The effect of Achilles Tendon Rupture on the Ankle Joint Mechanics during an Initial Acceleration Phase of Sprinting

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Abstract

Objective

1: To investigate sprint acceleration performance following an Achilles tendon rupture. 2: To assess deficits of peak power of lower limb joints during sprint acceleration performance. 3: To investigate correlations between the deficits in plantarflexor strength/power and ankle joint power during sprint acceleration.

Study Design

A cross-sectional observational study was conducted to assess participants across legs in the Achilles rupture (ACHL) group and between the ACHL and the Control (HEAL) group who were matched in age, gender, and activity-level.

Background

Significant deficits in kinetic and kinematic parameters as well as plantarflexor (PF) strength post Achilles tendon rupture have been observed during functional tasks. However, there are no studies that examined the biomechanics of maximal sprinting post injury despite the high prevalence of injury during the activity.

Method

A five-meter (5 m) sprint test was used to assess sprint acceleration performance; the 5 m sprint time, Horizontal impulse, and Ratio of Force (RF). The peak concentric power of the ankle, knee, and hip joints was measured to assess deficits.

PF isometric maximal strength and power were assessed on a supine leg press machine. A single leg heel rise (SLHR) test assessed maximum height performed. Relationships between these variables and peak ankle joint concentric power during sprint acceleration were assessed. Statistical comparison was made across legs and between the two groups using linear mix-effect model analyses and correlation coefficients.

Results

No significant difference in the 5 m sprint time between the two groups was observed. The ACHL group had a 16% deficit ($p < 0.05$) in horizontal impulse during the push-off phase compared to the HEAL group. No significant differences were observed in any other sprint performance variables. The ACHL group had a 27% deficit ($p < 0.05$) in peak ankle joint concentric power in the involved leg during the first step. There were no other significant differences for peak concentric power at the other lower limb joints across legs between the two groups.

A significant deficit of 7% and 22% in PF strength was observed at 0 and 20 degrees, respectively, in the ACHL group. The ACHL group had a 17% deficit ($p < 0.05$) in PF power (leg press) in the involved leg. The ACHL group had a 14% deficit ($p < 0.05$) in the involved limbs in the height attained in the SLHL test. A significant correlation ($r = 0.3$, $p < 0.05$) was found between PF power (leg press) and peak ankle concentric power (sprint) during the first step.

Conclusion

Achilles tendon rupture did not significantly affect 5 m sprint acceleration performance despite an inferior performance during the push-off phase and reduced (27%) peak ankle concentric power during the first step in the ACHL group. Although a significant correlation was found between peak ankle joint concentric power (sprint) and the deficits in PF muscle power (leg press) ($r = 0.3$), the contribution is questionable with the small correlation coefficient. Future study with larger sample size and multiple variables may support the conclusive evidence of effect of the injury on the biomechanics of sprint acceleration.

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Abbreviations

ACHL Group	Achilles Tendon Rupture Group
HEAL Group	Control Group
PF	Plantarflexor
5 m	Five Metre
RF	Ratio of Force
SLHR Test	Single Leg Heel Rise Test
ATRA	Achilles Tendon Resting Angle
CSA	Cross Sectional Area
MTU	Muscle-Tendon Unit
WBLT	Weight Bearing Lunge Test
ATRS	Achilles Tendon Rupture Score
FAOS	Foot and Ankle Outcome Score
MTJ	Musculo-Tendinous Junction
ADLs	Activities of Daily Livings
MRI	Magnetic Resonance Imaging
VISA-A	Victorian Institute of Sports Assessment - Achilles Tendon
US	Ultrasound
10 m	Ten Metre
ICC	Intraclass Correlation Coefficient
CALM	Copenhagen Achilles Length Measure
AOFAS	American Orthopaedic Foot and Ankle Society
RSA	Roentgen Stereophotogrammetric Analysis
SWE	Shear Wave Elastography
MG	Medial Gastrocnemius
LG	Lateral Gastrocnemius
DF	Dorsiflexion
CMJ	Countermovement Jump
LSI	Limb Symmetry Index
BW	Body Weight
GRF	Ground Reaction Force

COM	Centre of Mass
EMG	Electromyographic
CV	Coefficient of Variation
AMTI	Advanced Mechanical Technology Inc
QTM	Qualysis Tracking Manager
MTP	Metatarsal-phalangeal
3D	Three Dimensional
ASIS	Anterior Superior Iliac Spine
PSIS	Posterior Superior Iliac Spine
SPSS	Statistical Package for Social Science
SD	Standard Deviation

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 used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), 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:

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Chapter 1 : Introduction

1.1 Statement of the Problem

Achilles tendon rupture is one of the common tendon injuries in the active adult population (Lemme et al., 2018). The incidence of the injury has been increasing, reporting up to 55 cases per 100,000 people between 2010 to 2020 (Hoeffner et al., 2022; Huttunen et al., 2014; Lemme et al., 2018; Meulenkamp et al., 2018; Reda et al., 2020; Willy et al., 2017). New Zealand follows this trend with a 19% increase in Achilles tendon rupture reported from 1993 to 2003 (Tumilty, 2013) and the number continues to be on a rise (Clark et al., 2020). While the highest prevalence of the injury is in the young adult group (20 - 39 years old), the largest increase (78%) has been observed in the middle-age population (40 - 59 years old) from 2012 to 2016 in the United States (Lemme et al., 2018) due to increasing participation in recreational activities by this age group (Hoeffner et al., 2022; Ochen et al., 2019; Reda et al., 2020; Zellers et al. 2019a).

The Achilles tendon plays a crucial role in lower limb function (Freedman et al., 2014). As well as plantarflexing the ankle joint, the viscoelastic property of the Achilles tendon allows energy efficient function of lower limbs by using the stretch-shortening mechanism during functional tasks (Handsfield et al., 2020; Munteanu, 2015). The stretch-shortening mechanism of the tendon can also enhance the power production of lower limbs during ballistic activities (Munteanu, 2015; Schache et al., 2014). A rupture of Achilles tendon can significantly disrupt biomechanical properties and dynamic function of the tendon. Despite rehabilitation, the once-ruptured Achilles tendon has been shown to be unable to fully restore the pre-injury level of biomechanical properties and dynamic function (Aufwerber et al., 2020a; Freedman et al., 2014; Silbernagel et al., 2010; Zellers et al., 2019a). Once ruptured, the Achilles tendon can lead to a significant reduction of plantarflexor (PF) muscle strength and altered ankle joint mechanics which can in turn affect the entire lower limb function for several years (Hoeffner et al., 2022). The Achilles Tendon Total Rupture Score (ATRS) provides a perceived functional measure for Achilles tendon ruptures and a recent review (Hoeffner et al., 2022) observed a mean score of 82/100 at twelve months post injury and a minimal improvement in scores thereafter. There is notable variation in the level of functional recovery and satisfaction following rehabilitation based upon data from questionnaires (Ochen et al., 2019; Silbernagel et al., 2010). As a result, between 30 - 40% of the professional athletes and up to 20% of recreational athletes with a history of Achilles tendon rupture have been unable to return to the same level of sports and activities (Danilkowicz et al., 2019; Zellers et al., 2016).

The optimal management of Achilles tendon ruptures remains unclear (Ochen et al., 2019). The injury can be managed either surgically or conservatively. Historically, surgical management had been favored over conservative management due to a lower tendon re-rupture rate (Nilsson et al., 2021). The higher tendon re-rupture rate through the traditional conservative management may be explained by poor tendon healing due to prolonged cast immobilization of the ankle joint followed by functional ankle orthoses for up to four to six months (Nilsson et al., 2021). In recent years, the importance of earlier mechanical loading for the improvement of tendon healing has been highlighted in many studies (Willits et al., 2010). Early weight-bearing and functional movement of lower limbs post-surgery has been introduced and shown to stimulate the repaired Achilles tendons and increase collagen synthesis (Palmes et al., 2002). The introduced accelerated or early functional rehabilitation during conservative management has achieved fewer tendon re-rupture rate and better patient's satisfaction compared with the traditional immobilization approach (Twaddle & Poon, 2007; Willits et al., 2010; Zellers et al., 2019a).

Persistent deficits in lower limb function are displayed following Achilles tendon rupture regardless of the management options (Heikkinen et al., 2017b; Hoeffner et al., 2022). Although activities of daily living and low level of functional activities appear to be minimally affected by the injury, large asymmetries between the involved and uninvolved legs have been observed during more physically demanding functional activities such as running, jumping, and hopping (Brorsson et al., 2017; Jandacka et al., 2017; Willy et al., 2017; Zellers et al., 2021). Altered biomechanics of the ankle joint in the involved legs during functional activities has been reported to be associated with the deficits in strength and power of PF muscles post injury (Ochen et al., 2019; Silbernagel et al., 2010; Willits et al., 2010; Zellers et al., 2017).

Although several studies examined biomechanical parameters associated with ballistic activities post Achilles tendon rupture, no studies to date have examined the effect of the injury on maximum sprinting despite the activity being one of the most common causes of a rupture and re-rupture of Achilles tendon during sports (Della Villa et al., 2022). The importance of PF muscle-tendon unit (MTU) during maximum sprinting, particularly in the acceleration phase, has been extensively investigated in the healthy population (Bezodis et al., 2015; Debaere et al., 2015; Schache et al., 2014). The ankle joint and PF MTU have been reported to significantly contribute to horizontal force of the body mass during the push-off phase and the first two steps of sprint acceleration (Debaere et al., 2015). The ability to produce the larger horizontally orientated force or impulse during these phases of sprint acceleration was proportional to faster sprint time over the short distance, which is a vital component for team sports (Slawinski et al., 2017). Suboptimal recovery of PF MTU following

Achilles tendon rupture may significantly compromise sprint acceleration performance. Therefore, the purpose of this study is to investigate sprint acceleration performance and biomechanics of the lower limb joints following Achilles tendon rupture.

1.2 Purpose of the Study

The purpose of the present study was:

1 To investigate the effect of Achilles tendon rupture on sprint acceleration performance (sprint time, horizontal impulse, and Ratio of Force (RF)) during the push-off phase and the first step of the five-metre sprint compared with a control group without Achilles tendon rupture from a split standing start.

2 To investigate the difference in peak concentric power in the lower limb joints (ankle, knee, hip) between the involved (Achilles tendon ruptured) legs and the uninvolved legs, and both legs of the control group during the push-off phase and the first step of sprint acceleration from a split standing start.

3 To investigate correlations between deficits in plantarflexor muscle strength/power and maximum height achieved during the single leg heel rise (SLHR) test across legs and ankle joint concentric power during sprint acceleration from a split standing start following Achilles tendon rupture.

1.3 Hypotheses

It is hypothesized that sprint performance and peak ankle joint concentric power of the involved leg during sprint acceleration is significantly affected following Achilles tendon rupture. It is also hypothesized that the involved legs have a significant deficit in PF strength and power compared to the uninvolved legs in the ACHL group and legs of the control group. Finally, it is hypothesized that the deficits in PF muscle strength, power and maximum height achieved during the SLHR test would be significantly correlated with deficits observed in ankle joint peak power during sprint acceleration performance.

1.4 Significance of the Problem

This is the first study to examine the effect of the injury on sprint acceleration performance. The findings of the current study may have significant implications for healthcare providers and those who are involved in the rehabilitation and return to sports following Achilles tendon rupture. Understanding the mechanisms of sprint acceleration related to Achilles tendon rupture may highlight the biomechanical function of lower limbs post injury. Although the information is currently limited in a dynamic movement of sprint start, the findings may encourage healthcare providers and athletes to navigate a safe return to sporting activities for those who sustained Achilles tendon rupture. In addition, as there is no gold-standard rehabilitation protocol established to date, the results of this study may provide additional dimensions to the existing protocols to achieve better functional and quality of life outcomes.

Chapter 2 : Literature Review

2.1 Introduction

The first section of this chapter describes the search strategy which informed the literature review. A review of morphological and functional changes of the Achilles tendon following a rupture is then presented in the next section. The third section concerns the morphological changes of plantarflexor (PF) muscles and associated alteration of the PF strength. The fourth section highlights the effect of the Achilles tendon rupture on lower limb functional tasks. The final section reviews sprint acceleration and the role of the Achilles tendon and PF muscle-tendon unit (MTU) during the sprint acceleration phase.

2.2 Search Strategy

An extensive list of key terms was entered in the search platforms to obtain the relevant literature. The key terms used were Achilles tendon rupture, Achilles tendon repair, morphological change, structural change, architectural change, functional, neural, neuromuscular, biomechanical, dynamometer, shear wave elastography, viscoelastic, return to sport, epidemiology, ankle, plantarflexor, strength, power, sprint acceleration, horizontal impulse, ratio of force, five-metre sprint, standing start, kinetic, kinematic. Using these keywords, six electronic databases were searched. The databases used were AMED, PEDro, Sports Direct, MEDLINE, CINAHL and Sports Discus. The literature review was also enhanced by examining the reference lists of included articles and previous review papers on Achilles tendon rupture, and by utilising Scopus to locate articles.

2.3 Altered Structure and Biomechanical Properties of the Achilles Tendon following a Rupture

The structure of the Achilles tendon is compromised following tendon rupture which disrupts its biomechanical properties and function (Geremia et al., 2015). The injury can consequently affect PF muscle strength and lower limb function during functional tasks (Diniz et al., 2020; Silbernagel et al., 2010). In the year following injury, the common structural changes of the tendon observed following a rupture include elongation and increased cross sectional area (CSA) due to changes at a cellular level during the tendon healing process (Aufwerber et al., 2020a; Geremia et al., 2015). Histological studies have shown that healing tendon contains an

increased amount of type III collagen fibres and scar tissue formation often found in a curvy disorientated order compared with healthy tendons that have more tensile resistant type I collagen fibres in a linear orientation (Freedman et al., 2014). The healing tendons also contain a reduced amount of glycosaminoglycans, proteoglycans, elastin, and cross-links between tendon fibrils (Freedman et al., 2014; Geremia et al., 2015; Snedeker & Foolen, 2017; Zhang et al., 2016). The disrupted architecture of the Achilles tendon can significantly reduce its dynamic function, particularly the ability to transfer mechanical force and perform efficient storage and release of mechanical energy via stretch-shortening cycle (Diniz et al., 2020). Over a course of rehabilitation, tendons structural composition, architecture, and biomechanical properties can improve via a tendon remodeling process where tendon cells are stimulated to upregulate collagen synthesis. However, the level of biomechanical function of the tendons post injury can remain reduced for many years or permanently compared to the pre-injury level, resulting in long-term deficits of lower limb function (Hansen et al., 2020a; Zellers et al., 2017).

2.3.1 Tendon Elongation

Tendon elongation is one of the most consistently reported structural changes following Achilles tendon rupture (Silbernagel et al., 2010). The exact mechanism of tendon elongation remains unknown, although the scar tissue formation or gapping of the tendon matrix at the injury site during the rehabilitation process has been considered likely to play a role (Williamson et al., 2020). The average length of healthy adult Achilles tendons between the calcaneal insertion and the musculo-tendinous junction (MTJ) of gastrocnemius muscles is approximately 150 mm ranging from 110 mm to 260mm (Munteanu, 2015). A wide variation of tendon length in the healthy population can be associated with the anatomical variation, gender, tissue adaptation based on sports/activities, occupation, and activities of daily life (ADLs) requirement (Bohm et al., 2015; Butler & Dominy, 2016; Devaprakash et al., 2022). Many studies using ultrasound or MRI scans, reported a mean of 8 - 12% tendon elongation (ranging from 1.5 - 31 mm) in the involved side compared with the uninvolved side 12 months post tendon rupture (Barfod et al., 2015a; Diniz et al., 2020; Geremia et al., 2015; Hansen et al., 2020a; Hansen et al., 2013; Heikkinen et al., 2017a; Zellers et al., 2017). The degree of tendon elongation post injury seems to vary between individuals and the reason for the variation remains unclear (Freedman et al., 2014). Over the rehabilitation period, the largest increase in tendon length is often observed in the first three to six months post tendon rupture when mobilization of ankle joint typically commences following notable period of immobilization in foot orthoses in a plantarflexed position (Carmont et al., 2017; Eliasson et al.,

2018; Freedman et al., 2014). Subsequently, a gradual shortening of tendon proceeds from 6 to 12 months post injury with progressive loading through the Achilles tendon with increasing intensity of activities (Freedman et al., 2014). The pathway of tendon elongation over time appears to occur in most cases regardless of the rehabilitation protocols or surgical and non-surgical management (Eliasson et al., 2018).

