which was similar to the current study.

Other researchers have used a sprint cycling method and have shown similar optimal cadence to that produced during the Wingate test. For example, Hintzy et al. (1999) showed an optimal cadence/pedalling rate of 123 RPM for peak power output during a six second sprint cycle test in participants with a mean age of 25 years. The researchers reported a significant relationship between pedalling rate and maximal power, and identified greater peak power and optimal pedalling rate (cadence) in explosive exercise trained participants compared to endurance and intermediate trained participants. Similarly, Hautier et al. (1996) reported a mean optimal velocity of 120 RPM for peak power output during a five second sprint cycle test in healthy young adults. The researchers argued that the optimal velocity for peak power output is strongly associated with type II muscle fibres. Peak cadence in the current study was approximately 20 RPM lower than that recorded in bilateral studies. This was probably due to inability to utilise the contralateral leg to contribute to movement velocity and the additional muscle co-ordination demands in the unilateral test (Dunstheimer et al., 2001).

5.4.2 ACL case study findings for the Wingate test

The two ACL-reconstructed participants were assessed for comparison of peak power, mean power, and fatigue index during the unilateral WAnT. To the author's knowledge, this is the first study to assess unilateral lower limb muscle power in ACL reconstructed participants using the Wingate test. The female participant showed similar power profiles and peak and mean power to uninjured participants, and there were no differences in power measures between the reconstructed side and non-injured side. The female participant had undergone extensive exercise-based rehabilitation from the time of surgery and was undergoing strength and conditioning training at the time of testing. Although, there are currently no studies that have assessed unilateral power via the Wingate test in an ACL population, there are a number of studies that have assessed power LSI in this population using other methods. For example, Thomeé et al. (2012) assessed lower limb muscle power at 6, 12, and 24 months post-ACL reconstruction using knee flexion/extension power test and a leg press test. All participants performed a standardised rehabilitation protocol following reconstructive surgery and before assessment. At 24 months, Thomeé et al. (2012) reported a LSI of above 95 percent for the power tests which was similar to the current study where the female participant achieved a LSI of 94 percent.

In contrast to the female participant and the uninjured group, the male participant showed large deficits (27%) in lower limb power in the reconstructed side compared to the non-injured side during the unilateral Wingate anaerobic cycle test with an LSI of 73 percent for peak power. The peak power LSI of the male participant was considerably lower than that reported in the literature at 24 months after surgery and more reflective of previous research findings in patients at six to eight months post-ACL reconstruction. For instance, utilising knee flexion/extension and leg press power test, Neeter et al. (2006) reported power deficits of 10 to 25 percent in 60 to 85 percent of ACL reconstructed participants (mean age 28 years) at seven months post-ACL reconstruction. Based on average data, the limb symmetry index for quadriceps power in the knee extension test (75%) was similar to Wingate findings for the male participant in the current study; whereas a higher LSI of 84 percent was reported for power in the leg press test (Neeter et al., 2006). Similarly, Thomeé et al. (2012) reported an LSI of 85 percent for the leg press power test, 75 percent for the knee extension test, and 94 percent for the knee flexion power test in patients that were six months post-ACL reconstruction. Recently, Nagai et al. (2020) evaluated lower limb muscle power using a bilateral leg press test in participants who were eight months post-ACL reconstruction with a mean age of 22 years. Nagai et al. (2020) reported a LSI of 85 percent for peak power during the leg press test. One possible explanation for such large deficits in power at 24 months in the male participant is that he had not participated in any formal rehabilitation following surgery and cleared himself to return to sport and recreation activity. For example, it has been shown that a subgroup of ACL reconstruction patients who did not engage in formal rehabilitation had lower LSI for knee extensor torque than those who did (Ebert et al., 2018).

In the current study, both the female and male ACL-reconstructed participants showed a lower fatigue index in the ACL-reconstructed leg (44% for the female; 40% for the male) compared to the non-injured leg (49% for the female; 50% for the male). The fatigue index was also lower in both ACL reconstruction participants when compared to individuals in the uninjured group (fatigue index of 60%). To the author's knowledge, this is the first study to identify fatigue index in ACL-reconstructed participants using the modified unilateral Wingate test. The Wingate power profiles contributing to lower fatigue index in male and female ACL reconstructed participant differed. The female participant had similar peak power to uninjured subjects but had a higher torque at the end of the Wingate test. This finding indicates that the female participant was probably able to generate high force and recruit high threshold fast twitch fibres to attain peak power at the beginning of the test but was more fatigue resistant than uninjured participants near the end of the test.

In contrast, the male participant was only able to generate approximately half the power of uninjured participants in his reconstructed side at the beginning of the Wingate test, and there was minimal reduction in his power output through the remainder of task. This inability to generate high levels of power and low rates of fatigue may be associated with the metabolic and neuromuscular alterations following an ACL injury/reconstruction. For instance, Beretta-Piccoli et al. (2016) showed lower knee extensor fatigue in participants 24 months post-ACL reconstructed performing maximum isometric voluntary contraction of the knee extensors. Beretta-Piccoli et al. (2016) reported that alterations in motor unit recruitment strategies following ACL rupture and subsequent surgery causes selective atrophy of fast twitch muscle fibres resulting in fatigue resistance. Furthermore, Beretta-Piccoli et al. (2016) argued that a decrease in the inhibition of type II high threshold motor units leads to decreased fatiguability in ACL reconstructed patients. Noehren et al. (2016) also reported that type II muscle fibre composition of the vastus medialis muscle was significantly reduced following ACL injury and reconstruction. Stockmar et al. (2006) studied the metabolic alterations and fibre properties of the vastus medialis muscle in chronic ACL injury patients. In each fibre type, the researchers observed a shift to oxidative metabolism with decrease in glycolytic contribution. The researchers suggested that the shift towards oxidative metabolism and atrophy of muscle fibres reduces the ability to generate fast force and increases endurance of these muscle fibres (Stockmar et al., 2006). These findings may indicate that the lower peak power and fatigue index observed in the male participant may reflect the inability to generate high force due to selective atrophy of type II fibres.