Elongated Achilles tendon following rupture can significantly affect ankle joint function and PF muscle strength. Previous studies have reported a significant correlation between the increased tendon length and kinematic changes in the ankle joint during gait and reduced PF muscle strength particularly in the end range of plantarflexion (Agres et al., 2015; Brorsson et al., 2017; Heikkinen et al., 2017a). However, many studies found no significant correlations between Achilles tendon elongation and self-reported perceived functional outcome scores such as the Achilles tendon rupture score (ATRS), Victorian institute of sports assessment - Achilles tendon (VISA-A) or Foot and ankle outcome sore (FAOS) at 12 months following the injury (Carmont et al., 2015; Schepull & Aspenberg, 2013; Silbernagel et al., 2010; Silbernagel et al., 2012b; Zellers et al., 2017).

2.3.2 Achilles Tendon Resting Angle (ATRA)

Achilles tendon elongation/length is often measured using imaging modalities such as ultrasound (US) or Magnetic Resonance imaging (MRI) (Diniz et al., 2020). Due to the limited access of the imaging modalities in clinical settings, Carmont et al. (2013) developed a clinical test called Achilles tendon resting angle (ATRA), which indirectly measures Achilles tendon elongation. The ATRA involves measuring the absolute ankle joint resting angle with a goniometer in a prone knee bent position. A larger angle (more dorsiflexion) at the ankle joint indicates longer tendon length. The test was shown to be reliable with an Intraclass Correlation Coefficient (ICC) value of 0.84 - 0.92 (Carmont et al., 2013; Hansen et al., 2017). The test was validated against the Copenhagen Achilles Length Measure (CALM), which measures the length of tendon by measuring the distance between landmarks (Achilles insertion to calcaneous and MTJ of gastrocnemius muscles) identified under ultrasound imagining (Barfod et al., 2015b). Based on previous literature, an increase of each degree in ATRA equated to a mean tendon elongation of between 0.39 mm (Carmont et al., 2013; Hansen et al., 2020b) and 0.44 mm (Larsson et al., 2022). The association of the test with the perceived lower limb function is unclear. For example, a moderate correlation (r = 0.37 - 0.59) was reported between the ATRA and ATRS at twelve months post injury by Carmont et al. (2017) and Khair et al. (2022). In contrast, Cramer et al. (2022) and Larsson et al. (2022)

reported no significant correlation between ARTA and ARTS, a drop countermovement jump performance, and return to same level of activities at twelve months post injury.

2.3.3 Increased Tendon Cross-Sectional Area (CSA) following a Rupture

Another common structural change observed following Achilles tendon rupture is increased tendon cross-sectional area (CSA) (Aufewerber at al., 2020a; Geremia et al., 2015). Healthy Achilles tendons typically have a mean CSA of between 48 - 60mm^2, whereas a ruptured tendon may have a mean CSA of between 138 - 272mm^2 at twelve months post injury (Aufewerber et al., 2020a; Geremia et al., 2015; Hiramatsu et al., 2018; Suydam et al., 2015). The increased CSA of the healing Achilles tendons results from an increase in collagen synthesis and scar tissue formation as part of the healing process (Freedman et al., 2014). Restoring structural orientation of collagen matrix can require progressive loading over a prolonged period, therefore the increased tendon CSA is believed to be a temporary compensatory strategy to provide the structural strength for the biomechanically compromised tendons to perform activities of daily living (ADLs) in the early stage of rehabilitation (Hiramatsu et al., 2018). The CSA of the healing tendons increases through the initial rehabilitation period up to six months post injury followed by a gradual decrease in size towards twelve months post injury (Aufwerber et al., 2020a; Hiramatsu et al., 2018; Saarensilta et al., 2023). In some cases, the CSA of the tendon post injury remains increased after years. For example, compared with the uninvolved leg, Bravo-Sanchez et al. (2021) reported a 39% CSA increase of the Achilles tendon in the involved leg at six years post injury. The clinical implications for the increased CSA remains uncertain as no significant correlation has been found between the tendon CSA/thickness and self-reported functional outcome measures including the ATRS and the American orthopaedic foot and ankle society (AOFAS) at twelve months post rupture (Ciloglu & Gorgulu, 2020; Saarensilta et al., 2023; Wu et al., 2019).

2.3.4 Altered Biomechanical Properties and Function of the Achilles Tendon following a Rupture

The structural changes in the Achilles tendon post rupture can affect its viscoelastic properties, and therefore the function of the entire PF MTU, particularly the ability to store and release mechanical energy via the stretch-shortening mechanism of the tendon (Freedman et al., 2014). Tendons have an elastic property which allows the tissue to be stretched and deformed under a tensile load. The material property stiffness of a tendon is often quantified by the

"elastic modulus or Young's modulus", which is calculated from the slope of the linear region of the tendon stress-strain curve (Wang, 2006). Tendon stiffness is characterized as resistance to withstanding a change in tendon length against shear or tensile load and is dependent on the loading rate (Zellers et al., 2017; Zhang et al., 2016). Stiffness is an important biomechanical property enabling tendons to efficiently transfer force between contractile element of the muscles and attachment to bones (Wang et al., 2012). However, some research has suggested that there is no set level of optimal tendon stiffness to enhance performance of functional tasks (Freedman et al., 2014; Ueno et al., 2018; J. Wang et al., 2012). For physically demanding tasks such as jumping or high-speed running, a stiff tendon may enhance performance via increasing the force and power production (Monte et al., 2023; Wang et al., 2012). On the other hand, for repetitive tasks such as steady pace running, a more compliant tendon may enhance performance via a more effective stretch-shortening cycle (Ueno et al., 2018). Tendons possess the ability to adapt their biomechanical properties according to loading type and intensity (Bohm et al., 2015). The difference in tendon stiffness depending on choice of activities has been shown in the healthy population. Dirrichs et al. (2019) identified up to 55% difference in tendon stiffness between a group of competitive athletes and non-competitive athletes. Furthermore, age can significantly change tendon stiffness. Smith et al. (2024) found 30% reduced tendon stiffness in older (mean age = 74 years) adults compared with younger (mean age = 21.7 years) adults and suggested that this was due to general decrease in activity levels and the aging process.

Tendon stiffness can be measured using different modalities such as an isokinetic dynamometer, Roentgen stereophotogrammetric analysis (RSA), and Shear wave Elastography (SWE). An isokinetic dynamometer can be used to measure stiffness of the entire PF MTU complex (Agres et al., 2015; Barfod et al., 2015a; Bressel & McNair, 2001; Geremia et al., 2015; McNair et al., 2013). McNair et al. (2013) observed between 20 - 40% reduced stiffness of the PF MTU throughout the testing range in the involved leg six months post Achilles tendon rupture. In contrast, Barfod et al., (2015a) reported 13 - 24 % reduced stiffness of PF MTU in plantarflexed range but 8 - 40% increased stiffness of MTU towards 10 - 20 degrees (°) of dorsiflexed range six months post injury. Both McNair et al. (2013) and Barfod et al., (2015a) also measured the changes in energy storage capacity of PF MTU complex post injury through measurement of the area under a torque angle curve from a dynamometer. Both researchers reported a 20 - 26% reduced energy storage ability of the MTU complex in the involved leg six-month post-surgery. In addition, both authors observed up to 11% increased torque during relaxation in the involved leg, suggesting increased dissipation of load (decreased return of the stored energy), likely resulting from the changed structure of the healing tendon.

RSA measures tendon stiffness by implementation of tantalum beads within the ruptured Achilles tendon during a surgical procedure. When the tendon is put under load, the implanted beads send signals to computer system to calculate tendon mechanical properties. Schepull et al. (2007) reported 6.5 times increase in tendon stiffness from week 6 to week 52 post-surgery. A significant positive correlation (r = 0.88) was also found between Young's modulus of tendon and the heel rise index (total work achieved during the heel rise test) at 52 weeks post-surgery (Schepull et al., 2007), but not with the ATRS (Schepull & Aspenberg, 2013; Schepull et al., 2012). The results suggested that measuring Young's modulus early in the rehabilitation stage may have a potential predictive ability of heel rise function but not the entire lower limb function a year post-surgery (Schepull & Aspenberg, 2013; Schepull et al., 2007; Schepull et al., 2012).

SWE is a non-invasive high-resolution ultrasound image technique to measure stiffness and elasticity of the Achilles tendon via measurement of the velocity of shear waves created by a US transducer. These waves generate local tissue strain to the tendons and the velocity of shear waves through tendons is measured as it has been found to be proportional to Young's modulus of tendon (Laurent et al., 2020). Following Achilles tendon rupture, tendon stiffness was reported to improve relatively early in the rehabilitation period with the involved legs showing up to 65% tendon stiffness of the contralateral side by week 12 post injury (Ciloglu & Gorgulu, 2020; Frankewycz et al., 2020; Laurent et al., 2020), and achieving nearly to 90% recovery to the contralateral side by 16 weeks post injury (Yoshida et al., 2023; Zhang et al., 2016). Mixed results were reported for tendon stiffness measured after 24 weeks post injury. For example, Karatekin et al. (2018) and Yoshida et al. (2023) reported 9 - 47% and 22 - 27%, respectively, increased stiffness of the Achilles tendon in the involved leg between 24 weeks to seven years post injury. No significant correlation between tendon stiffness and self-reported functional outcome measures (AOFAS and ATRS) was found (Yoshida et al., 2023). In contrast, 20 - 80% deficits in tendon stiffness were reported between 24 weeks to seven years post tendon rupture (Ciloglu & Gorgulu, 2020; Frankewycz et al., 2018; Ivanac et al., 2021). Contrasting evidence may be related to the testing protocols and different age demographics in these studies. In general, decreased stiffness of tendon has been reported under SWE over 12 months following Achilles tendon rupture, although some contrasting evidence has been reported. The degrees of tendon stiffness may vary between individuals and the healing of tendon biomechanical property may be associated with age. Further studies are required to validate tendon stiffness using a SWE following an Achilles rupture.

2.3.5 Weight Bearing Lunge Test (WBLT)

Stiffness of PF MTU as well as ankle dorsiflexion range can be measured indirectly via the Weight Bearing Lunge Test (WBLT). The test was originally developed to measure functional ankle dorsiflexion range (Bennell et al., 1998) and is reported to have a predictive ability for ankle and Achilles injuries (de Noronha et al., 2006; Rabin & Kozol, 2012). A high reliability of the test (ICC = 0.93 – 0.99) was reported and it was suggested that the difference across legs should be used to assess the effect of ankle injuries on functional dorsiflexion range (Chisholm et al., 2012). Some ultrasound measurements suggest that the free part (mid portion) of Achilles tendon length in the healthy population is associated with the lunge test (r = 0.61) (Wawrzyński et al., 2022). In an Achilles tendon rupture group, Bąkowski et al. (2017) and Kiedrowski et al. (2022) observed a significantly shorter (1.2 - 2 cm) distance in the involved legs than the uninvolved leg 2 - 3 years post injury. However, caution is required for interpretation of such results in the involved leg as the test could be influenced by a restriction of ankle joint structures including subtalar joints, ligaments, capsule, and bone as well as PF MTU length (Koshino et al., 2024) .

In summary, altered structures and biomechanical properties of tendons following the Achilles tendon rupture have been consistently reported in literature. Most Achilles tendons post injury have been found to present with elongation and increased CSA of the tendons and such structural changes appear to increase the stiffness of Achilles tendons but reduce the energy storage and release capacity of the entire MTU of PF muscles. Although the tendons can improve their structure and biomechanical properties via remodeling process through a rehabilitation period, there is a large variation of degrees of tendon healing between individuals and the reason for the variation remains unknown. In some cases, the altered structural properties of the tendons post injury may remain permanent after 12 months post injury. Mixed results were reported for the perceived functional outcomes with the structural changes in Achilles tendons post tendon rupture. Most studies showed no significant correlation between the structural changes of Achilles tendons and the self-reported functional outcome measures at 12 months post rupture.

2.4 Effect of Achilles Tendon Rupture on Morphology and Strength of Plantarflexor Muscles

An alteration of biomechanical properties of the tendon following Achilles tendon rupture will also affect the morphology/architecture of PF muscles, particularly triceps surae (medial (MG)

and lateral gastrocnemius (LG) and soleus)(Baxter et al., 2018; Hullfish et al., 2019; Khair et al., 2022). Although a large variation in PF muscle morphology between individuals can be present in the healthy population (Bolsterlee et al., 2018; May et al., 2021; Takahashi et al., 2022), the changes in the architecture of triceps surae muscles in the involved leg are commonly observed compared with the uninvolved leg following Achilles tendon rupture. These changes of the muscles can also affect their strength, power, endurance capability, and ultimately lower limb function. This section reviews the structural changes in the contractile elements of the triceps surae muscles and in relation to functional outcomes following Achilles tendon rupture.

2.4.1 Morphological Changes in Triceps Surae Muscles following Achilles Tendon Rupture

The common morphological changes observed in triceps surae muscle group post Achilles tendon rupture can include shorter fascicle length and increased pennation angles (Baxter et al., 2018; Hullfish et al., 2019; Khair et al., 2022; Nicholson et al., 2020; Staudle et al., 2022). Such changes were reported to commence within weeks after Achilles tendon rupture (Hullfish et al., 2019). For example, 15 - 26% shorter fascicle length and 9 - 21% increased pennation angles in the muscles were observed in the involved leg within 12 - 16 weeks post injury compared with the uninvolved leg (Agres et al., 2020; Hullfish et al., 2019). Persistent changes were observed at one year post injury with 23.8% shorter fascicle length and 23.8% increased pennation angles (Khair et al., 2022), and with 12.1 - 34% shorter fascicle length and 18 - 45% increased pennation angles observed in the involved leg between 2 - 7 years post injury (Nicholson et al., 2020; Staudle et al., 2022).

Shorter fascicle length and increased pennation angles in the triceps surae muscles can be explained as a compensatory strategy for biomechanically compromised Achilles tendons post rupture, particularly elongation of the tendon (Baxter et al., 2018). Shortening fascicle length can take up the “slack” created by the elongated tendon. This is thought to be crucial for the entire PF MTU as it may in part restore tension to maintain the stretch-shortening mechanism of the tendon for more efficient lower limb function (Baxter et al., 2018; Khair et al., 2022). Increased pennation angles can result from an anatomical adaptation to shorter fascicle length but can also preserve the force production of PF MTU in the altered force-length relationship (Khair et al., 2022). Staudle et al. (2021) used a computer simulation model to demonstrate the possible force production of MG muscles with shorter fascicle length alone compared with shorter fascicle length combined with increased pennation angle. The model demonstrated

that the MG muscles with only shorter fascicle length showed a deficit of 26% and 68% force production with knee joint extended and flexed, respectively, whereas the deficit would reduce to 6% and 57%, respectively when pennation angle of the muscles was increased (Staudle et al., 2021). The preservation of force output with these morphological changes in triceps surae muscles post injury can be crucial and may be sufficient for lower limbs to perform low to moderate level activities (Khair et al., 2022). For example, gait analysis following Achilles tendon rupture showed no significant effect of the injury on walking speed (Khair et al., 2022) and spatiotemporal parameters (Baxter et al., 2018; Nicholson et al., 2020; Staudle et al., 2022) despite the involved leg showing the significant altered fascicle length and pennation angle of MG muscles. However, these architectural adaptations in the triceps surae muscles would still significantly compromise the dynamic function of sarcomere cross-bridging, resulting in a reduced overall force production of the muscles and reduced performance of lower limbs during more physically demanding functional activities (Zellers et al., 2021). Compromised dynamic function has been associated with these morphological changes utilizing a self-reported functional outcome measure. Peng et al. (2019) found a significant correlation between the Lower Extremity Functional Scale and fascicle length ($r = -0.83$) and pennation angle ($r = 0.58$). Based on these findings, the morphological changes can reduce overall lower limb function.

2.4.2 Effect of Achilles Tendon Rupture on Size of Plantarflexor Muscles

The morphological changes of triceps surae muscles following Achilles tendon rupture include a reduced size of the muscles (Eken et al., 2021; Goren et al., 2005; Heikkinen et al., 2017a; Heikkinen et al., 2017b; Khair et al., 2022; Willits et al., 2010). The reduced volume of the triceps surae muscles is believed to be associated with a disuse and reduced neural activation following the injury (Zellers et al., Khair et al., 2022; 2019b). The size of the PF muscles is often monitored to assess the overall progress of recovery throughout the rehabilitation period (Eliasson et al., 2018) due to its significant correlation ($rho = 0.41 - 0.56$) with the PF muscle strength (Heikkinen et al., 2017a), and prediction of functional recovery (Khair et al., 2022). The size of PF muscles can be measured using imaging techniques such as ultrasound (US) or magnetic resonance imaging (MRI) or a clinical measurement with calf circumference.

Imaging techniques (US or MRI) are often used to calculate/estimate CSA and muscle volume of individual PF muscles following Achilles tendon rupture (Eken et al., 2021; Heikkinen et al., 2017a; Heikkinen et al., 2017b; Nicholson et al., 2020). Heikkinen et al. (2017a) reported 18%, 15% and 11% loss of the CSA of soleus, MG, and LG muscles, respectively, 18 months post

tendon rupture. The same group of authors also investigated the long-term effect of the injury on the muscle size 14 years after the injury and showed persistent 13% reduction in the CSA of soleus and MG muscles as well as 11% reduction in the LG muscle (Heikkinen et al., 2017b). These authors also identified a 5% increase in the CSA of flexor hallucis longus muscles which was thought to be a compensatory hypertrophy for the reduced triceps surae size. Amongst triceps surae muscle group, the size of soleus muscle seems to be most affected following Achilles tendon rupture. For instance, Zellers et al. (2019) found no significant difference in CSA of MG and LG muscles between the sides but observed a 30% reduction in soleus 12 months post injury. Similarly, a loss of muscle thickness in soleus (21.1%) muscles was significantly greater than the muscle loss in MG (9.1%) 7 - 8 years in the involved legs compared with the uninvolved legs post injury (Nicholson et al., 2020). The distribution of muscle fibre types may explain the greater muscle atrophy and more fatty infiltration in soleus muscle (Heikkinen et al., 2017a). Soleus has been found to contain a large proportion of fatigue-resistant type I muscle fibers and previous work (Wang & Pessin, 2013) has demonstrated a faster degradation of type I muscle fibres following an immobilization of the ankle joint. Another study (Eliasson et al., 2018) observed the effect of immobilization on atrophy of soleus muscles and reported greater atrophy in the standard non-weight bearing immobilization group (9 weeks) compared to the early weight-bearing group (0 - 4 weeks) and the early mobilization group (3 - 6 weeks) following Achilles tendon rupture. Another possible reason for the greater atrophy in soleus compared to gastrocnemius muscles is that gastrocnemius crosses the knee and ankle joints, allowing the muscles to remain partially active during immobilization (Heikkinen et al., 2017a). Furthermore, Hug et al. (2021) identified an independent neural drive to each triceps surae muscle during functional activities. A separate neural drive “rate” to each muscle may lead to a different magnitude of atrophy or recovery through rehabilitation.

In clinical setting, measuring calf circumference across legs following Achilles tendon rupture has been shown to be a reliable (ICC = 0.97 - 0.98) (Moller et al., 2005). The measurement was also validated against measuring the cross-sectional area (CSA) ($R^2 = 0.86$, $p < 0.001$) and the volume ($R^2 = 0.82$) of triceps surae muscles under MRI (Eken et al., 2021). Willits et al. (2010) identified 1.3 cm smaller calf circumference in the involved leg compared with the uninvolved leg one year post injury and the deficit increased to 1.5 - 1.7 cm between legs two years post injury. The result was comparable with 1 - 1.6 cm smaller calf circumference observed in the involved legs compared with the uninvolved legs 12 months post injury in a more recent study (Zellers et al., 2017). The reduced calf muscle size can remain long-term where 0.6 cm smaller calf circumference in the involved legs was identified seven years post injury compared with

the uninvolved legs (Eken et al., 2021). Interestingly, these authors found no significant correlation between the difference in calf circumference and self-reported functional outcome measures such as ATRS, American Orthopaedic Foot and Ankle Society Ankle-Hindfoot Score (AOFAS) and the Leppilahti score (Eken et al., 2021).

2.4.3 Effect of Achilles Tendon Rupture on Plantarflexor Muscle Strength

PF muscle strength can be significantly affected following Achilles tendon rupture due to the aforementioned changes in the morphology and the size of muscles. Up to 20 - 30% of strength deficit has been reported in PF muscles of the involved legs during the first 12 months and the deficit can remain for several years or can permanent in some cases (Barfod et al., 2015a; De la Fuente et al., 2022; Don et al., 2007; Horstmann et al., 2012; Khair et al., 2022; McNair et al., 2013). As expected, PF muscle strength was found to be at its lowest in the first few months after a removal of ankle orthoses for initial immobilization, and then a gradual improvement in strength follows with increased activity level over time (Eliasson et al., 2018). The evaluation of PF muscle strength through the rehabilitation process is thought to be important to monitor as returning to the pre-injury level of sports is significantly correlated with ankle PF strength (Holzgrefe et al., 2020).

The strength of PF muscles can be accurately quantified using an isokinetic dynamometer (ICC = 0.74 - 0.89) following Achilles tendon rupture (Chester et al., 2003; Möller et al., 2002). Hence, the device has been a popular choice by many researchers to monitor progress with PF muscle strength following tendon rupture (Barfod et al., 2015a; De la Fuente et al., 2022; Don et al., 2007; Geremia et al., 2015; Heikkinen et al., 2017a; Hurmeydan et al., 2020; Khair et al., 2022; McNair et al., 2013; Staudle et al., 2021). However, questions remain regarding the optimal testing protocols to assess PF strength following injury such as the positions of the testing leg (knee straight versus flexed), posture of subjects (supine, seated or prone lying), range of motion to assess, mode of muscle action (isometric, concentric and/or eccentric), and angular velocity (ranging from 5 deg/sec to 240 deg/sec). As a result of differences in testing procedures in previous studies, a direct comparison of results can be challenging (Backer et al., 2019). Despite such a challenge, the reduced PF muscle strength has been consistently reported in the involved leg and PF muscle strength may remain relatively unchanged after 12 months from the injury and thereafter (Geremia et al., 2015; Heikkinen et al., 2017a; Jallageas et al., 2013; Khair et al., 2022; Maffulli et al., 2011; McNair et al., 2013; Mullaney et al., 2006; Orishimo et al., 2018; Porter et al., 2014; Staudle et al., 2021; Talbot et al., 2012).

Amongst many published protocols, an isometric test using an isokinetic dynamometer is one method to examine PF strength post Achilles tendon rupture (De la Fuente et al., 2022; Geremia et al., 2015; Khair et al., 2022; Mullaney et al., 2006; Orishimo et al., 2018; Staudle et al., 2021). Investigating peak isometric PF strength at various ankle angles can be useful to identify a potential shift in muscle operating range due to tendon elongation or the morphological changes of PF muscles post injury (Staudle et al., 2021). A shift towards dorsiflexion range in optimal length-force relationship curve has been reported in the previous computer simulation study (Staudle et al., 2021). A variation of isometric test protocols measuring peak PF strength included an investigation at various ankle joint angles (20°, 10° dorsiflexion (DF), neutral, 10° and 20° plantarflexion) with fully extended knee in a seated position (Mullaney et al., 2006; Orishimo et al., 2018; Staudle et al., 2021) or at neutral ankle joint range in a supine position (Lantto et al., 2015b), a prone lying (De la Fuente et al., 2022) and a seated position (Geremia et al., 2015; Khair et al., 2022; Maffulli et al., 2011). Mullaney et al. (2006) and Orishimo et al. (2018) observed a deficit of 17 - 20% and 27 - 34% in peak isometric PF strength in the involved legs compared with the uninvolved legs at 10° and 20° plantarflexion, respectively, whereas no significant difference across legs was reported at neutral or in DF range. On the other hand, a mean deficit of 31% peak isometric PF strength in the involved legs was observed throughout the ankle range between 10° DF to 20° PF (Staudle et al., 2021). Furthermore, a deficit of 9 - 25% peak isometric PF strength was observed at a neutral angle in the involved leg 1 - 2 years post tendon rupture (De la Fuente et al., 2022; Geremia et al., 2015; Khair et al., 2022; Maffulli et al., 2011), although the PF strength deficit has been reported to be reduced notably to 2.4% at 11 years follow-up (Lantto et al., 2015b). The wide range of deficits across studies highlights the effect of the varying testing protocols. Based on these results, the PF strength deficit in the involved leg may be more evident in the plantarflexion range and less or no deficit is observed in dorsiflexion. Evidence supports that a peak of length-tension curve shifted towards dorsiflexion likely due to shortened fascicle length and tendon elongation.

Like the isometric protocols, there is a large variability in the isokinetic test protocols across studies. Testing at slow angular velocities, (30 and 60 deg/sec), was the most frequently used protocol as these velocities are believed to be the closest representation of the maximum PF force based on a force-velocity and force-length relationship (Backer et al., 2019; Hurmeydan et al., 2020). At these velocities, a 19 - 22% deficit (Hurmeydan et al., 2020; Jallageas et al., 2013; Möller et al., 2002) and a 7 - 14 % deficit (Horstmann et al., 2012; Porter et al., 2014) of PF muscle strength, respectively, were reported between 1 - 10 years post Achilles tendon rupture. On the other hand, Don et al. (2007) and Wenning et al. (2021) observed a deficit of

30% and 10%, respectively, in peak PF eccentric torque 12 months post injury at 30 deg/sec, while no deficits were observed during concentric muscle action. Nicholson et al. (2020) and Walker et al. (2020) observed no significant deficits at both 30 and 60 deg/sec testing velocity.

Other testing velocities at 90 and 120 deg/sec were selected to represent a similar angular velocity to normal gait cycle (Hurmeydan et al., 2020). A 5% deficit (Talbot et al., 2012) and 16 - 19% deficit (Jallageas et al., 2013; Porter et al., 2014) of peak concentric PF strength were identified at 90 and 120 deg/sec testing velocities, respectively, while Hurmeydan et al. (2020) observed no significant difference across legs at 120 deg/s.

At higher angular velocities (180 and 240 deg/sec), both Möller et al. (2002) and Porter et al. (2014) observed 14% and 20% PF strength deficit at 180 deg/sec, respectively, between 1 - 7 years post injury. Similarly, a 12.5 - 18 % deficit was observed between six months to two years post injury at 240 deg/sec testing velocity (Holzgrefe et al., 2020; McNair et al., 2013; Talbot et al., 2012; Willits et al., 2010). One study observed no significant deficit at 180 deg/sec testing protocol 12 months post injury (Horstmann et al., 2012).

In summary, shorter fascicle length and increased pennation angles of triceps surae muscles have been commonly observed in the presence of Achilles tendon elongation following a rupture. Despite a wide range of deficits (6.7 - 34%) likely as a result of testing protocol disparity, PF muscle weakness was apparent in the involved leg regardless of the testing protocols following an Achilles tendon rupture over the first twelve months and also at longer-terms up to 14 years post injury. Marked weakness of PF muscles was observed towards the end range section of plantarflexion. Although not consistent, these strength deficits seem to negatively impact upon functional activities with some research highlighting significant correlations between strength deficit and self-reported functional outcome measures.

2.5 Changes of Lower Limb Kinetics and Kinematics during Functional Activities following Achilles Tendon Rupture

Many studies have examined the effect of an Achilles tendon rupture on the biomechanics of the lower limbs during functional activities such as walking, running, horizontal jump, counter-movement jump (CMJ) or hopping (Brorsson et al., 2017; Jandacka et al., 2017; Powell et al., 2018; Silbernagel et al., 2012b; Speedtsberg et al., 2019; Sun et al., 2020; Tengman & Riad, 2013; Willy et al., 2017). In general, large deficits in kinetic and kinematic parameters between the involved leg during these activities have been observed post injury (Aufwerber et al., 2020a; Silbernagel et al., 2010). The degree of kinetic and kinematic deficits appears to depend

on the mechanical demand required during tasks (Hansen et al., 2023). The amount of peak load through healthy Achilles tendons during various functional activities has been calculated and listed in a recent study (Baxter et al., 2021). The peak load through the Achilles tendon was estimated to be 3.3 body weights (BW) during walking, 5.2 BW during running, 5.5 BW during a single leg drop jump, and 6.7 BW during single leg hopping (Baxter et al., 2021). This section will review the changes in biomechanical parameters in the lower limb during some common functional activities examined following an Achilles tendon rupture.

2.5.1 Walking post Achilles Tendon Rupture

While walking speed (Khair et al., 2022) and spatiotemporal parameters (Baxter et al., 2018; Nicholson et al., 2020; Staudle et al., 2022) can be unaffected post Achilles tendon rupture, altered kinetics and kinematics at the ankle joint have been consistently reported in the involved legs across the literature (Aufwerber et al., 2020b; Brorsson et al., 2017; Nicholson et al., 2020; Speedtsberg et al., 2019; Sun et al., 2020; Tengman & Riad, 2013; Willy et al., 2017). The changes in kinetic and kinematic values at the ankle joint is believed to be associated with the affected biomechanical properties of the ruptured Achilles tendon, particularly with increased length and stiffness of the tendons (Agres et al., 2018; Aufwerber et al., 2020b; Brorsson et al., 2017).

Regarding kinematic changes during gait post injury, a change in DF and plantarflexion range during the stance phase are the most commonly observed biomechanical alteration during walking. The increased tendon length post injury seems to shift the ankle joints operating range more towards DF during stance phase to restore a tension of the PF MTU for effective energy absorption and subsequent generation, resulting in reduced PF angles at toe off (Staudle et al., 2022; Sun et al., 2020). For example, Tengman and Riad (2013) reported 22% reduced PF angle at toe off in the involved leg compared with a leg of the control group three years following the tendon rupture. Similarly, Agres et al. (2015) and Speedtsberg et al. (2019) showed 7.6% reduced peak PF angle and 11.6 - 13.6% increased peak DF angle in the involved leg compared with the uninvolved leg between 2 - 6 years post injury. Sun et al. (2020) also reported 30% increased peak DF angle and 37% reduced peak PF angle exhibited across legs.

In addition to ankle joint kinematics, changes in the ankle joint kinetics during stance phase of walking post injury have been also reported. Tengman and Riad (2013) showed a 6% deficit in peak PF moment during terminal stance phase of walking. Similarly, Aufwerber et al. (2022) reported a 7% and a 14.5% deficit in the PF moment and peak ankle joint power, respectively, in the involved leg. Hansen et al. (2022) reported a 7% deficit in the peak PF power during

push-off phase in the involved leg 12 months post injury. No significant deficit was found in the ankle PF moment in other studies (Agres et al., 2015; Sun et al., 2020)

The results consistently showed altered ankle joint kinematics with a shift in operating angles (increased DF and a reduced PF peak angle during stance phase) in the involved leg during walking likely due to in part to increased Achilles tendon length following the tendon rupture. In contrast, ankle joint kinetics during walking showed mixed results. Kinetic deficit was generally reported in the involved leg, but overall, evidence was not conclusive. The inconsistent findings across these studies may be explained by the relatively small amount of force and peak load required by PF muscles and the Achilles tendon during walking.

2.5.2 Running post Achilles Tendon Rupture

Following an Achilles tendon rupture, altered patterns of lower limb biomechanics continues to be present when the gait speed and mechanical demand increases during running (Brorsson et al., 2017; Jandacka et al., 2017; Jandacka et al., 2013; Sun et al., 2020). During running, the PF muscle-tendon complex has been shown to increase the exploitation of the tendon's stretch-shortening system for energy efficient gait cycle compared to walking (Starbuck et al., 2021). The passive recoil nature of the tendon can minimize energy consumption and allow the triceps surae muscle group to operate isometrically in a mid-range of muscle length (Schache et al., 2014). An increase of 18.6% in the peak Achilles tendon load was reported when the running speed increased from 3.3 to 5.6 ms^{-1} (Starbuck et al., 2021). The peak load through the tendons has been found to progressively increase with running speed and peak at 6.0 - 7.0 ms^{-1} (Komi et al., 1992). Several studies investigated the effect of an Achilles tendon rupture during running were all at running speed below 6.0 ms^{-1} (Brorsson et al., 2017; Jandacka et al., 2017; Jandacka et al., 2013; Silbernagel, Willy, et al., 2012; Sun et al., 2020).

Two case studies (Jandacka et al., 2013; Silbernagel et al., 2012b) assessed running mechanics of a participant pre and post Achilles tendon rupture. At 12-month post injury, Silbernagel et al. (2012b) assessed a subject at 3.35 ms^{-1} and demonstrated significantly reduced kinetics and kinematics in the involved leg. The involved leg had a 15% increased peak DF angle during stance phase post injury compared with the same leg at pre-injury. The involved leg also demonstrated a 6% deficit in peak PF moment and 21% reduced horizontal ankle joint power compared to the uninvolved side post injury. The deficits in the ankle joint of the involved leg seemed to be compensated for at the ipsilateral knee joint where 25% and 10% higher power absorption and generation respectively were recorded (Sibernagel et al., 2012b). At a similar running speed (3.2 ms^{-1}), Jandacka et al. (2013) assessed a subject at 4.5 years post-surgery.