In the current study, the cadence/pedalling rate profile of the female and male ACL participants differed considerably. The female participant showed an optimal cadence of 105 RPM for peak power which was achieved in the initial five seconds and there was no difference between the reconstructed and non-injured leg. The rate of decline in peak cadence was similar between reconstructed and non-injured leg which was also similar to uninjured healthy participants in the current study. These findings indicate that the female participant was probably able to recruit high threshold type II fibres to achieve peak cadence followed by a gradual decline in cadence and power output. In contrast, the male participant exhibited large difference in peak cadence between the reconstructed leg and uninjured leg. The male participant was only able to achieve a peak cadence of only 85 RPM in his reconstructed leg with a minimal decrease in cadence over 30 seconds, which was similar to his power profile in the reconstructed leg. The uninjured leg also showed lower peak cadence (95 versus 103 RPM in the uninjured group) when compared to uninjured participants. There are currently no studies that have assessed unilateral cadence/pedal velocity using the modified Wingate test in ACL reconstructed participants. Although direct comparisons cannot be made, it can be argued that atrophy of type II muscle fibres and inability to recruit high threshold type II fibres following ACL reconstruction (Beretta-Piccoli et al., 2016) may contribute to the inability to achieve optimal cadence. Researchers have identified a significant positive relationship between composition of fast twitch type II fibres and optimal velocity/cadence and maximal power output during sprint cycling (Hautier et al., 1996). Therefore, a reduction in type II motor units associated with ACL reconstruction may inhibit the ability to generate optimal cadence and lower limb power during maximal cycling (Douglas et al., 2021).

5.4.3 Peak power, mean power, and fatigue index in the Isokinetic test

Knee extensor power profiles of healthy participants during the isokinetic testing were similar to power profiles during the Wingate test, and there was no difference in peak power between the left and right sides. Peak knee extensor power occurred within the first five repetitions and was followed by a relatively linear decline in power throughout the test. Maffiuletti et al. (2007) are the only other group who have measured knee extensor power over 20 repetitions during isokinetic testing at similar velocity. Maffiuletti et al. (2007) did not document peak power in their study. However, based on their peak torque values at an angular velocity of 180 degrees per second, participants would have achieved peak power of approximately 6 W/kg, which was higher than the 4.8 W/kg for right and 4.97 W/kg for left leg in the current study. Maffiuletti et al. (2007) did calculate average power throughout 20 repetitions, which was 3.2 W/kg. This was comparable to the average power values 3.5 W/kg for the right leg and 3.7 W/kg for the left leg over 30 repetitions in the current study.

Neder et al. (1999) also calculated average power at a joint angular velocity of 300 degrees per second for 30 repetitions in non-athletic males and females aged between 20 and 80 years using an isokinetic dynamometer. Neder et al. (1999) observed a mean power of 2.9 W/kg and 2.12 W/kg in males and females respectively, which was lower than the current study. The lower average power could be explained by the difference in angular velocities tested and participant demographics. Participants in Neder et al. (1999) study were older (mean age 49 and 51 years) than participants in Maffiuletti et al. (2007) study (mean age of 30 years) and the current study (mean age of 25 years). It has been shown that with ageing, there are decreases in muscle power (Petrella et al., 2005). Iossifidou and Baltzopoulos (2000) also suggested that inaccuracies in peak power measurement may occur during isokinetic testing at velocities 300 degree per second because of the small-time window where a “true” velocity of 300 degrees per second is achieved.

Other studies have measured peak power during isokinetic testing over a small range (4–8) of repetitions (Lisee et al., 2019; Zabka et al., 2011). Zabka et al. (2011) found no significant difference in maximal power between the dominant and non-dominant legs in soccer players with a mean age 23 years using an isokinetic dynamometer at an angular velocity of 240 degrees per second (six repetitions) and 60 degrees per second (four repetitions). Zabka et al. (2011) reported peak power of 4.1 W/kg for knee extensors at 240 degrees per second, which was slightly lower than the current study, and 2.1 W/kg at 60 degrees per second. Lisee et al. (2019) calculated average power over eight maximal repetitions of concentric isokinetic knee extension and reported power values of 3.34 W/kg when testing at 180 degrees per second, which was lower than that reported in the current study. The possible explanation for such differences in average power across these studies can be due to different angular velocities used. In the current study, knee joint angular velocity was set at 180 degrees per second. This angular velocity has been shown to be reliable to assess knee extensor average power and produces higher peak knee extensor power than velocities of 60 degrees per second (Maffiuletti et al., 2007).

In the current study, there was no significant difference between peak isokinetic knee extensor power of the weaker and stronger sides. Further, interlimb comparison revealed an LSI of 90 percent which was similar to current findings for peak power LSI during the Wingate test (90%). The LSI in the current study is similar to previous findings by Lisee et al. (2019) who showed a LSI of 90 percent in males and 91 percent in females at angular velocity of 180 degrees per second. Furthermore, the LSI for knee extensor power tended to be lower in athletes (88%) when compared to nonathletes (92%). The researchers argued that setting a perfect LSI of 100 percent as a return to sport criteria following ACL-reconstruction may be unrealistic as healthy subjects typically have a LSI of greater than or equal to 90 percent. Similar findings have also been reported in female soccer players who had a mean age of 20 years. Östenberg et al. (1998) assessed LSI of isokinetic peak torque at two joint angular velocities (60 and 180 degrees per second). The researchers identified an LSI of 94 percent at 180 degrees per second between "weak" leg and "strong" leg. However, when the results were compared between dominant and non-dominant leg, the LSI was 100 percent. In the current study LSI was calculated as the difference between the strongest and weakest side and yielded an LSI of 90 percent. However, if the LSI index was calculated as the difference between the dominant and non-dominant side, the LSI would have increased to 99 percent. Östenberg et al. (1998) argued that calculating the LSI between weak and strong leg of healthy participants is more beneficial than LSI of the dominant and non-dominant side when making comparisons with ACL injured participants.