The involved leg had 7% and 20% reduced horizontal and vertical ground reaction force, respectively, when comparing the same leg pre and post injury. The net PF joint moment for the involved leg was reduced by 13% compared with the uninvolved leg.

Results from studies with larger sample sizes supported many of the case study findings (Brorsson et al., 2017; Jandacka et al., 2017; Sun et al., 2020). Jandacka et al. (2017) reported a 21% reduced peak ankle PF angle during stance phase and a 28% increased peak knee flexion angle at initial contact in the involved leg compared with the same side of leg of the control group. Interestingly, no significant difference between the legs was found in both ankle and knee joint moments during jogging and in the vertical ground reaction force (GRF) during stance phase (Jandacka et al., 2017). Brorsson et al. (2017) observed a 14% reduced concentric PF power and a 56% reduced peak PF angle in the involved leg during the stance phase of running. No significant differences in eccentric PF power and peak Achilles force between the legs were found. Willy et al. (2017) reported 6.5% reduced plantarflexion angular velocity in the involved leg during the jogging (2.4 ms^{-1}) following the tendon rupture, although no difference was found between the legs during walking (1.34 ms^{-1}). These findings highlighted the further deficit in the ankle joint kinematics observed during functional tasks with an increased physical demand on Achilles tendon post injury. Sun et al. (2020) reported a 19% increased peak DF angle and a 57% reduced peak PF angle in the involved side during a self-selected jogging speed. When the running speed increased from self-selected jogging to faster running, the deficit of peak DF range and peak PF range changed to a 9% increased DF angle and a 11%, respectively. These results showed a decrease in the total ankle joint operating range of motion during stance phase of faster running compared with jogging. Furthermore, the deficit of PF moment in the involved leg reduced from 25% during jogging to 9% during faster running. A compensatory strategy at the knee joint was observed where the difference in knee joint moment between the limbs increased from 0% during jogging to 22% faster running (Sun et al., 2020) .

In summary, like walking, a similar pattern of kinematic changes at ankle joint (increased DF and reduced PF) in the involved leg was observed during running post Achilles tendon rupture. In general, the degree of kinetic deficit (7 - 22%) appears to be higher during running compared with walking, although some studies showed no kinetic changes during running. These results can suggest that the kinetic deficits in the involved leg post injury may depend on the physical demand of task.

2.5.3 Jumping and Hopping post Achilles Tendon Rupture

A significant difference for biomechanics in the involved and the uninvolved legs post Achilles tendon rupture has been observed during ballistic activities such as jumping or hopping. During ballistic movement, the Achilles tendon plays an important role to enhance power production by using the viscoelastic properties of the tendon (Handsfield et al., 2020; Munteanu, 2015; Schache et al., 2014; Staudle et al., 2021). The PF MTU exploits the passive recoil system of the tendon to increase the total power output. A higher peak force is generated through the Achilles tendon during ballistic activities compared with walking and running (Baxter et al., 2021). Deficits in kinetic and kinematic parameters are often observed during these activities, and high physical demand placed upon the Achilles tendon may be associated with an increased risk of ruptures compared with any other functional activities (Powell et al., 2018).

Several studies investigated the kinetic and kinematic changes of lower limb joints during jumps or counter-movement jumps (CMJ) as well as actual performance of the tasks post Achilles tendon rupture. During a drop CMJ test, Nilsson-Helander et al. (2010) and Olsson et al. (2013) reported 9 - 13% deficit and 18 - 20% deficits in the involved leg of the surgical group and non-surgical group, respectively. Brorsson et al. (2017) reported a 5% deficit across legs during a single-leg-hop for distance test seven years following an Achilles tendon rupture. These authors also reported a 55% deficit in PF peak angle, a 20% deficit in concentric PF power, and a 12% deficit in eccentric PF power. Willy and colleagues (2017) found between 27 - 46% decreased PF angle and an 18% decreased concentric ankle joint power. The affected ankle joint power was thought to be compensated a by 15 - 17% elevated concentric knee joint power during hopping (Willy et al., 2017). Similarly, Powell et al. (2018) observed a 20% deficit across legs in ankle concentric power in the involved leg during the take-off phase of a drop CMJ. A 22% deficit in eccentric power at the ankle joint was accompanied with 17% increased eccentric knee joint power during landing phase of a drop CMJ test. The deficit in ankle joint power was reflected in 40% increased vertical GRF during the test and the authors believe the increased load may increase risk for other lower limb joints during single leg tasks. In contrast, no compensatory mechanism at the knee joint was observed by Zellers et al. (2021), despite a 19 - 28% deficit in the peak ankle PF angle and a 20 – 26% deficit in peak concentric PF work during hopping and a CMJ following an Achilles tendon rupture. These authors believed that the involved legs may be capable of producing a similar amount of joint power by adjusting the operating range of the ankle joint to the shifted optimal range created by tendon elongation and PF fascicle shortening.

2.5.4 Single Leg Heel Rise Test (SLHR) for Achilles Tendon Rupture

A single leg heel rise (SLHR) test has been widely used to measure PF muscle function following Achilles tendon rupture. The test was shown to have good reliability (ICC = 0.78-0.84) in healthy subjects (Moller et al., 2005). The test was later validated and standardized by Silbernagel et al. (2010) for a cohort with a history of Achilles tendon rupture. The test protocol involves a person performing a heel-raise by standing on one leg on a 10° incline board that places the foot in dorsiflexion at the lowest point of the test. A linear transducer attached to the heel measures the vertical distance that the body moves, and the maximum height achieved along with the number of repetitions allows a calculation of total work achieved during the test. Silbernagel et al. (2010) reported 20% and 24% deficits in height and work achieved respectively, but no difference in repetitions achieved in the involved leg compared to the uninvolved leg at 12 months post rupture. The same test protocol was repeated in a follow-up study (Silbernagel et al., 2012a) and a 32% deficit in heel-rise height but no difference in repetition across legs was reported. A significant negative relationship (r = - 0.74) between the heel-rise height and the tendon elongation was observed, but no correlation was found between the SLHR test and a perceived function outcome measure (ATRS) twelve months post injury. Based on the findings, Silbernagel and colleagues (Silbernagel et al., 2010; Silbernagel et al., 2012b) suggested that maximal height and work achieved during the test were of notable clinical importance and should be included in testing during the rehabilitation programme. A review of data collected from previous randomized controlled studies (Westin et al., 2020) showed a deficit in the SLHR test, with a mean LSI of 81% for height achieved, 90% for repetitions achieved, and 73% for work achieved at twelve months post Achilles tendon rupture. The deficit in maximal height was correlated with tendon elongation post injury. However, as mentioned above, no significant correlation was found between the test and self-perceived functional outcome scores. Furthermore, cautious interpretation of the test result may be required as a recent study demonstrated that the test had no significant correlation with maximal PF strength measured on isokinetic dynamometer in healthy subjects and therefore the test is not a surrogate for PF muscle strength testing (Sara et al., 2021). This is perhaps not surprising as the energy systems associated with the repetitive motion of the SLHR test are likely different to that utilized in a few maximal effort repetitions to assess strength.

In summary, common kinematic changes of ankle joint during the functional activities included increased dorsiflexion and reduced plantarflexion in stance phase. These changes are believed to be associated with the shifted operating range of ankle joint due to tendon elongation post injury. From a kinetics perspective, the ankle joint tends to have reduced PF moment at toe off

of stance phase during walking and running. A large deficit in ankle concentric power during ballistic activities such as jumping and hopping was observed and was thought to be compensated by increased knee joint power. The degrees of kinetic deficits may be associated with the physical demands required at ankle and the Achilles tendon. The reduced kinetics at ankle joint are likely to be related to reduced PF force production as a result of shortened muscle fascicle of triceps surae muscle groups post injury.

2.6 Sprint Acceleration and Role of Plantarflexor Muscle-Tendon Unit during Activity

Sprint acceleration is one of the leading causes of rupture or re-rupture of Achilles tendons. A retrospective video analysis by Della Villa et al. (2022) reported that accelerating to sprint from a standing position was the most common mechanism of injury (25% of all cases) in professional football in the United Kingdom. The high incidence of Achilles tendon rupture during sprint acceleration may be associated with the magnitude and rate of force transferred through the Achilles tendon (Pandy et al., 2021). The force developed during sprint acceleration is estimated to be up to 16 BW (Hess, 2010; Pandy et al., 2021), and the amount of force transmitted to Achilles tendon can be estimated up to 8 BW during the acceleration phase (Jielile et al., 2010). Furthermore, a forward motion of body during sprint acceleration will place the Achilles tendons in a significantly stretched position (Della Villa et al., 2022). Excessive lengthening of the tendon coupled with large amount of force during sprint acceleration will increase the risk of mechanical failure within the tendon (Loturco et al., 2021). In addition to mechanical demand of sprint acceleration, the maximal strain of the Achilles tendon reduces with age (Kubo et al., 2007). Reduced capacity of tendon strain combined with high force levels during sprint acceleration may explain the increased rate of injury in the age group of 30 years and older (Lemme et al., 2018). Despite the high injury rate, no studies have investigated the effect of Achilles tendon ruptures on maximum effort sprinting. The importance of the PF muscles and the Achilles tendon during sprint acceleration has been highlighted by many researchers (Hamner & Delp, 2013; Hebert-Losier et al., 2023; Lai et al., 2014). This section will review the ankle joint biomechanics, and the role of PF MTU and the Achilles tendon during sprint acceleration.

Sprinting can be divided into three phases; acceleration, maximum velocity, and deceleration/speed maintenance phase (Healy et al., 2019). Sprinting performance is typically

measured by the time taken over a covered distance. The first two phases of sprinting (acceleration and maximum velocity) have been extensively investigated in sports science research with the aim most often being to increase performance. Particularly, the initial acceleration phase is believed to be the most important phase for short sprint because the acceleration phase could dictate the overall sprint performance by reaching the maximum speed phase in the shortest time possible (Monte & Zamparo, 2019). In many team sports, sprinting distance is relatively short and the initial acceleration stage particularly over the first 5 – 10 metres can be a crucial parameter of individual performance (Bezodis et al., 2017; Slawinski et al., 2017). For example, in rugby, the average sprint time during the game is only 1 – 3 seconds and the ability to accelerate 6 – 10 metres was reported to constitute 46% of line breaks (Gabbett, 2012; Wild et al., 2018). In football, the ability to quickly accelerate to fast running speed has been shown to be one of the key determinants for scoring goals (Faude et al., 2012).

2.6.1 Direction of the Force Profile During Sprint Acceleration

Sprint acceleration requires explosive horizontal force to propel the centre of mass (COM) in a forward direction (Slawinski et al., 2017). The maximum amount of horizontal force is generated at the start of the acceleration phase and then progressively decreases towards the maximum speed phase at approximately 35 – 40 metres from the start (Nagahara et al., 2020; Nagahara et al., 2018; Schache et al., 2019). The changes in horizontal force through the acceleration phase show a similar profile to the acceleration of the COM where the largest acceleration (~5.8 ms^{-2}) has been observed at the first foot contact of sprinting. The acceleration speed has been found to be halved (3.0 ms^{-2}) by 7^{th} foot contact, followed by a further decrease (1.41 ms^{-2}) at 19^{th} foot contact over approximately 40 metres (Pandy et al., 2021). Conversely, a gradual increase in vertical force through the acceleration phase was reported before reaching a peak towards the end of the phase (Lai et al., 2016; Nagahara et al., 2020; Nagahara et al., 2018; Schache et al., 2019). A gradual increase in vertical force through the acceleration phase is related to a gradual decrease in net horizontal force through the phase as the braking force increases, and the body needs to be maintained its upright position against gravity (Nagahara et al., 2021).

2.6.2 Horizontal Impulse and Ratio of Force (RF)

Horizontal force production during sprint acceleration has been extensively investigated to assess performance due to its strong association with sprint time over short distances

(between 5 – 100 m) (Bezodis, Willwacher, et al., 2019; Morin et al., 2012; Valamatos et al., 2022). Horizontal force production is often presented as a raw ground reaction force (GRF) or impulse (product of force and time) and the ratio of force (RF) (Bezodis et al., 2021; Bezodis et al., 2019a; Morin et al., 2011; Slawinski et al., 2017). The net horizontal impulse is a sum of the positive propulsive impulse and the negative braking impulse in an anterior-posterior direction during stance phase and the value is calculated with the area of the force curve over a duration of stance phase (Morin et al., 2015; Nagahara et al., 2018). In particular, horizontal impulse and GRF during the push-off phase and the first and the second steps of sprint acceleration have been a main focus in the research area (Bezodis et al., 2019b; Nagahara et al., 2018; Slawinski et al., 2017). During the push-off phase of the block start of sprinting, Otsuka et al. (2014) observed that the elite sprinters performed 7% and 8% larger horizontal impulse and 16% and 33% larger horizontal GRF compared with sub-elite or non-sprinter, respectively. A similar result was reported during the first step of sprint acceleration by Slawinski et al. (2010). These authors observed that the elite sprinters had a 5% faster sprint time over 5 m and 33 – 34% larger net horizontal impulse during the first step of sprint acceleration compared with the sub-elite sprinters. A large horizontal impulse performed by elite sprinters was associated with slightly longer foot contact time during the first step of sprint acceleration (Slawinski et al., 2010). The finding was consistent with study by Ciacci et al. (2017) who compared the kinetic parameters of sprint acceleration phase between the world-class sprinters and the elite sprinters. These authors concluded the world class sprinters produced larger horizontal impulse with slightly longer foot contact time during the push-off and the first step compared with sub-elite sprinters, resulting in achieving higher velocity and longer subsequent steps (Ciacci et al., 2017; Slawinski et al., 2010). Interestingly, the elite sprinters had shorter foot contact times from the second step onwards and demonstrated a superior ability of maintaining the net positive horizontal impulse by producing greater horizontal propulsive during stance phase compared with sub-elite sprinters (Ciacci et al., 2017; Morin et al., 2015).

The RF is the ratio of horizontal component GRF divided by the resultant GRF during stance phase i.e., RF = $F_{horizontal}/F_{resultant}$ (Morin et al., 2011). Different calculation methods for RF included either the instantaneous RF of the particular stance phase or mean RF averaged over a number of steps (Bezodis et al., 2021). Regardless of the calculation methods, a strong correlation has been found between RF values and short distance sprint time. For example, a significant negative correlation was found between the instantaneous RF value during the push-off (block) phase and 40 m sprint time by Rabita et al. (2015). These authors also observed a high correlation ($R^2 = 0.93$) between the step-averaged RF and 40 m sprint

performance. Moreover, the elite sprinters demonstrated a superior ability to produce higher RF values (9.7%) than the sub-elite sprinters (Rabita et al., 2015). Similarly, a significant inverse correlation (r = - 0.61) was reported between instantaneous RF during the push-off phase from standing start and sprint time over 5 metres with a group of physical education students (Slawinski et al., 2017). Conversely, the team sport athletes demonstrated a slower 10 m sprint time, and a lower step-averaged RF value was recorded when their sprint technique was manipulated with specific verbal instructions (Bezodis et al., 2017). These results suggested a consistent relationship between the sprint time and the RF value.

The horizontal force production or RF value during sprint acceleration can depend on starting posture, technical skills, and strength/power of lower limb joints (Frost & Cronin, 2011). For starting posture, Kugler and Janshen (2010) found a strong correlation (r = 0.93) between a forward orientated angle of the COM and horizontal impulse during the push-off phase from block start. A lower vertical position of COM from a crouching start has also been found to contribute to larger horizontal force production compared with a standing start (Macadam et al., 2019; Slawinski et al., 2017; Wild et al., 2018). Distance between feet or the angles of the starting block can alter the horizontal force production (Nagahara et al., 2021). Feet placement further away posteriorly from the COM has been found to increase forward orientated posture and force production, although the optimal setup needs to be individualized to achieve the best kinetic and kinematic advantage of lower limb joints for maximal horizontal force production (Cavedon et al., 2019). Technical skills including kinematics and spatiotemporal parameters can influence horizontal force production or RF values in the first few steps of sprint acceleration. Bezodis et al. (2015) reported that a more posterior foot placement in relation to the COM has been found to increase horizontal force production during the first and second step of sprint acceleration. A similar positive correlation (r = 0.54) between horizontal force production and touchdown distance from the COM during the first step was found in sprinters (Wild et al., 2018). Furthermore, King et al. (2022) reported a significant positive relationship (r = 0.73) between increased ankle DF and higher RF of the first and the second step of sprint acceleration. The respective study concluded that increased DF with touchdown distance further away from the COM allows the ankle joint to rotate further to propel the COM in a forward direction, resulting in larger horizontal force production.

2.6.3 Ankle Joint/Plantarflexor Muscle Contribution during Sprint Acceleration

The contribution from each lower limb joint or individual muscle group can be quantified via computer-simulated musculoskeletal models that include measuring electromyographic (EMG)

activity of muscles. Based on such models, a large contribution of overall horizontal and vertical force was observed at the ankle and hip joints, and the ankle joint, respectively, during sprint acceleration from block start (Debaere et al., 2015; Dorn et al., 2012; Lai et al., 2016; Pandy et al., 2021; Schache et al., 2014). During the push-off phase, the PF MTU has been found to undergo a short stretch-shortening cycle and this accounted for a significant contribution to horizontal force along with large hip joint power from a block start (Brazil et al., 2017). Contributions by the ankle joint to overall lower limb power output during the push-off phase from a block start were 31% and 30% from the rear and front blocks, respectively, whereas 61% and 43% contributions by the hip joint were observed from the rear and front blocks (Brazil et al., 2017). However, Cavedon et al. (2019) reported up to 55% variance of horizontal force production by lower limb joints with the largest variance observed at the ankle joint (23%) of the back leg. Therefore, a large variation in ratio of lower limb joints during the push-off phase between individuals can be expected. During the first two steps of sprint acceleration, the ankle joint and PF muscles generated the largest propulsive horizontal force (Debaere et al., 2013, 2015; Pandy et al., 2021). For example, Debaere et al. (2015) reported 67% and 93% of the entire COM propulsion force in a horizontal direction was produced at the ankle joint during the first and second step of sprint acceleration respectively. At a muscular level, gastrocnemius contributed 25% and 29%, and soleus contributed 32% and 27% of the COM horizontal propulsion during the first and second steps respectively. The authors also identified the ankle joint significantly contribute to the vertical acceleration of the COM (50%) during the first step (Debaere et al., 2015). Using a computer-simulated model, Pandy et al. (2021) conducted a similar analysis of the contribution of muscle groups to horizontal and vertical forces during sprint acceleration. During the first and the second steps of the sprint acceleration phase, the highest horizontal propulsive force was generated by gastrocnemius (0.58 BW) followed by the soleus (0.46 BW) and the hamstring muscles (< 0.15 BW). The combined horizontal positive propulsion force significantly exceeded the negative braking force generated by quadriceps (0.35 BW) muscles during the same phase. The study also observed a large contribution by the soleus muscle (44%) and gastrocnemius (21%) to vertical impulse during the first step of sprint acceleration. Interestingly, Slawinski et al. (2022) reported higher contribution by the hip joint to overall kinetic energy during the first phase (0.9 seconds from the push-off phase) from a standing start. These results highlighted the importance of the PF muscle group during the initial phase of sprint acceleration (Pandy et al., 2021).

2.6.4 Role of Achilles Tendon and Interaction with Plantarflexor MTU during Sprint Acceleration

The Achilles tendons of sprinters have been reported to be stiffer than non-sprinters (Bohm et al., 2015). The role of the tendon has been reported to enhance and modulate the force production of PF MTU (Schache et al., 2014). To generate a large amount of force during the first few steps of the sprint acceleration phase, the PF muscle fascicles undergo significant shortening to produce large positive work (Lai et al., 2016; Werkhausen et al., 2021). Additionally, the PF MTU exhibited a stretching-shortening behaviour during the push-off phase and the first step (Aeles et al., 2018; Brazil et al., 2017). The velocity of tendon shortening has been found to exceed that of muscle contraction velocity, and the behaviour of the PF MTU during the push-off and the first two steps of sprint acceleration would suggest an exploitation of the stretch-shortening mechanism to increase power output (Schache et al., 2014). An animal study showed the ability of MTU of hind-limb of frogs to produce seven times more peak power output than total muscle fascicle capacity alone during jumping (Peplowski & Marsh, 1997). Similarly, enhanced power output through PF MTU was observed in human sprinting. Using the computer-simulated model, Lai et al. (2016) observed 63% higher positive work produced by the MTU of the soleus and MG muscles during sprint acceleration compared with potential power output by muscle fascicles only. Positive work generated by the muscle fascicles early in stance phase is likely to induce elastic strain energy within the tendon to enhance power output of the entire PF MTU (Lai et al., 2016).

Another role of the Achilles tendon during sprinting is to modulate the force production of PF muscles (Lai et al., 2016). The force required from the PF MTU can vary depending on the speed or the phase of running. A complex interaction between the muscle and the tendon enables the entire MTU to determine the ratio of force required from each structure for the task (Lai et al., 2014). As previously mentioned, increases in the Achilles tendon force was observed with increasing running speed to conserve energy expenditure before reaching a peak and plateau at approximately 6.0 – 7.0 ms^{-1} running speed (Komi et al., 1992; Lai et al., 2014). Beyond this speed, PF muscle activity significantly increases as the efficiency of tendon stretch-shortening function deteriorated due to the increased demand of force production over a shorter ground contact time (Dorn et al., 2012). It is hypothesized that a complex interaction between the tendon and muscle can adjust the operating length of contractile element in the muscles depending on the demand required for a task (Schache et al., 2014). During the sprint acceleration, the PF muscle was found to operate in the descending slope of the length-tension relationship curve (Schache et al., 2014). Operating in that slope allows muscle fibers to operate at an optimal area of the curve to increase overall force production

required to accelerate the COM. In contrast, muscle fibres tend to operate in the ascending slope of the curve during the maximum speed phase (Schache et al., 2014). Although this is an unfavourable area of the curve for force production, PF muscles can increase the speed of contraction and rapidly re-distribute the force to the tendon recoil system to maintain power output during the shorter ground contact time observed in sprinting (Schache et al., 2014). The joint position of other lower limb joints may also contribute to the different lengths and tensions of the PF MTU. Increased dorsiflexion at ankle and extension at knee joints are typically observed during the push-off and the first two steps of sprint acceleration compared with the later stage of acceleration phase (Bezodis et al., 2019b). Particularly, high dorsiflexion angle at ankle joint would increase the length and tension of the entire MTU to operate across the favorable descending slope of the curve for power output (Lai et al., 2016). Furthermore, a high dorsiflexion angle at ankle joint during the push-off and the first two steps of sprint acceleration may enable the joint to rotate to propel the COM more in a forward direction (Bezodis et al., 2015; King et al., 2022).

2.6.5 Association of Power with Sprint Performance

The ability to produce large force and power during stance phase can be one of the most critical factors for improving sprint performance (Nagahara et al., 2014). Significant correlations between short sprint time and peak strength and power activities/exercises have been reported in previous studies. For example, 5 m sprint time has been reported to be negatively correlated with maximal squat strength (r = - 0.77) and an isometric mid-thigh pull test (r = - 0.63) (Brady et al., 2020; Lockie et al., 2012; Seitz et al., 2014). Power can often be assessed via ballistic functional tasks (Lockie et al. 2012), with 100 m sprint time correlated with squat jump (R^2 = 0.62), CMJ (R^2 = 0.55 – 0.56), the five-bound test (r = - 0.48) and ankle rebounding jump height (r = - 0.53) (Jouira et al., 2024; Lockie et al., 2012; Nagahara et al., 2014). In addition, some studies investigated a correlation between short sprint time and ankle PF strength (Hebert-Losier et al., 2023; Mock et al., 2018). Mock et al. (2018) reported a significant correlation between one repetition maximal calf raise strength and sprint time at 5 m (r = - 0.48) and 30 m (r = - 0.72) with physical education students. Similarly, Hebert-Losier et al. (2023) found a large significant correlation (r = - 0.63) between 10 m sprint time and PF power measured with the calf raise test.

2.6.6 Standing Start vs Crouching Start

Sprint acceleration is typically measured from a static position; either a standing start or a crouching start with or without starting blocks (Slawinski et al., 2017). The choice of starting techniques often depends upon requirements and rules of the sport. Generally, sprinters can achieve a faster time and speed from a crouching start with the blocks due to larger horizontal force production mentioned above compared with a standing start over the same distance. For example, Slawinski et al. (2017) found that a three-point crouching start produced 4.4% faster 5 m sprint time with 7.5% greater RF and 25% higher horizontal GRF compared to a standing start. The authors reported that the lower COM and more forward posture with a hand placed at the front of legs at the start contributed to the greater RF from a crouching start. Similarly, Macadam et al. (2019) compared the two starting techniques and demonstrated that well-trained sprinters recorded 5% and 3.5% faster time over the first 5 and 10 meters from a crouching block start compared to a standing start. Superior performance from the crouching start was explained by a larger net horizontal impulse (6.5%) generated by pushing against the starting blocks during the push-off phase (Macadam et al., 2019). However, effective crouching starts particularly with the blocks seems to depend on a specific technique and may not be suitable for some non-sprint trained athletes (Bezodis et al., 2019b). Multiple factors such as block placement, foot plate angles, knee angles, weight distribution between the legs and finger placement can all influence the push-off/block clearance performance. The specific skillset and motor coordination can be crucial for an effective crouching start (Bezodis et al., 2019). A few previous studies have also demonstrated the inferior performance by non-sprinters from the crouching start over the standing start (Duthie et al., 2006; Ostarello, 2001). Therefore, as a more practical option, a standing start is a preferred option to measure the performance of short sprints in many team sports athletes (Wild et al., 2018).

The standing start techniques can include parallel start, jump start, false start, and split start. The parallel start features starting with both feet in parallel. A jump start begins by jumping in the backward direction with both feet. A false stance begins by stepping back from a parallel stance and a split start begins with placing the back leg comfortably behind (staggered stance) (Slawinski et al., 2017) Cronin et al. (2007) demonstrated 5.9% and 8.3% faster time over 5 and 10 m, respectively, from the split and the false start compared with the parallel start. There was no significant difference between the split start and false start. Johnson et al. (2010) observed a 2% faster time from the split start than the false start over 15 feet sprint with college volleyball players. Frost and Cronin (2011) also reported similar sprint times between the split and the false stance over 5 m. However, the horizontal impulse and the horizontal force generated was slightly larger (2.8%) when performing the split start, indicating the

potential for a faster time over a longer sprint distance. More recently, Slawinski et al. (2017) compared parallel, false and jump starts. These authors concluded that the false start was superior to the other two standing start techniques. Overall, split stance has been generally found to be the fastest standing start technique for 5 – 10 m as well as being the most practical stance for the team sports athlete.

2.6.7 Five-Metre (5 m) Sprint Test

The 5 m sprint is a common test to measure athletes' sprint acceleration performance. The test is particularly used for many team sports athletes whose average sprinting distance can be 5 to 10 m during games (Bezodis et al., 2017; Standing & Maulder, 2017). It is also noted that in the 100 m sprint event, elite sprinters can reach their maximum speed within the first 10 m (Nagahara et al., 2014; Rabita et al., 2015) Therefore, the 5 m or 10 m sprint test are typically chosen to assess the acceleration performance and the reliability of the tests has been investigated. Cronin et al. (2007) reported a high reliability (coefficient of variation (CV) < 2.2% and > 1.7%) for both 5 m and 10 m sprint times. McMahon et al. (2017) compared results across gender for 5 and 10 m sprints. These authors reported a high reliability for the 5 m sprint test across sessions for males (ICC = 0.81, CV = 2.05) and a moderate reliability for females (ICC = 0.61, CV = 3.13). The reliability of 10 m sprint was higher for males (ICC = 0.86, CV = 1.4) and females (ICC = 0.74, CV = 1.8). The reliability of between sessions for 5 m sprint was high for both males (ICC = 0.83, CV = 1.6) and females (ICC = 0.78, CV = 2.1). The reliability for the 10 m sprint between trials was similar for males (ICC = 0.83, CV = 1.50) and higher for female (ICC = 0.93, CV = 0.91). In contrast, low reliability (ICC = 0.37) was reported by Standing and Maulder (2017) for 5 m sprints and a moderate reliability was reported (ICC = 0.67) for 10 m sprints from split start. The authors acknowledged potential reasons for the inconsistent results with other studies. One is the nature of the test where the difference between the trials can be 0.01 or 0.02 seconds and small variations can affect the reliability of the test with a small sample, in this case, a total of 10 individuals. Another reason for the inconsistency is the starting posture. As mentioned earlier, different limb positions at the start can influence the acceleration performance. In summary, although the 10 m sprint test was found to be more reliable than 5 m sprint test based on the literature review, the 5 m sprint test has good reliability and within the confines of a small indoor lab environment it is likely to be appropriate.

2.7 Summary of Literature Review Chapter

Achilles tendon rupture has been reported to significantly affect lower limb function during functional activities. The functional deficits have been associated with biomechanical changes of the tendon including tendon elongation, increased tendon CSA and reduced stiffness/energy storage capacity of the tendon post injury. Such changes have been reported to reduce PF muscle strength and induce morphological changes in the PF muscles including shortened fascicles, increased pennation angles, and the reduced size post injury. Compromised PF MTU following injury has been found to alter kinematic and kinetic parameters during functional activities. The common changes in biomechanics of the ankle joint were increased dorsiflexion and reduced plantarflexion during stance phase of gait, and reduced PF moment and ankle joint power during running, jumping and hopping. The larger deficits at the ankle joint were associated with more physically demanding tasks such as jumping and hopping and have been found to be compensated by increased knee joint power. Despite the high prevalence of Achilles tendon rupture, no studies have examined the effect of the injury on maximal sprinting. Significant contribution by the ankle joint/PF MTU to the horizontal force and the COM velocity during the push-off phase and the first step of sprint acceleration has been highlighted. With affected PF muscles and the Achilles tendon function post injury, potential deficits in sprint acceleration performance are hypothesized.

Chapter 3 : Method

3.1 Introduction

The primary purpose of this study was to examine the biomechanics of lower limb joints during sprint acceleration 1 - 5 years post Achilles tendon rupture. The study compared the sprint acceleration performance; five-meter (5 m) sprint time, horizontal impulse, and Ratio of Force (RF) across legs in an Achilles tendon rupture (ACHL) group and between the ACHL group and a control (HEAL) group consisting of healthy, age and gender matched participants. In addition, lower limb joint peak concentric power during sprint acceleration was compared across legs in the ACHL group and between the ACHL and the HEAL groups. Finally, the study investigated the relationship between deficits in plantarflexor (PF) muscle strength, power, and height achieved during the single leg heel rise (SLHR) test across legs and peak ankle joint concentric power during sprint acceleration.

This chapter includes details of recruitment, perceived functional measures and procedures for physical performance tests. Additional details of equipment, protocols, data analyses and statistical tests undertaken are provided.

3.2 Study Design

A cross-sectional observational study was conducted to assess participants across legs in the ACHL group and between the ACHL and the HEAL groups.

The research protocol and methodology were reviewed and approved by the Auckland University of Technology Ethical Committee (Reference number: 21/318). All participants received a participant information sheet (Appendix A), which contained full details of the study prior to participation. Following an opportunity to ask any questions they had, all participants read and signed a consent form (Appendix B) prior to the test procedure.

3.3 Participants

Participants were recruited via advertisement (Appendix C) on noticeboards in local gymnasiums, universities, physiotherapy practices, various sports clubs, accident and emergency clinics, musculoskeletal specialists, and orthopaedic surgeons' private clinics across wider Auckland region. The primary researcher contacted accident and emergency clinics,

musculoskeletal specialists, and orthopaedic surgeons in the Auckland region to distribute emails with the advertisement of the study to the potential candidates who met the study criteria (Appendix C).

Each potential participant initially contacted the primary researcher via phone or email to express their interest in participating. The primary researcher then screened each potential participant in accordance with the inclusion and exclusion criteria. A participant information sheet (Appendix D) was provided to those who met the criteria, and a period of two weeks was given for them to decide if they wished to participate.

The study sample size was calculated using G*Power (version 3.1.9.7, Faul et al., 2007). The calculation was based on comparing concentric ankle joint power data between the involved and the uninvolved legs following an Achilles tendon rupture during a countermovement jump from a study by Brorsson et al. (2017). With an alpha value set at 0.05 and a beta value of 0.80, to obtain a 15% percent difference across legs, 15 subjects were required.