The current study found that during isokinetic testing the knee extensor power began to decline in a linear manner from repetition 4-5 onwards, and this rate of decline was similar for dominant and non-dominant sides in uninjured participants. This was reflected by a mean fatigue index of 55 percent for the dominant and non-dominant side. The current power findings are similar to previous research that assessed changes in peak torque over multiple repetitions. Maffiuletti et al. (2007) showed a linear decline in peak torque during maximal isokinetic knee extension and flexion test for 20 repetitions at a joint angular velocity of 180 degrees per second. Maffiuletti et al. (2007) calculated percentage loss in torque and work over 20 repetitions and showed 26 percent decrease in torque. Pincivero et al. (2001) evaluated the quadriceps muscle fatigue index for work between the non-dominant leg and dominant leg in healthy male and female participants using 30 repetition concentric isokinetic knee extension and flexion test at a joint angular velocity of 180 degrees per second. Pincivero et al. (2001) identified a fatigue index of 38 percent for dominant side and 39 percent for non-dominant side which was comparatively lower to the current findings.

Other studies have used slope measures to describe fatigue during isokinetic knee extensor testing. Bosquet et al. (2015) calculated the slope of peak torque during a 30-

repetition isokinetic test at a joint angular velocity of 180 degrees per second in male cyclists with mean age of 30 years. The researchers reported that the slope had a moderate to high correlation with anaerobic capacity (peak power) assessed in the Wingate test. Bosquet et al. (2015) argued that the phosphagen system is the primary energy source for attaining peak torque, and participants who achieve a higher peak torque or power showed greater fatigue due to depletion of stored phosphagen. Pincivero et al. (2001) also suggested that torque generated over the 30 repetitions of isokinetic testing was primarily anaerobic, and proposed that the linear decline in torque may partly be due to a decrease in firing frequency of high threshold motor units.

In the current study, the fatigue index calculated from the unilateral Wingate test was slightly higher (60%) compared to the isokinetic testing at 180 degrees per second (55%). To the author's knowledge, this is the first study to compare unilateral fatigue index during Wingate test with the isokinetic testing. Previous research has also shown greater fatigue index during the bilateral Wingate test when compared to isokinetic testing. Brown et al. (1994) identified a fatigue index of 42 percent during isokinetic knee extension test at 180 degrees per second for 30 repetitions and 46 percent during the Wingate test in healthy males with a mean age of 25 years. Similarly, Tsaklis (2002) observed a fatigue index of 45 percent during an isokinetic knee extension test at 240 degrees per second for 30 repetitions and 49 percent during the Wingate test in male athletes aged 17 to 28 years. Baltzopoulos et al. (1988) used different measures but also reported a greater fatigue index of 15.6 W/sec during the Wingate test than the 11.9 W/sec during the isokinetic knee extension endurance test for 30 repetitions at a joint angular velocity of 240 degrees per second. Baltzopoulos et al. (1988) argued that higher fatigue index in the Wingate test compared to isokinetic testing can be attributed to activation of additional muscle groups and the higher muscle contraction velocities in the Wingate test.

5.4.4 ACL case study findings for the isokinetic test for power

The female participant showed similar isokinetic power profiles to the uninjured group with no side-to-side difference between reconstructed knee and non-injured knee. Further, inter-limb comparison revealed an LSI for peak power of 97 percent which was higher than the isokinetic LSI of the uninjured group (89%) and the peak power LSI in the Wingate test (94%). Previous literature has shown similar findings for isokinetic peak torque LSI at 12 to 24 months following ACL reconstructive surgery. For instance, Ohji et al. (2021) reported a 91 percent LSI for peak isokinetic knee extension torque at a joint angular velocity of 180 degrees per second in participants (mean age of 21 years) who were 12 months post-ACL reconstruction. Brosky Jr et al. (1999) reported higher LSIs of 99 and 100 percent for peak torque at velocities 60 and 360 degrees per second respectively in participants 28 months post ACL reconstruction. However, these relatively high LSIs do not seem to be the norm, as a recent systematic review reported that the LSI of knee extensor strength following quadriceps and patellar tendon reconstruction was not greater than 90 percent at 24 months after surgery (Johnston et al., 2020).

In contrast to the female, the male participant showed large deficits in peak and average knee extensor power in the reconstructed side compared to the non-injured side with an LSI of 66 percent for peak power. Further, peak and average power of knee extensors in the non-injured side were lower when compared to the female participant and the uninjured group. The current findings for isokinetic LSI of the male participant are similar to the LSI in ACL reconstructed participants in earlier stages of rehabilitation (6-8 months post reconstruction). For instance, Nagai et al. (2020) showed a mean LSI of 84 percent at a velocity of 180 degrees per second in young athletes with a mean age 22 years at eight months post-ACL reconstruction. Similarly, Xergia et al. (2015) showed a LSI of 79 percent for peak knee extension torque at joint angular velocity of 180 degrees per second in slightly older athletes (mean age of 28 years) seven months post-ACL reconstruction.

The lack of formal rehabilitation was probably a major contributor to the low LSI for peak knee extensor power in the male participant in the current study. Ebert et al. (2018) identified that 12 months after ACL reconstruction, 70 percent of patients did not achieve a LSI of greater than 90 percent. Within this group, patients who did not receive community level post-operative rehabilitation, and who failed to continue rehabilitation after three months, had a lower LSI than those involved in rehabilitation (Ebert et al., 2018).

During isokinetic testing, the fatigue index of the female participant (53% for the ACL reconstructed side; 52% for the non-injured side) was similar to the uninjured group (55%). In contrast, the fatigue index of the male participant was lower on the injured side (26%) compared to non-injured side (43%), and lower compared to female participant and the uninjured group. The fatigue index for the non-reconstructed side in the male participant was also considerably lower than the 38-45 percent reported in the healthy populations who have undergone multiple repetition isokinetic testing (Pincivero et al., 2001). Other studies have also found less fatiguability in knee extensors on the affected side after ACL reconstruction. Norte et al. (2018) assessed knee extension maximal voluntary isometric contraction (MVIC) nine months post-ACL reconstruction. Norte et al. (2018) reported a lower fatigue index in the injured side (14%) compared to the non-injured side (19%) in this group of patients. Norte et al. (2018) hypothesised that atrophy of type II fibres occurs early after ACL injury due to disuse, and persistent weakness is associated with poor morphological recovery.

The low fatigue index displayed by the male participant on his reconstructed side may be due to the physiological and neuromuscular adaptations that have been associated with strength and power deficits following ACL injury and reconstruction. It has been proposed that in non-injured individuals, high threshold fast twitch muscle fibres (type IIa) are recruited early during repetitive isokinetic knee extensions and that the decline in torque or power throughout the test is due to fatigue of these fibres which have low numbers of mitochondria and primarily use anaerobic mechanisms to generate muscle power (Bodkin et al., 2021). Researchers have shown that following ACL reconstruction, there is selective atrophy and reduced frequency of type IIa fibres in the vastus lateralis of the ACL-reconstructed limb (Noehren et al., 2016). Furthermore, observations on decrease in MFCV during maximum voluntary isometric knee extension tests indicate that firing rate or recruitment of these high threshold type II motor units is decreased in the reconstructed side (Bryant et al., 2008; Nuccio et al., 2020). Thus, selective atrophy and decreased recruitment and firing rate of high threshold motor units may have contributed to the male participant in the current study being unable to generate maximal power and having a lower rate of fatigue than the uninjured group resulting in lower fatigue index.

5.4.5 Functional performance tests

In the current study, three functional performance tests (single leg hop, triple hop, vertical jump) were assessed for between limb comparisons. For the vertical jump test, power was also predicted from jump height and body mass using the equation developed by Sayers et al. (1999). The uninjured group showed no significant difference between the right and left leg during the single leg hop test, triple hop for distance, and vertical jump test, with mean LSI scores of 95 percent, 96 percent, and 91 percent respectively. The current findings are similar to previous studies that have shown no difference between dominant and non-dominant leg for the functional performance tests (Caffrey et al., 2009; Kockum & Annette, 2015; Lobato et al., 2018; Petschnig et al., 1998; Swearingen et al., 2011). The LSI values of the hop test were similar to the findings of Munro and Herrington (2011) who reported a LSI of 98 percent and above for four hop tests (single leg hop, triple hop for distance, cross over hop, and timed hop) in healthy participants with a mean age of 22 years. A number of authors have also reported similar LSI findings of above 95 percent in healthy participants of similar age (18 to 40 years) for the single leg hop tests (Baltaci et al., 2012; Fältström et al., 2017; Leister et al., 2018). Previous literature has also shown a LSI of greater than 90 percent for vertical jump test which is similar to current findings (LSI of 91%) (McGrath et al., 2016; Pairot de Fontenay et al., 2014). Researchers have stated that a LSI of greater than 90 percent is deemed normal for healthy participants (Bookbinder et al., 2019; Ericsson et al., 2013; Reid et al., 2007; Scinicarelli et al., 2021).

5.4.6 ACL case study findings for the functional performance test

In the current study, the female participant exhibited similar findings between the injured and non-injured leg and scored a LSI of 97 percent for the single leg hop, 99 percent for the triple hop for distance, and 100 percent for vertical jump test similar to the uninjured group. The functional test LSI findings of the female participant were similar to the unilateral Wingate test peak power LSI (94%) and isokinetic knee extensor average power LSI (97%). Previous researchers have reported that patients who underwent early standardised rehabilitation achieved a LSI for hop test of greater than 95 percent between seven months and two years following ACL reconstruction (Ericsson et al., 2013; Gokeler et al., 2017). Previous findings by Logerstedt et al. (2013) have shown that ACL reconstruction patients who undergo vigorous rehabilitation reach a LSI of above 90 percent at six months and above 95 percent at 12 months post-operative in the single leg hop and triple hop for distance test. Gokeler et al. (2017) reported a mean LSI of 95.4 percent for three single leg hop tests (single leg hop for distance, triple hop for distance, side hop) in ACL-reconstruction patients who received early rehabilitation (mean duration of seven months) after reconstructive surgery. However, when compared to an uninjured group, ACL reconstructed subjects revealed bilateral deficits in all three-hop tests. It seems unlikely that a bilateral deficit was evident in the female participant in the current study as her hop test results were similar to the uninjured group. The functional test LSI results of the female participant reflect conclusions made in a systematic review where subjects who undergo ACL reconstruction followed by extensive rehabilitation recovered their lower limb strength and functional performance eight months after surgery and the LSI was 90 percent or higher for those who adhered to strict exercise protocols (Ericsson et al., 2013).

In contrast to the female participant, the ACL-reconstructed male participant had a large side-to-side difference between the injured and non-injured limb in all functional performance tests, with a LSI of 77 percent for single leg hop, 78 percent for triple hop for distance, and 89 percent for vertical jump test. These findings were not typical of someone two years post ACL reconstruction (Ericsson et al., 2013) and tend to be similar to functional performance between four to six months following ACL reconstruction surgery (Farmer et al., 2021; Pairot de Fontenay et al., 2015; Rohman et al., 2015). For example, Farmer et al. (2021) reported that patients who were five months post ACL reconstruction had an LSI index for the single leg hop of 81 percent for their non-dominant jumping limb. This figure was slightly higher than the male participant in the current study who also injured his non-dominant jumping limb. Pairot de Fontenay et al. (2015) assessed single and triple leg hop distance in patients seven months post ACL reconstruction. Their participants had an LSI of 79 percent for the single leg hop test and 80 percent for the triple hop test, which was similar to the male participant in the current study. The deficits in functional performance tests in the male participant may have been associated with reduced quadriceps strength and power. In the current study, the male participant exhibited large deficits in lower limb peak and average power during unilateral Wingate test and isokinetic knee extensor testing. Thomeé et al. (2012) suggested that apart from neuromuscular deficits, inadequate rehabilitation may contribute to difficulty restoring muscle size and strength following ACL reconstruction. This was supported by findings of Ebert et al. (2018), who showed that participants who were not engaged in regular post-operative rehabilitation did not reach an LSI of greater than 90 percent for the functional performance tests (single leg hop and triple hop for distance) 12 months following ACL surgery. The researchers argued that lack of pre and post-operative rehabilitation in community level was a key factor for not regaining an LSI of greater than 90 percent at 12 months, potentially increasing the risk of re-injury.