Eligibility Criteria

Achilles Tendon Rupture (ACHL) group

Inclusion Criteria

- Age between 25 - 39 years old
- Unilateral mid-substance Achilles tendon rupture within 1 - 5 years
- Discharged from all medical care for the injury
- Returned to recreational/sporting activities involving running or sprinting
- Understands written and spoken English

Exclusion Criteria

- Current or previous significant lower limb injuries which prevents them from sprinting safely
- More than one episode of Achilles tendon rupture
- History of a neurological disorder
- Use of systemic steroids for any reason in the last six months (due to increased risk of tendon injuries (Hersh & Heath, 2002))

- Inability to provide informed consent

Control (HEAL) group

Inclusion Criteria

- Age between 25 – 39 years old
- Understands written and spoken English

Exclusion Criteria

- Current or previous significant lower limb injuries which prevented them from sprinting safely
- History of a neurological disorder
- Use of systemic steroid for any reason in the last six months (due to increased risk of tendon injuries (Hersh & Heath, 2002))
- Inability to provide informed consent

Effort was made to match the control group participants to those with Achilles tendon rupture using the following characteristics: age, sex, height, mass, and participation level in recreational activities. In this study, all participants were recreational athletes. Their activity participation level was divided into competitive or social sports participation, or recreational activities such as regular running or attending the gym. Competitive sports participation was defined as training session and game/match play at a competitive league level for a minimum of once per week each, social sports participation was defined as one game match per week at social competition level.

There was limited availability of participants with Achilles tendon ruptures due to restriction associated with Covid-19. As previous research (Ochen et al., 2019) has highlighted little difference between these treatment options in perceived function, PF strength, and the SLHR test, both surgically and conservatively managed participants was recruited.

3.4 Procedure and Location

All of the assessments took place in the Biomechanics Lab, at the Health and Rehabilitation Research Institute, AUT North Shore Campus, Northcote, Auckland, New Zealand. The primary researcher conducted all assessments.

All participants completed a consent form (Appendix E), two functional outcome measures (see Appendix F and G), one psychological readiness to return to sports measure (Appendix H), and a questionnaire relating to their demographics (Appendix I). For the rupture group: rupture management option (surgical or non-surgical) was also recorded. The questions containing the post-injury rehabilitation protocol were also collected (Appendix J). Testing order was standardized across participants. Figure 3.1 shows the chronological order of the testing.

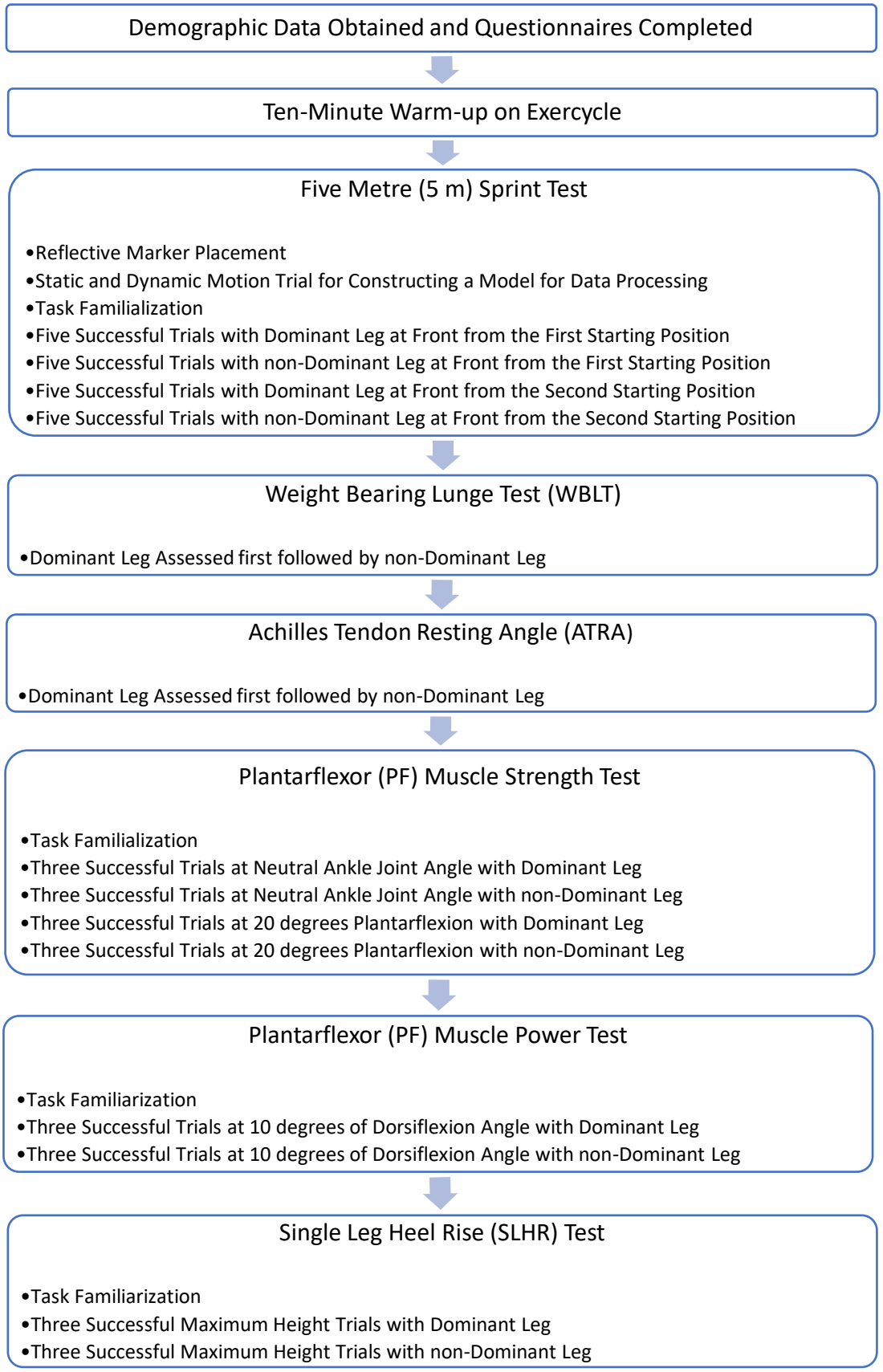


Figure 3.1 A Flowchart of the Testing Protocol in Chronological Order

3.5 Protocol

3.5.1 Perceived Functional Outcome Measures

The Foot and Ankle Outcome Score (FAOS) is a generic self-reported questionnaire for various ankle and foot injuries. The questionnaire consists of 42 items in five subscale categories: pain (9 items), other symptoms (7 items), function in activities of daily living (17 items), function in sports and recreation (5 items) and quality of life (4 items) (Roos et al., 2001). A 5-point Likert scale (from 0 to 4) was used for each item and a total score of each subscale was divided by the maximum possible score of each subscale. The normalized scores were converted to the scale of 0 to 100 where 0 indicates severe disability and 100 indicates no problem. This questionnaire has been reported to have moderate to high reliability with the mean ICC value of 0.70 - 0.92 across five subscales (Roos et al., 2001). A moderate to high structural validity (r = 0.73 – 0.94) was reported for various ankle and foot orthopaedic injuries (Tapaninaho et al., 2022).

The Achilles Tendon Total Rupture Score (ATRS) is a 10-item self-report questionnaire developed specifically for Achilles tendon rupture (Nilsson-Helander et al., 2007). Each item is scored out of 10 with a total maximum total score of 100. A high score indicates a high lower limb function level. The questionnaire has been shown to be reliable with an Intraclass Correlation Coefficient (ICC) of 0.98 (Nilsson-Helander et al., 2007). The ATRS has been shown to have a moderately high correlation with other validated lower limb functional questionnaires such as the FAOS (r = 0.84) and the Victorian Institute of Sports Assessment – Achilles (VISA-A) questionnaire (r = 0.78) (Nilsson-Helander et al., 2007).

Psychological Readiness to Return to Sport Questionnaire is a 6-item self-reported questionnaire developed to assess players' confidence to return to sports following the injury (Glazer, 2009). Each item is scored out of 100 where 100 is full confidence to return to sports. The sum of total score across questions for from each item is divided by 10 to provide a final score out of 60. A high reliability (ICC = 0.88) and a fair structural validity (r = 0.59 - 0.60) was reported for the questionnaire (Dunlop et al., 2023).

Participants were asked to describe the contents of their rehabilitation programme. Previous research studies have highlighted a large variability in the rehabilitation programme following an Achilles tendon rupture. Therefore, the aim of our questions was to determine a qualitative impression of the key elements in which they engaged without the intention of conducting an analysis with statistical tests. Questions were answered 'yes' or 'no'. Of most interest was the inclusion of range of motion, body weight and resistance strength exercises, balance exercises,

plyometric exercises, and sports specific exercises. Participants overall satisfaction with their rehabilitation process was also collected.

3.5.2 Five-Meter Sprint Test

3.5.2.1 Experimental Setup

A five-meter (5 m) sprint test was used to assess sprint acceleration performance and the biomechanics of lower limb joints during sprint acceleration. A split standing start was selected due to its practicality in recreational sports (Salo & Bezodis, 2004; Slawinski et al., 2017). Two AMTI in-ground force plates (Advanced Mechanical Technology, Inc., Model MSA-6, USA) positioned in series were used to collect the ground reaction force (GRF) data, at sampling rate of 2000 Hz. A 13-camera motion analysis system (Qualysis Tracking Manager Inc., version 3 Gothenburg, Sweden, 2023) captured three dimensional (3D) kinematic data, sampled at 250 Hz (Figure 3.2). Kinematic and kinetic data were captured simultaneously. Two different starting positions were marked with tape on the floor. The initial starting position was marked inside the force plates (Figure 3.3 and Figure 3.4a). The second starting position was marked behind the initial position according to the participants' leg length (distance from greater trochanter to the floor) to allow their initial steps to include landing on one of the force plates (Figure 3.3 and Figure 3.4b). Two sets of timing gates (Speed Light, Swift Performance, Australia) were placed at 0.3 meters and 5.3 meters from the starting positions at one metre height from the floor (Altmann et al., 2015).

Twenty-nine single retroreflective markers were placed at anatomical locations on the seventh cervical spinous process, manubrium, the seventh thoracic spinous process, and bilaterally on acromion processes, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), Iliac crest, medial and lateral aspects of knee joints, medial and lateral ankle malleoli, calcaneus, lateral foot, head of the fifth metatarsals, head of the first metatarsal joint (Figure 3.5). Anatomical marker placement was in accordance with previously described procedures (Besier et al., 2003; Cappozzo et al., 2005; Donnelly et al., 2012). Calcaneous, lateral foot, metatarsal-phalangeal (2^{nd} MTP) joint markers in addition to rigid cluster markers, consisting of four single retroreflective markers, that were placed on thigh and shank segments were used as tracking markers (Cappello et al., 1997; Weir et al., 2020).

Figure 3.2 5 m Sprint Test Setup in the Biomechanics Lab with Two Built-in AMTI (American Mechanical Technology Inc) Force Plates, QTM (Qualysis Tracking Manager) with 13 Cameras and Two Sets of Timing gates

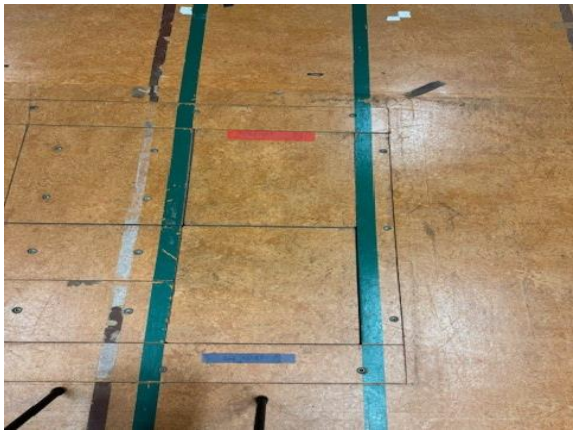


Figure 3.3 The Initial Starting Position (Red (top) Line) Inside the Force Plates and the Second Starting Position (Blue (bottom) Line) outside the Force Plates

(a) *(b)*

Figure 3.4 Initial Sparting Position inside the Force Plates (a). The Second Starting Position outside the Force Plates (b)

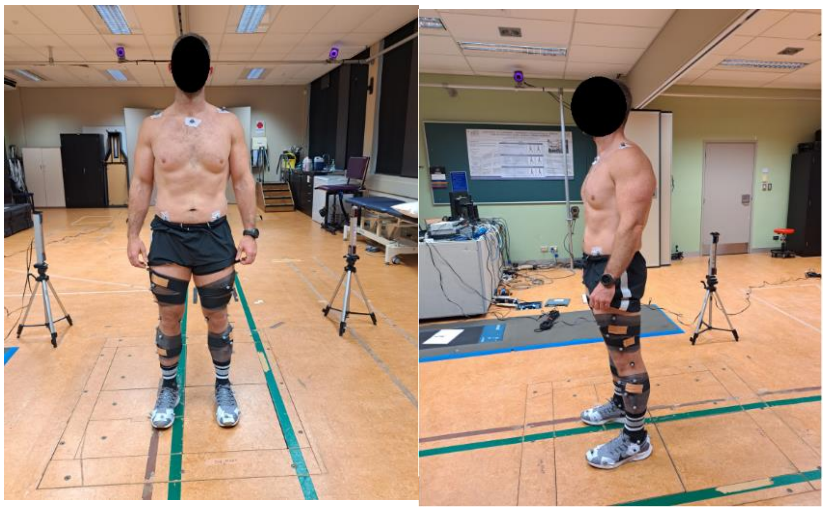


Figure 3.5 Reflective Markers; C7, Acromion Processes, Manubrium, T7, ASIS (Anterior Superior Iliac Spine), PSIS (Posterior Superior Iliac Spine), Iliac crest, Medial and Lateral Knee Joints, Medial and Lateral Ankle Malleoli, Head of 5th Metatarsals (MTP), Head of 1st Metatarsals

3.5.2.2 Data Collection

All participants wore their own running shoes for the testing. An initial recording of participants in a standing position was used as a reference posture ("static" trial). Participants then performed a series of squats and circular leg movements to determine the left and right knee and hip joint centres respectively using a functional joint estimation approach (Schwartz & Rozumalski, 2005). The markers attached to anatomical landmarks of the ankles, knees and the first metatarsals were removed during the subsequent sprint trials to avoid interference the gait pattern.

Prior to the sprint testing, each participant performed a standardized protocol which included a 10-minute self-directed warm-up on exercycle, task familiarization and three submaximal trials. During the task familiarisation period, the starting posture was standardized with participants aligning their toe on the first starting position and placing the back leg where they feel comfortable. Both feet were inside the force plate boundaries (Figure 3.3). Participants were instructed to start sprinting without rocking or swinging motion at their own timing. No hands and fingers were allowed to touch the floor at the start. Once comfortable with sprint start instructions, participants performed five maximum effort sprints with their dominant leg at the front, and subsequently another five maximum sprints with their non-dominant leg at the front. Dominant leg was defined as the leg to kick a ball. The same protocol was repeated from the second starting position. A one-minute break was provided between each trial as per previous protocols (Comfort et al., 2012; McBride et al., 2009).

3.5.2.3 Data Processing

All trajectory markers were identified and labelled using QTM (Qualysis Tracking Manager). Three-dimensional (3D) marker coordinate data were imported to Visual 3D software (C-Motion, Inc, USA, 2023). A 3D rigid-link dynamic biomechanical model consisting of eight segments (the trunk, pelvis, and right and left lower limbs) was constructed in Visual 3D (Figure 3.6). Functional joint centres were calculated, and segments were defined from static trial and functional joints. Orthogonal axes were aligned to the longitudinal axis passing through the segment endpoints in static. Personalised models were developed and scaled according to height and mass of each participant. The developed model was applied to all dynamic trials for the respective participants. Marker coordinates and the GRF data were smoothed using a 4^{th} order Butterworth low-pass filter with a cut-off frequency of 15 Hz (Lai et al., 2016; Pandy et al., 2021). Inverse dynamics was used to calculate the net joint reaction forces at the ankle, knee, and hip joints. These reaction forces were orientated according to the segmental co-ordinate system of the proximal segments.

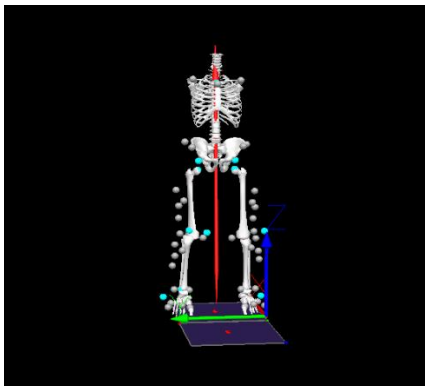
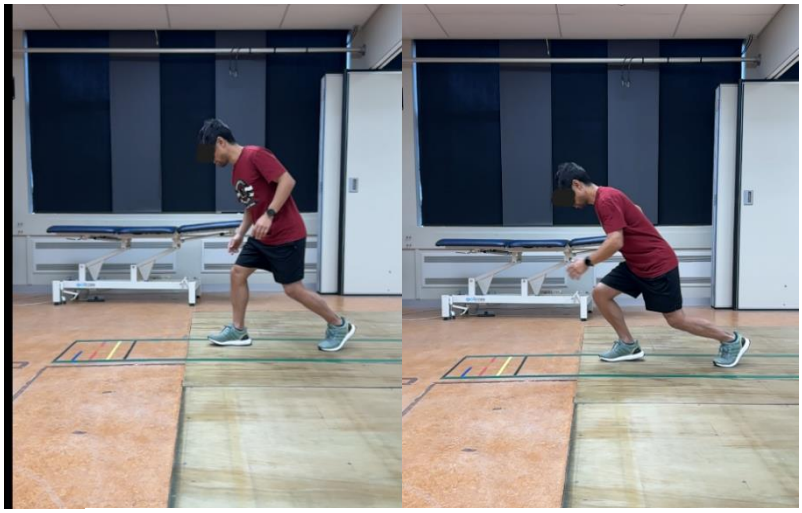


Figure 3.6 Three-Dimensional (3D) Dynamic Biomechanical Model in Visual 3D Software

3.5.2.4 Data Analysis

Data analyses was performed on the stance phases of the “push-off” and the “first step” phases. The “push-off” phase was defined as the stance phases of both the front and back legs during take-off (from an initial movement of the knee joint of the back leg to the front leg leaving the ground). The “first step” was defined as the stance phase of the first step after the “push-off” phase. Gait events were defined using the GRF where possible, and kinematics where the GRF data was unavailable (Wyatt et al., 2019; Zeni et al., 2008). For the events where kinetic data was available, the vertical GRF of > 10N and < 10N thresholds were used to determine for the start and the end of stance phase, respectively. For the events defined using kinematics, the beginning of the stance phase during the “push-off” phase was identified as an initial movement of the knee joint for the back leg, and at the lowest vertical position of the

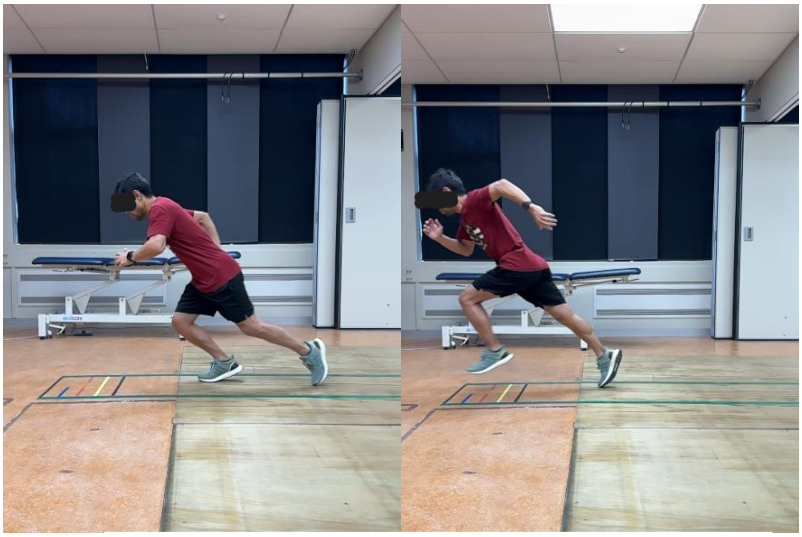
PSIS marker for the front leg (Figure 3.7a and 3.7b, respectively). For the “first step” phase, the beginning of the stance phase was identified at the vertical position of the 2nd MTP trajectory marker < 0.05 m threshold (Figure 3.8). The end of the stance phase was defined at the vertical position of the 2nd MTP markers > 0.05 m (Figure 3.9a and 3.9b). All gait events were checked visually. Marked events with more than two motion frames away from the expected timing of the events were considered as an error and manual adjusted.



(a) (b)

Figure 3.7 Beginning of the Stance Phase for the Back (Left) Leg (a) and for the Front (Right) Leg (b)

Figure 3.8 Beginning of the Stance Phase for the First Step



(a) (b)

Figure 3.9 End of the Stance Phase for the Back (Left) Leg (a) and the Front (Right) Leg (b)

Four main variables were selected for analyses for comparison across legs in the Achilles tendon ruptured (ACHL) group and between the ACHL and the HEAL groups and in the correlational analyses. These variables were: 1) 5 m sprint time (seconds).; 2) Horizontal impulse (Ns kg^{-1}) over stance phase. The horizontal impulse was calculated as the sum of positive and negative impulses during the stance phase.; 3) Ratio of Force (RF) (%) over stance phase. The RF was calculated as a percentage contribution of the horizontal component of GRF to the resultant GRF during stance phase.; 4) Peak concentric power (W kg^{-1}) generated at the lower limb joints (ankle, knee, and hip) over stance phase. Concentric joint power was calculated as the product of the joint angular velocity and the joint moment. The calculated kinetic variables (Horizontal impulse, RF and peak concentric joint power) were grouped into the "push-off" phase and the "first step" phase. During the push-off phase, the extracted horizontal impulse (Ns kg^{-1}) and RF (%) of the front leg and the back leg were combined and averaged for right and left legs. For the kinetic analyses, 3D sagittal plane external joint moment at the ankle knee and hip joints were calculated and normalized to body weight and height.

3.5.3 Weight-Bearing Lunge test (WBLT) and Achilles tendon resting angle (ATRA)

3.5.3.1 Weight-Bearing Lunge Test (WBLT)

The present study followed the similar protocol described by Vicenzino et al. (2006). The WBLT assesses maximum ankle dorsiflexion range of movement in weight bearing. Each participant placed a foot firmly on the floor while performing a forward lunge towards the wall. The furthest distance (toe to the wall in centimeter (cm)) they can reach the wall with their knee without lifting their heel off the floor was recorded for each leg (Figure 3.10). The WBLT has an excellent inter-rater (ICC = 0.99) and intra-rater reliability (ICC = 0.98) (Bennell et al., 1998). The test has been shown to significant correlated (r = 0.61) with the free part of Achilles tendon length in a healthy population (Wawrzyński et al., 2022).

Figure 3.10 The Weight Bearing Lunge Test (WBLT)

3.5.3.2 Achilles Tendon Resting Angle (ATRA)

The present study followed the protocol described by Hansen et al. (2017). Each participant lay in a prone position on a plinth with their knee flexed at 90°. Three points (the fibular head, the distal point of fibula and the middle of 5th metatarsal head) were palpated and marked with a pen. A standard goniometer was placed against the marks with the fulcrum at the distal point of fibula and the acute angle (degree (°)) was recorded for each leg (Figure 3.11).

The ATRA was developed as an indirect clinical measure of Achilles tendon elongation following Achilles tendon ruptures and has been widely used across numerous studies (Carmont et al., 2015; Olsson et al., 2014; Zellers et al., 2016). The test has been shown to be reliable (ICC = 0.91) and validated with the ultrasound measurement of Achilles tendon length where an increase of each degree in ATRA equated to a mean tendon elongation of 0.39 mm (Carmont et al., 2013; Hansen et al., 2020b) or 0.44 mm (Larsson et al., 2022).

Figure 3.11 Achilles Tendon Resting Angle (ATRA)

3.5.4. Plantarflexor Isometric Strength and Power

PF muscle isometric strength was assessed using a protocol described by Cronin et al. (2003). It is performed on an instrumented supine leg press machine (Fitness Works, Auckland, NZ) (Figure 3.12).

Figure 3.12 Supine Leg Press Machine

3.5.4.1 Experimental Setup

A force plate (NDI True Impulse, Northern Digital Inc., Canada, 2013) was set vertically on the foot plate of the leg press machine. To measure horizontal displacement, a linear transducer (P-80A, Unimeasure, Oregon) was attached to a trolley upon which participants lay (Figure 3.12). When participants pushed off the force plate, horizontal force and displacement data were transmitted to a computer based digital data collection system (InstruNet, GW Instruments, Model - 100B, version 3.7, MA USA) at a sampling rate of 1000 Hz. Data were saved and analysed utilising custom built software routines in DasyLab software (Measurement Computing MA, version 14.0.1, USA, 2018). This system provided a measure of isometric PF muscle strength (N kg^{-1}), and concentric power (W kg^{-1}) generated. Power was

calculated as the product of velocity (derived from the linear displacement transducer data) and force data.

3.5.4.2 Data Collection

Each participant lay on the trolley of the supine leg press machine with their testing knee in full extension without footwear. The foot placement of the testing leg was standardized for each participant with their base of 5th metatarsal at the bottom line of the force plate (Figure 3.13a). The participants placed their other leg in 90° of hip and knee joint flexion. Custom-built heel rests were attached to the force plate frame to allow isometric testing at these angles. The isometric strength of the PF muscles (N kg^{-1}) was assessed at 0° and 20° of PF (Figure 3.13a and 3.13b, respectively). The weight stack was loaded to the level where the trolley remains stationary during the isometric strength test. For power assessment, the start position was 10°of dorsiflexion (Landin et al., 2015) and a custom-built heel rest that allowed standardization of this position (Figure 3.13c). For assessing PF muscle power (W kg^{-1}), the weight stack was unloaded to enable the trolley to move with minimal horizontal resistance.

Familiarization of the test and three submaximal attempts were allowed for each participant before each testing protocol. For the PF isometric strength test, each participant was instructed to push the toes of the testing leg against the force plate as hard as possible with their knee joint fully extended for three seconds. Three maximal effort trials were recorded on each leg for both at 0° and 20°, from which the peak PF isometric force (N kg^{-1}) was selected for analysis. The peak PF force was normalized to body weight. For the PF power test, each participant was instructed to push off at ankle joint to push the trolley as “fast and hard” as they could. Similar to the isometric test, the peak PF power (W kg^{-1}) was selected from three trials and normalized to body weight for analysis.

(a) (b)

(c)

Figure 3.13 Plantarflexor Isometric Strength Assessed at 0 (a) and 20 degrees (b) on a Supine Leg Press Machine. Power Assessed at 10 degrees Dorsiflexion (c).

3.5.5 Single Leg Heel Rise (SLHR) Test

The present study followed the protocol of Silbernagel et al. (2010) except the current study only included the test assessing the maximum height achieved (cm). A linear transducer (P-80A, UniMeasure, Oregon) was attached on the bottom of a custom-built heel rise board (Figure 3.14). Displacement data were transmitted to a computer based digital data collection system (InstruNet, GW Instruments, Model - 100B, version 3.7, MA USA) at a sampling rate of 1000 Hz. Data were saved and analysed utilising custom built software routines in DasyLab software (Measurement Computing MA, version 14.0.1, USA, 2018).

Each participant stood on one leg on the 10-degree incline board. They were allowed to place their fingertips on the wall for support and encouraged to keep their knee as straight as possible during the task. The linear transducer was attached to the heel of their shoe. Their

foot was placed on the board to vertically align a wire of the transducer, and their toe position was marked with a tape on the platform.

Familiarization of the test and three submaximal attempts were allowed before data collection. The participants were instructed to raise their heel as high as possible and the distance travelled (cm) was recorded for each leg via the linear transducer. Three attempts were collected, and the maximum height achieved was utilised for analysis.

Figure 3.14 Single Leg Heel Rise (SLHR) Test on a 10 degrees Incline Board

3.6 6 Statistical Analyses

Statistical analyses were performed using the Statistical Package for Social Science (SPSS) software program (IBM Version 29, Chicago, USA). The alpha level was set to 0.05 for all the tests. Data were checked for normality using a combination of the Shapiro-Wilks test, skewness and kurtosis values, histogram plot and the normal Q-Q plot. Errors and outliers were checked using descriptive statistics, the box and whisker plot, and Grubb's test.

An independent sample t-test was performed to investigate any significant differences between the Achilles tendon rupture (ACHL) group and the control (HEAL) group regarding age, height, and weight.

For the assessment of sprint performance variables across legs, a linear mixed-effect model using the maximum likelihood algorithm was performed with the fixed factors being group (ACHL and HEAL), legs (involved and uninvolved in the ACHL group and right and left legs in the HEAL group) anomaly, and interaction effect. Given the potential for demographic variables (height, weight, and age) confounding findings across groups, Pearson Product Moments were calculated to highlight relationships with key biomechanical variables of interest: ATRA, WBLT, horizontal impulse, RF, peak concentric power of the lower limb joints, PF isometric strength,

PF power, and SLHR height test. Where a significant relationship was found, the confounding variable was included in the linear mixed-effect model as a fixed effect. A random intercept was utilized in models with observations clustered within each participant. SPSS generates a "goodness of fit" measure (Conditional Pseudo-R Square; (Nakagawa et al., 2013)) and the adjusted ICC with measures variance associated with individuals as a proportion of the total variance (Johnson, 2014; Nakagawa & Schielzeth, 2010). Model improvement was also assessed from differences in the -2 Log likelihood of the base model and the subsequent model with a covariate present (Twisk et al., 2013). In all final models, assessments were undertaken to determine the linearity, normality, and homogeneity of the residuals (Zheng et al., 2010).

Due to non-normal distribution, non-parametric statistical analyses (Wilcoxon-Mann-Whitney) were used to compare the difference of the 5 m sprint time between the ACHL and the HEAL group.

Similarly, due to non-normal distribution, non-parametric analyses (Wilcoxon-Mann-Whitney) were used to compare the difference across legs in the ACHL group and between two groups for the height achieved during the SLHR test.

Specific associations between peak ankle joint concentric power during sprint acceleration and PF strength/power (leg press), and the maximum height achieved during the SLHR test were undertaken using the Pearson product-moment correlation coefficient or the Spearman's Rho correlation coefficient.

Chapter 4 : Results

4.1 Introduction

The first section of this chapter contains the demographic details of the participants. The next section outlines the results of the sprint acceleration performance across legs in the Achilles tendon rupture (ACHL) group and the control (HEAL) group. The third section shows the results of plantarflexor (PF) power and PF isometric strength of both groups. The fourth section outlines the findings of the Single Leg Heel Rise (SLHR) test for both groups. Finally, correlations of the findings from each test with sprint acceleration performance are included in this section.

4.2 Participants

Firstly, the recruitment process was significantly impacted due to the restrictions imposed via covid-19 related lockdown in the region. A total of thirty-two participants were recruited for the study. Of these, seventeen participants were recruited into Achilles tendon rupture (ACHL) group. One participant completed the test, but the data was excluded for from analyses due to meeting the exclusion criteria of a history of bilateral Achilles tendon rupture. Another participant terminated the five-metre (5 m) sprint test early due to pain developed in the ankle joint during the test. The sprint data of this participant was excluded from the final analysis. However, the remaining test protocols were completed by this participant without any discomfort and their results were included in the final analysis. Therefore, a total of sixteen participants were investigated for data analysis. Fifteen age-, gender and activity level-matched participants were recruited into the control (HEAL) group. All completed the full battery of tests without concerns or injury.

The Achilles tendon rupture (ACHL) group consisted of nine males and seven females. The ACHL group had a mean age, height, and mass of 33 years (± 7.8), 1.78 m (± 0.18) and 87 kg (± 44.2), respectively. The mean time since injury was 28.4 months (± 16.7 months), ranging from 14 – 59 months. Nine participants had experienced Achilles tendon ruptures in their dominant legs. Eight participants underwent surgical repair of the tendon, and eight participants were managed conservatively.

The control (HEAL) group consisted of nine males and six females with mean age, height, and mass of 32 years (± 7.3), 1.74 m (± 0.25) and 74 kg (± 22.4) respectively. There was no

significant difference for age and height between ACHL and HEAL groups. The ACHL group had significantly greater body mass ($p < 0.05$) than the HEAL group. However, all the test results were normalized by body weight for data analysis, no confounding effect was expected. 81% of the ACHL group had returned to recreational level sports including rugby, football, netball, cricket, Australian football, tennis, squash, and ultimate frisbee. Only 56% had returned to their pre-injury level of sports. The demographic details of all participants are displayed on Table 4.1.

The results from the questions regarding individual rehabilitation exercise elements are displayed in Table 4.2. There was considerable variation in the number of individuals partaking in typical elements of an Achilles tendon rupture rehabilitation programme. Of note, 33% of participants had undertaken strengthening exercises with weights. All participants received physiotherapy input for rehabilitation post injury. Concerning satisfaction with rehabilitation programme, 83% indicated they were satisfied. 41% of participants experienced a disruption to rehabilitation due to Covid-19 related restrictions.