5.5 Relationship between Wingate test, Isokinetic testing, and Functional tests

The findings of the current study showed a moderate positive linear relationship between peak power in the Wingate test and isokinetic knee extension average power (r=0.57; p<0.05). To the author's knowledge, there are no previous research findings comparing unilateral Wingate peak power with isokinetic average power over 30seconds/repetitions. The current findings are similar to Brown et al. (1994) who assessed peak power, mean power, and fatigue percentage utilising a bilateral Wingate test and an isokinetic test at a joint angular velocity of 180 degrees per second for 30 seconds in healthy male and female participants with a mean age of 25 years. The researchers identified a moderate significant correlation between mean power in the Wingate test and isokinetic peak power (r=0.54; p<0.05) and strong significant correlation between peak power (r=0.84; p<0.05). Two other researchers have shown moderate to high correlations between peak power during the Wingate test and isokinetic testing at higher velocities than the current study. Baltzopoulos et al. (1988) identified a strong significant positive linear relationship between isokinetic knee extension peak power at a joint angular velocity of 240 degrees per second with the bilateral Wingate test (r=0.86) in healthy male (mean age 20 years) and female populations (mean age 22 years). Recently, Daameche et al. (2021) found a fair to moderate correlation between the bilateral Wingate test peak power and isokinetic test mean power (r=0.36-0.53; p<0.05) at 60 degrees per second, and similar correlation at 300 degrees per second (r=0.27-0.58; p<0.05). These findings may indicate that the average power measured during isokinetic testing does not reflect peak power measures during Wingate testing. The variation in findings may also be due to the variation in cadence during the Wingate test, the different angular velocities used during isokinetic testing, and the types of joint motion used during the different testing procedures. For example, it has been argued that isokinetic testing is an open kinetic chain test that involves knee extension and flexion where velocity is controlled, whereas the Wingate test is a multi-joint closed kinetic chain test that uses a number of muscle groups in both lower limbs to generate power (Baltzopoulos et al., 1988; Daameche et al., 2021).

The current study identified a weak positive correlation for the fatigue index between the modified Wingate test and isokinetic testing for power (r=0.438; r=0.25). Currently, there is no previous research comparing the unilateral fatigue index calculated from the Wingate test and the isokinetic test. However, the current findings were similar to previous findings by Brown et al. (1994) who assessed the fatigue index utilising a bilateral Wingate test and unilateral isokinetic test. Brown et al. (1994) reported a weak correlation (r=0.37) between fatigue index of the Wingate test and maximal isokinetic test lasting 30 seconds at a joint angular velocity of 180 degrees per second. Brown et al. (1994) argued that the low correlation was due to more muscle groups being utilised in cycling, which may have different power outputs than leg extension and flexion, thus affecting the change in performance across 30 second test. Two other authors have used different isokinetic angular velocities and showed a moderate to high correlation for fatigue index between isokinetic and Wingate tests. Tsaklis (2002) assessed fatigue index over 30 repetitions isokinetic testing at a joint angular velocity of 240 degrees per second with the bilateral Wingate test and identified a weak correlation (r=0.485) with the fatigue index of the Wingate test in male athletes aged 17 to 28 years. However, Baltzopoulos et al. (1988) identified a strong positive linear relationship (r=0.84) between the fatigue index of Wingate test and that calculated for the knee extensors during a 30 second maximal isokinetic test for knee extension at a joint angular velocity of 240 degrees per second. Baltzopoulos et al. (1988) argued that both isokinetic and Wingate tests fatigue indexes provided similar measures of anaerobic capacity accounting for 70.6 percent variability in factors between two tests. The strong correlation observed in Baltzopoulos et al. (1988) study may be attributed to the angular velocities tested. For example, previous research on joint specific power during maximal cycling revealed that knee extensor power peaked at 240 degrees per second, which is claimed to be the best representation of knee joint angular velocity during the Wingate test (McDaniel et al., 2014).

In the current study, a high significant positive correlation (r=0.841; r=0.859; p<0.01) was observed between the peak power in modified unilateral Wingate test and the peak power calculated from the unilateral vertical jump test. Although this is the first study to compare unilateral Wingate peak power with vertical jump power, previous researchers have shown similar findings using bilateral Wingate test and vertical jump test. For instance, in volleyball players of different age groups, Kasabalis et al. (2005) identified a strong positive correlation between vertical jump height and the Wingate test peak power ($r=0.82$; $p\leq 0.001$). Furthermore, a significant positive linear relationship was found for athletes ($r=0.86$; $p\leq 0.001$) and non-athletes ($r=0.84$; $p\leq 0.01$) between vertical jump height and peak power in the Wingate test. Kasabalis et al. (2005) argued that the strong correlation between peak power and vertical jump height is related to the primary components of explosive power in both tests, and jumping reflects the anaerobic power measured during the Wingate Anaerobic test. Other authors have reported more moderate correlations. For example, Hoffman et al. (2000) reported a moderate correlation between vertical countermovement jump and peak power ($r=0.59$) and mean power ($r=0.76$) in the Wingate test in youth national basketball players. Similarly, in high school basketball players with mean age of 15 years, Changela and Bhatt (2012) reported a positive relationship between vertical jump test height and the peak power in the Wingate test ($r=0.044$). These researchers argued that moderate relationship may be attributed to difference in assessment methods between the two tests. The vertical jump utilises a larger muscle mass and the upper body musculature plays a significant role in generating muscle power (Changela & Bhatt, 2012); whereas in the unilateral Wingate test, only the leg muscles are activated during cycling to generate power.

The current study also identified a poor to moderate relationship between the single leg hop ($r=0.2$; $r=0.5$) and triple hop for distance ($r=0.42$; $r=0.54$) with the unilateral Wingate test. To the author's knowledge, there is no previous study which has identified correlation between unilateral Wingate test and hop tests. However, the poor correlation may be because these tests measure a different construct and differ in muscle activation patterns. For instance, it has been argued that the Wingate test necessitates the participant to pedal as quickly as possible for 30 seconds, requiring greater coordination of hip, knee, and ankle joint muscles to generate power (Martin & Brown, 2009); whereas the hop test requires the participant to jump horizontally where there is less activation of quadriceps muscle than the hamstring and gastrocnemius muscles, with increased muscular activity in hip extension and ankle plantar flexion (Ohji et al., 2021).

5.6 Conclusion and Clinical Implications

The current findings provide initial evidence of a simple clinical test (the unilateral Wingate test) that can potentially be utilised to assess unilateral lower limb muscle power and anaerobic capacity in healthy young adults. In respect to peak power, mean power, and fatigue index measured in the unilateral Wingate test over 30 seconds, all healthy participants achieved an LSI of 90 percent. This may indicate that using LSI that is above 90 percent as a benchmark for “normal” may be unrealistic for patients returning to sport following knee injury (Lisee et al., 2019). The LSI data from the two ACL participants would indicate that there is potential for the unilateral Wingate test to identify deficits in power following ACL reconstruction. This has important implications because the unilateral Wingate test has the potential to be used in earlier stages of rehabilitation than traditional tests of power that place high loads through the knee (McNair & Marshall, 1994; McNitt-Gray, 1991). However, care should be taken when interpreting these results as only two ACL participants were assessed in this study, and they were two years post-surgery. Hence, the feasibility of the unilateral Wingate test in ACL reconstruction patients across the different stages of rehabilitation warrants further investigation.

The power profiles during the 30 second unilateral Wingate test were similar to that described for the bilateral Wingate, indicating that this test primarily targets the anaerobic energy system (Julio et al., 2019; Smith & Hill, 1991). These power profiles provided information on peak power output as well as a measure of fatigue (fatigue index). The male ACL reconstruction participant in the current study showed peak power deficits as well as lower levels of fatigue when compared to healthy participants, which was further supported by isokinetic test findings. Fatigue resistance of the quadriceps muscles has been identified as an important factor in ACL patients with significant deficits in strength and function (Stockmar et al., 2006). Therefore, the ability of the unilateral Wingate test to assess fatigue, in addition to peak power, can provide information over and above traditional tests that tend to focus on peak measures of strength and power.

The current findings for muscle power in unilateral Wingate test were similar to power profiles of the maximal isokinetic testing over 30 repetitions with a similar LSI of 90 percent. Although Wingate test is a multi-joint test and isokinetic is single joint test, both tests seem to measure a similar construct of anaerobic capacity. One of the advantages of using this simple clinical test (unilateral Wingate test) is that it requires relatively inexpensive equipment and can be easily performed in a short-time period; compared to isokinetic testing which requires expensive equipment and is time consuming. However, the moderate correlation between peak power in the unilateral Wingate test and isokinetic testing, and poor correlation between fatigue index of the two tests, indicates that power measures generated in a single joint task such as isokinetic knee extension do not necessarily reflect power output during a Wingate test which involves multiple lower limb joints.

Hop tests that are commonly used in rehabilitation to assess a player's readiness to return to sport had a poor correlation with peak power in the unilateral Wingate test. It has been suggested that hop tests assess power primarily in the horizontal direction (Kotsifaki et al., 2021), and place dynamic balance and neuromuscular co-ordination demands that differ to Wingate test (Hamilton et al., 2008). In contrast, power calculated from the vertical jump had a significant positive relationship with peak power in the unilateral Wingate test. This may indicate that both tests measure similar constructs of muscle power and anaerobic capacity. However, clinicians must interpret these findings with caution because of the smaller sample size in the uninjured group and only two ACL reconstructed participants were tested.

5.7 Limitations

A few limitations must be considered. First, the sample size in the uninjured group was small because of the short time frame and scope of this project. This brings significant bias into the results and has an influence on the data analysis. Further, the validity and reliability of the unilateral Wingate test was not assessed. However, Hebestreit et al. (1999) have previously found the unilateral Wingate to be reliable in adolescents and young adults.

Second, it is difficult to determine the physiological and neuromuscular changes over 30 seconds in the unilateral Wingate test as measures of electromyography were not used in the current study. Measuring these parameters would have provided additional information regarding muscle activation patterns in the unilateral Wingate test.

Third, kinetic and kinematic profiles of individual joints and muscles were not analysed during the unilateral Wingate test and functional performance tests (single leg hop, triple hop for distance, vertical jump test). This would have provided additional information concerning joint specific power and contribution of individual muscles to generate power.

Fourthly, is that all four tests were completed in a single session with a five to seven minute rest time in between each test. In terms of blinding, all the testing methods were carried out by a single person. However, the test methods were similar for all participants. Analysis of the data was also performed by the current author and another researcher who was blinded to testing.

Another limitation is that functional, isokinetic and the Wingate test were not randomised completely. The functional test was performed first followed by isokinetic or the Wingate test.

Finally, there were only two ACL reconstruction participants who participated in the study. These participants did provide the opportunity to compare power and functional measures between an elite athlete who underwent extensive and ongoing rehabilitation with a recreational athlete who did not partake in any formal rehabilitation. Nonetheless, further research is recommended to determine the feasibility and validity of the unilateral Wingate test as a measure of lower limb power at different timelines of ACL rehabilitation.

5.8 Recommendations for Future Research

Although the current study observed no side to side difference in a small sample of healthy participants, future studies with a larger sample size would be beneficial to determine if there are similar power profiles to the bilateral test and assess its validity, feasibility, and reliability.

There is currently no study which has assessed neuromuscular and energy system changes over 30 seconds in the unilateral Wingate test. It would be interesting to find whether similar motor unit recruitment strategy through electromyographic analysis exists, and identify whether similar energy system contribute to peak power.

In the current study, joint specific power and individual muscle contribution were not calculated. Future investigation on unilateral Wingate test assessing kinetic and kinematic profiles would be of interest to see whether power contribution from each muscle and joint were similar across legs.

Only two ACL-reconstructed participants were assessed for comparison in the current study. Further investigation using a large cohort of ACL injured participants will provide better information concerning deficits in muscle power during ACL rehabilitation.

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APPENDICES

Appendix A

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Lower extremity muscle power and functional performance for healthy population.

Date Information Sheet Produced:

23-04-2021

Project Title

Development of a simple clinical test to assess unilateral lower limb power in healthy and knee-injury populations.

An Invitation:

Kia Ora, my name is Avinash Vazhapandal Nandakumar. I am a Masters student at the Health and Rehabilitation Research Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at Auckland University of Technology (AUT). I would like to invite you to participate in my research project 'that is looking at developing a simple clinical cycle test to assess single lower limb power in healthy and knee-injury populations'. This research will help me to gain a Master of Health Practice qualification. Participation in this project is not mandatory and it will not affect the ability to access physiotherapy services in future. You are free to withdraw from the study anytime without any consequence.

What is the purpose of this research?

The purpose of this study is to develop a simple clinical test (single leg Wingate test using the exercycle) to assess the lower extremity muscle power at greater than nine months after a major knee injury or ligament repair and compare the results with uninjured leg and population with no existing knee injury. Muscle power will also be compared with the results of functional tests and questionnaires. Muscle power is essential in sports and recreational activities. Therefore, it is necessary to evaluate muscle power 9-12 months following a knee ligament repair or injury, as this is the common time point for return to sports. This project will be a part of my Masters thesis and will be written up for publication in international journal. This phase of project involves assessing lower extremity muscle power and knee function using a series of hop test, vertical jump test and written questionnaires. Additionally, knee strength will also be assessed using a specialist testing machine called a Biodex Dynamometer.

How was I identified and why am I being invited to participate in this research?

You have been identified as a participant because, you have responded to an advertisement or been informed verbally which directed you to make contact with myself, Avinash Vazhapandal Nandakumar. You will have no past history of a major knee injury on both legs and no knee pain within the past 3 months. The results obtained from the non-injured population will be used to compare with results obtained from the injured and uninjured leg of knee injured group to identify is there any significance difference. You might be excluded from the study if you have any cardiovascular, neurological, bone and joint disease, or if you do not understand/written English. You will be excluded from participation if you are currently being taught by the primary supervisor Dr Grant Mawston.

How do I agree to participate in this research?

If you agree to participate in this study, you are required to complete a consent form before participating in the study. It will be done on the testing day, prior to testing. The testing session will be scheduled once you have agreed to participate in this study.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

If you choose to participate in the study, you are required to attend one session at Biomechanics Lab, Health and Rehabilitation Research Institute, AUT Northshore campus. The testing session lasts between 45-60 minutes. Participants will be required to wear loose and comfortable clothes on the testing day. During the testing session, you will be required to complete a written consent form prior to testing and few written questionnaires related to your knee function.

After completion of questionnaires, you will be asked to perform a strength test on the Biodex isokinetic dynamometer. You will be seated on the machine with one leg being strapped. Your knee strength will be assessed by bending and straightening your knee with as much effort as possible. The results will be recorded on computer and the test will be used similarly to the opposite leg. Following this you will perform functional test (hop test and vertical jump test) and the Wingate Anaerobic cycle test. The selection of test will be randomised by flipping a coin. For hop test, you will be required to perform two different hops to measure knee function in both legs. The test involves single leg hop and triple hop for distance. Once completing the hop tests, you will perform the vertical jump test. You will be placed on force plate and instructed to jump as high as possible. For the Wingate Anaerobic cycle test, you will be positioned on a Watt bike with one leg on the pedal and other leg on a box. You will perform a 3-minute warmup of submaximal level cycling. Following warmup, you will be required to pedal as fast as possible against a predetermined resistance for 30seconds. Peak and mean power will be recorded in the computer. Similarly, the test is repeated for the opposite leg.

What are the discomforts and risks?

There are no significant risks associated with the test. These tests are generally used to assess players performance following a knee ligament injury to assess knee function for return to sport. However, you might experience a mild discomfort in the knee or muscles surrounding knee joint. These tests are developed to mimic normal daily and sporting activities (e.g., cycling, jumping, running) and therefore you should not experience any discomforts.

How will these discomforts and risks be alleviated?

If you experience a greater discomfort than explained above, you may stop the test. A physiotherapist who has appropriate knowledge and skill to manage pain and swelling will carry out all test and will be able to provide appropriate advice to you and how to manage any discomfort.

What are the benefits?

Participation in this study will provide you information regarding your knee muscle strength, knee performance and lower extremity muscle power. The results will identify any deficits in your knee, and it will be helpful to improve your lower limb muscle power and knee strength. This study is also a part of my Masters thesis, and will help me to gain a qualification of Masters in Health Practice.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Once you have entered the study, you will be given an identity code and your name will not be used on data or records obtained. The consent form will contain both your name and identification code and will be stored securely in a locked cabinet at Health and Rehabilitation Research Institute, AUT north campus. Only the primary researcher and the supervisor will be able to access the forms. Also, you will not be identifiable in the final report.

What are the costs of participating in this research?

There is no direct cost for participation in this study, only your personal time. However, participants will receive a petrol voucher worth $30.

What opportunity do I have to consider this invitation?

You will be provided 2-4 weeks to consider the invitation. We will contact you after 7 days you receive the information sheet. If additional time is required to consider the invitation, just let us know.

Will I receive feedback on the results of this research?

A one page summary of the study results will be sent to you via post or email after completion of the study on request.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Grant Mawston, grant.mawston@aut.ac.nz phone: +64 9 921 9999 extn 7180 and Peter McNair, peter.mcnair@aut.ac.nz, phone: +64 9 921 9999 extn 7143.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, *ethics@aut.ac.nz*, (+649) 921 9999 extn 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Avinash Vazhapandal Nandakumar, AUT university, north campus

Ph: +64 22 062 7098

Email: avinashnandakumar26@gmail.com

Project Supervisor Contact Details:

Dr Grant Mawston, AUT north campus

Ph: +64 9 921 9999 extn 7180

Email: grant.mawston@aut.ac.nz

Dr Peter McNair, AUT north campus

Ph: +64 9 921 9999 extn 7143

Email: peter.mcnair@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 11 June 2021, AUTEC Reference number 21/133. *Note: The Participant should retain a copy of this form.*

Appendix B

11 June 2021

Grant Mawston
Faculty of Health and Environmental Sciences

Dear Grant

Re Ethics Application: **21/133 Development of a clinical test to assess unilateral lower extremity power in healthy and knee-injury samples.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 10 June 2024.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: avinashnandakumar26@gmail.com; Peter McNair

Appendix C

Consent Form

Healthy and Knee injured participants for the study

Project title: Development of a simple clinical test to assess unilateral lower limb power in healthy and knee-injury populations.

Project Supervisor: Dr Grant Mawston and Professor Peter McNair

Researcher: Avinash Vazhapandal Nandakumar

○ I have read and understood the information provided about this research project in the Information Sheet dated 23rd April 2021.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I had a history of knee ligament injury/meniscal injury within the last three years.

○ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), or any neurological illness or cardiovascular disease, any infection, any history of low back pain in the past 6 months, any previous history of recurring hamstring injury of either leg, co-existing grade IV chondral lesion (full thickness) and/or recent large meniscal/ACL tear or repair, or previous notable knee injury in either leg that impairs my physical performance.

○ I agree to take part in this research.

○ I wish to receive a summary of the research findings (please tick one):

Yes○ No○

Participants signature : ....

Participants Name : ....

Participants Contact Details (if appropriate) : ……………………………………..

……………………………………………………………………………………………..

Date :

Approved by the Auckland University of Technology Ethics Committee on 11 June 2021, AUTEC Reference number 21/133. *Note: The Participant should retain a copy of this form.*

Appendix D

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Demographic questionnaire:

First name : ....

Middle name : ....

Last name : ....

Age : ....

Sex : ....

Height : ....

Weight : ....

Ethnicity : ....

Working status:

Employed ☐ **Unemployed** ☐

History of knee injury: Yes ☐ **If yes affected side: Right** ☐

No ☐ **Left** ☐

Type of injury sustained and duration of rehabilitation period:

....

....

Approved by the Auckland University of Technology Ethics Committee on 11 June 2021, AUTEC Reference number 21/133.

Appendix E

APPENDIX 1: LOWER-LIMB TASKS QUESTIONNAIRE

ACTIVITIES OF DAILY LIVING SECTION

Patient: _______________ **Date:**_____________

INSTRUCTIONS

Please rate your ability to do the following activities in the **past 24 hours** by circling the number below the appropriate response.

If you did not have the opportunity to perform an activity in the **past 24 hours**, please make your *best estimate* on which response would be the most accurate.

Please also rate how important each task is to you in your daily life according to the following scale:

1. = Not important
2. = Mildly important
3. = Moderately important
4. = Very important

Please answer all questions.

		NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE	IMPORTANCE OF TASK			
1.	Walk for 10 minutes	4	3	2	1	0	1	2	3	4
2.	Walk up or down 10 steps (1 flight)	4	3	2	1	0	1	2	3	4
3.	Stand for 10 minutes	4	3	2	1	0	1	2	3	4
4.	Stand for a typical work day	4	3	2	1	0	1	2	3	4
5.	Get on and off a bus	4	3	2	1	0	1	2	3	4
6.	Get up from a lounge chair	4	3	2	1	0	1	2	3	4
7.	Push or pull a heavy trolley	4	3	2	1	0	1	2	3	4
8.	Get in and out of a car	4	3	2	1	0	1	2	3	4
9.	Get out of bed in the morning	4	3	2	1	0	1	2	3	4
10.	Walk across a slope	4	3	2	1	0	1	2	3	4
			TOTAL (/40) :_____							

RECREATIONAL ACTIVITIES SECTION

Patient: _______________ **Date:**_____________

INSTRUCTIONS

Please rate your ability to do the following activities in the **past 24 hours** by circling the number below the appropriate response.

If you did not have the opportunity to perform an activity in the **past 24 hours**, please make your *best estimate* on which response would be the most accurate.

Please also rate how important each task is to you in your daily life according to the following scale:

1. = Not important
2. = Mildly important
3. = Moderately important
4. = Very important

Please answer all questions.

		NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE	IMPORTANCE OF TASK			
1.	Jog for 10 minutes	4	3	2	1	0	1	2	3	4
2.	Pivot or twist quickly while walking	4	3	2	1	0	1	2	3	4
3.	Jump for distance	4	3	2	1	0	1	2	3	4
4.	Run fast/sprint	4	3	2	1	0	1	2	3	4
5.	Stop and start moving quickly	4	3	2	1	0	1	2	3	4
6.	Jump upwards and land	4	3	2	1	0	1	2	3	4
7.	Kick a ball hard	4	3	2	1	0	1	2	3	4
8.	Pivot or twist quickly while running	4	3	2	1	0	1	2	3	4
9.	Kneel on both knees for 5 minutes	4	3	2	1	0	1	2	3	4
10.	Squat to the ground/floor	4	3	2	1	0	1	2	3	4
			TOTAL (/40):___							

Approved by the Auckland University of Technology Ethics Committee on 11 June 2021, AUTEC Reference number 21/133.

Appendix F

KOOS KNEE SURVEY

Today's date: _____/______/______ Date of birth: _____/______/______

Name: ____

INSTRUCTIONS: This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms
These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness
The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Pain

P1. How often do you experience knee pain?

Never	Monthly	Weekly	Daily	Always
☐	☐	☐	☐	☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P3. Straightening knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P4. Bending knee fully

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A4. Standing

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A14. Sitting

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
□	□	□	□	□

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

SP1. Squatting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP2. Running

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP3. Jumping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP4. Twisting/pivoting on your injured knee

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

SP5. Kneeling

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never	Monthly	Weekly	Daily	Constantly
☐	☐	☐	☐	☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all	Mildly	Moderately	Severely	Totally
☐	☐	☐	☐	☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all	Mildly	Moderately	Severely	Extremely
☐	☐	☐	☐	☐

Q4. In general, how much difficulty do you have with your knee?

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Thank you very much for completing all the questions in this questionnaire.