The scores from the self-perceived subjective questionnaires for the ACHL group are shown in Table 4.3. Participants scored a mean total score of 89.7 (Standard deviation (SD) = 7.8) for the Ankle and Foot Outcome Score (AFOS), ranging from 74.6 - 97.5 across five subscales. For the Achilles Tendon Total Rupture Score (ATRS), participants reported a mean score of 74/100 (SD = 20.4). The mean score of the Psychological Readiness to Return to Sport Questionnaire was 56 (SD = 18.7).

Table 4.1 Demographic Data of Participants

	Achilles Tendon Rupture (ACHL) Group	Control (HEAL) Group
Gender (Count)		
Total	16	15
Male	9	9
Female	7	6
Ethnicity (Count)		
NZ Pākehā	6	9
NZ Māori	3	0
Pacific	1	0
Asian	2	2
Other European	3	4
Caribbean	1	0
Age		
Mean (SD)	33 (4)	32 (4)
Male Mean (SD)	34 (3)	32 (4)
Female Mean (SD)	31 (5)	32 (4)
Range	25 - 38	25 - 38
Height (m)		
Total Mean (SD)	1.78 (0.1)	1.74 (0.1)
Male Mean (SD)	1.84 (0.1)	1.79 (0.1)
Female Mean (SD)	1.71 (0.1)	1.68 (0.1)
Weight (kg)		
Mean (SD)	86.8 (19.8) *	74.3 (13.3)
Male Mean (SD)	98.7 (18.0) *	82 (8.7)
Female Mean (SD)	71.5 (7.3)	63 (10.1)
Dominant Side (Count)		
Right	13	14
Left	3	1
Time since Injury (months)		
Mean (SD)	29 (17)	-
Male Mean (SD)	37 (18)	
Female Mean (SD)	20 (5)	
Range (Months)	14 -59	
Management (Count)		
Surgical	8	-
Conservative	8	-
Return to Sports (Count)		
Yes	13 (M = 89%, F = 71%)	-
No	3	-
Return to Sports at pre-injury level (Count)		
Yes	9 (M = 44%, F = 71%)	-
No	7	-

Note: * indicates statistically significant difference between groups ($p < 0.05$). M = Male, F = Female

Table 4.2 Questions Regarding Rehabilitation Exercise Elements of Achilles Tendon Rupture Group

Received Rehabilitation Consisting of		
	Range of Movement Exercise	83%
	Body Weight Strengthening	67%
	Resisted Strengthening (with Weights)	33%
	Balance Exercise	67%
	Plyometric Exercise	58%
	Sports Specific Training	50%

Table 4.3 Self-Perceived Ankle Function Subjective Questionnaires for the Achilles Tendon Rupture Group

		Mean Score (SD)
AFOS	Total (/100)	89.7 (7.8)
	Subcategories (/100)	
	Pain	91.0 (14.2)
	Symptoms	84.0 (11.2)
	Activities of Daily Living (ADLs)	97.5 (4.2)
	Sports, and Recreational Activities	83.8 (12.1)
	Quality of Life	74.6 (16.9)
ATRS	Total (/100)	74.0 (20.4)
Psychological Readiness to Return to Sports (/60)		56.2 (18.7)

Note: AFOS = Ankle and Foot Outcome Score. ATRS = Achilles Tendon Total Rupture Score

Table 4.4 shows mean values of the Weight Bearing Lunge Test (WBLT) and the Achilles Tendon Resting Angle (ATRA). For the WBLT, a significant interaction effect ($p < 0.05$) showed that the involved leg (mean = 8 cm) demonstrated 3 cm (31%) shorter distance than the uninvolved leg (mean = 11 cm) in the ACHL group. Similarly, for the ATRA, a significant interaction effect ($p < 0.05$) showed that the involved leg (mean = 52°) showed 9° (19%) greater ankle resting angle (towards dorsiflexion) than the uninvolved leg (mean = 43°) in the ACHL group.

Table 4.4 Mean data (SD) for Weight Bearing Lunge Test (WBLT) and Achilles Tendon Resting Angle (ATRA) in the Achilles Tendon Rupture (ACHL) Group and the Control (HEAL) Group

	ACHL Group (n = 16)			HEAL Group (n = 15)		
	Involved Leg Mean (SD)	Uninvolved Leg Mean (SD)	Difference	Right Leg Mean (SD)	Left Leg Mean (SD)	Difference
WBLT (cm)	8.0 (4.3) **	11.0 (3.0)	3.0	12.6 (3.2)	12.8 (3.0)	0.2
ATRA (degrees)	52.0 (5.4) **	43.0 (7.9)	9.0	47.1 (8.2)	46.5 (7.6)	0.2

Note: ** indicates statistically significant leg*group interaction effect ($p < 0.05$) across legs. WBLT = Weight Bearing Lunge Test. ATRA = Achilles Tendon Resting Angle

4.3 Sprint performance

The results concerning sprint performance and the kinetic variables of interest during the five-metre (5 m) sprint test are displayed in Table 4.5.

4.3.1 Sprint time

The mean 5 m sprint time for the ACHL and the HEAL group was 1.193 and 1.198 seconds (s), respectively. There was no significant difference ($p > 0.05$) between the two groups.

4.3.2 Kinetic parameters (Horizontal Impulse and Ratio of Force)

During the push-off phase, a significant ($p < 0.05$) group effect showed that the ACHL group performed 16% lower horizontal impulse (mean = 1.78 Ns kg^{-1}) than the HEAL group (mean = 2.09 Ns kg^{-1}). There was no significant ($p > 0.05$) difference across legs or an interaction effect. There was no significant ($p > 0.05$) main or interaction effects for a Ratio of Force (RF) during the push-off phase.

During the first step of the 5 m sprint test, there was no significant ($p > 0.05$) leg or interaction effects for either horizontal impulse or RF.

4.3.3 Peak Joint Concentric Power

During the push-off phase, there was no significant ($p > 0.05$) leg or interaction effects for peak joint concentric power of the ankle, knee, and hip joints.

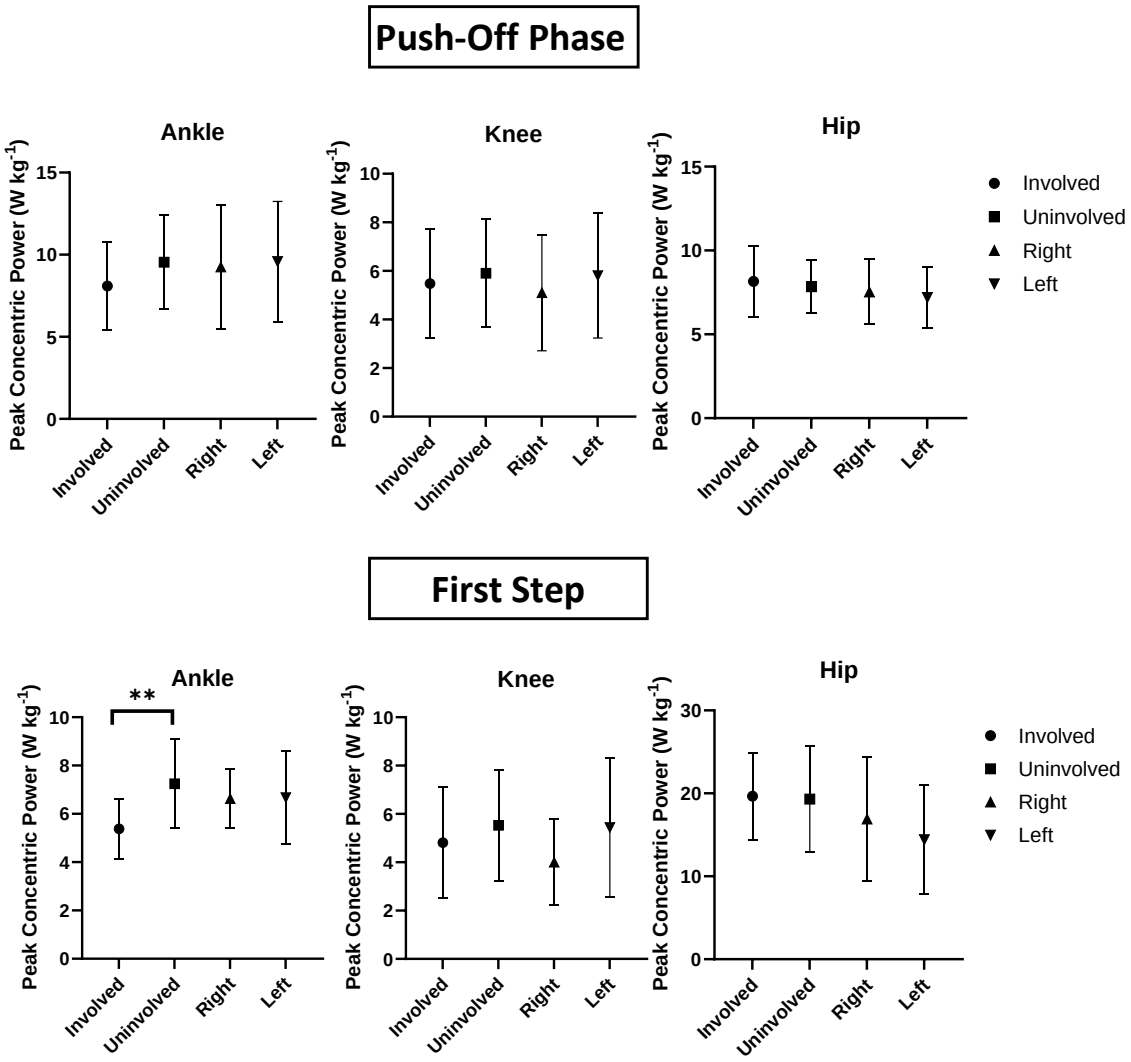
During the first step of sprint acceleration, a significant interaction effect ($p < 0.05$) showed that the involved legs (mean = 5.53 W kg^{-1}) generated 27% lower peak ankle joint concentric power (sprint) than the uninvolved legs (mean = 7.24 W kg^{-1}) of the ACHL group.

There was no significant leg or interaction effects ($p > 0.05$) for the knee and hip peak concentric joint power during the first step of sprint acceleration. Figure 4.1 displays the peak concentric power of lower limb joints across legs in the ACHL and between two groups during the 5 m sprint test.

Table 4.5 Five-Meter Sprint Acceleration Performance and Lower Limb Joint Peak Concentric Power during the Test

		ACHL Group (n = 15)		HEAL Group (n = 15)	
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
	Sprint Time (s)		1.193 (0.085)		1.198 (0.107)
		Involved Leg	Uninvolved Leg	Right Leg	Left Leg
Push Off	H. Impulse (Ns kg^{-1})	1.76 (0.4) *	1.80 (0.4)	2.05 (0.5)	2.14 (0.4)
	RF (%)	40.4 (8.8)	40.2 (8.8)	43.8 (8.5)	39.5 (8.5)
	Peak Concentric Power (W kg^{-1})				
	Ankle	7.67 (2.8)	9.11 (2.9)	9.50 (2.8)	9.82 (2.8)
	Knee	5.23 (2.1)	5.66 (2.1)	5.35 (0.5)	6.05 (0.5)
	Hip	7.78 (1.6)	7.61 (1.6)	7.63 (1.5)	7.22 (1.5)
1st Step	H. Impulse (Ns kg^{-1})	0.79 (0.1)	0.88 (0.1)	0.82 (0.1)	0.90 (0.1)
	RF (%)	29.6 (3.6)	32.3 (3.6)	30.7 (3.5)	32.0 (3.5)
	Peak Concentric Power (W kg^{-1})				
	Ankle	5.53 (1.8) **	7.24 (1.8)	6.53 (1.7)	6.55 (1.7)
	Knee	4.82 (2.2)	5.53 (2.2)	4.00 (2.1)	5.26 (2.1)
	Hip	20.12 (7.1)	19.31 (6.7)	16.82 (1.7)	14.91 (1.7)

Note: * indicates significant difference between groups ($p < 0.05$). ** indicates leg*group interaction effect ($p < 0.05$). ACHL Group = Achilles tendon rupture Group. HEAL Group = Control Group. H. Impulse = Horizontal Impulse, RF = Ratio of Force: the ratio of horizontal ground reaction force over the resultant ground reaction force during stance phase.



Note: ** indicates a significant leg*group interaction effect ($p < 0.05$).

Figure 4.1 Peak Concentric Power of Ankle, Knee, Hip Joints in the Involved and the Uninvolved legs in Achilles Tendon Rupture (ACHL) Group and Right and Left Legs in the Control (HEAL) Group during the Push-Off and the First Step of Sprint Acceleration

4.4 Plantarflexor Isometric Strength and Power

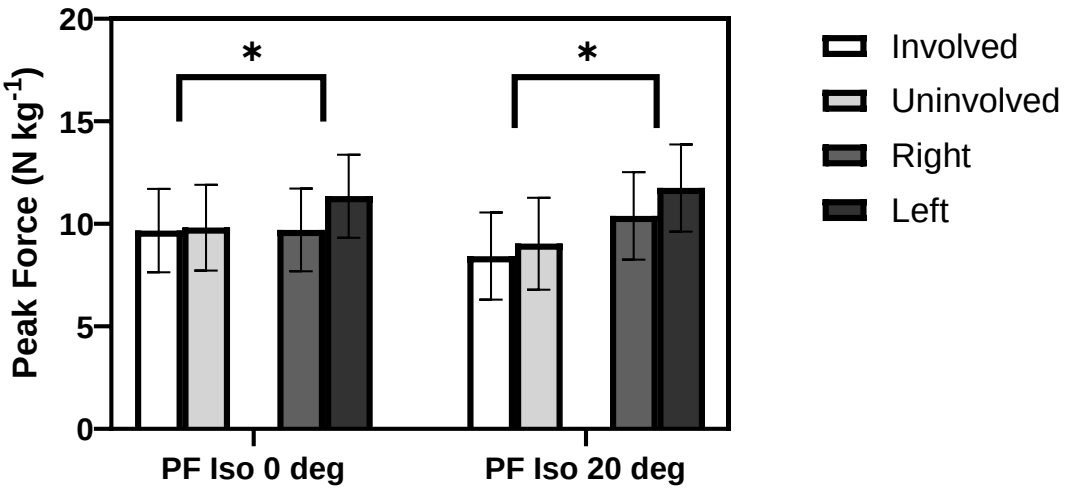
The results of PF power and isometric strength at 0° and 20° are shown in Table 4.6. For the isometric PF strength at 0°, a significant ($p < 0.05$) group effect showed that the ACHL group (mean = 9.8 N kg^{-1}) had a 7% strength deficit compared to the HEAL group (mean = 10.5 N kg^{-1}). There was no significant ($p > 0.05$) leg or interaction effect. Similarly, for the isometric PF strength at 20°, a significant ($p < 0.05$) group effect showed that the ACHL group (mean = 8.7 N kg^{-1}) had a 22% strength deficit compared to the HEAL group (mean = 11 N kg^{-1}). There was no significant ($p > 0.05$) leg or interaction effect (Figure 4.2).

In respect of PF power (leg press), a significant ($p < 0.05$) interaction effect showed that the involved legs (mean = 5.1 W kg^{-1}) performed 17% lower than the uninvolved legs (mean = 6.2 W kg^{-1}) in the ACHL group.

Table 4.6 Plantarflexor (PF) Isometric Strength at 0 degree and 20 degrees and Power of the Involved and the Uninvolved Legs in the Achilles Tendon Rupture (ACHL) Group and Right and Left Legs in the Control (HEAL) Group

	ACHL Group		HEAL Group	
	Involved	Uninvolved	Right	Left
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
PF Iso 0° (N kg^{-1})	9.7 (2.0) *	9.8 (2.1)	9.7 (2.1)	11.4 (2.1)
PF Iso 20° (N kg^{-1})	8.4 (2.1) *	9.0 (2.2)	10.4 (2.1)	11.4 (2.1)
Ankle Power (W kg^{-1})	5.1 (1.7) **	6.2 (1.7)	6.7 (1.7)	6.9 (1.7)

Note: * indicates a significant difference between groups ($p < 0.05$). ** indicates a significant leg*group interaction effect ($p < 0.05$). PF = Plantarflexion. Iso = Isometric.



Note: * indicates a significant difference between groups ($p < 0.05$). PF = Plantarflexion. Iso = Isometric

Figure 4.2 Plantarflexor (PF) Strength at 0 and 20 degrees for the Involved and the Uninvolved Legs in the Achilles Tendon Rupture (ACHL) Group and Right and Left legs of the Control (HEAL) Group

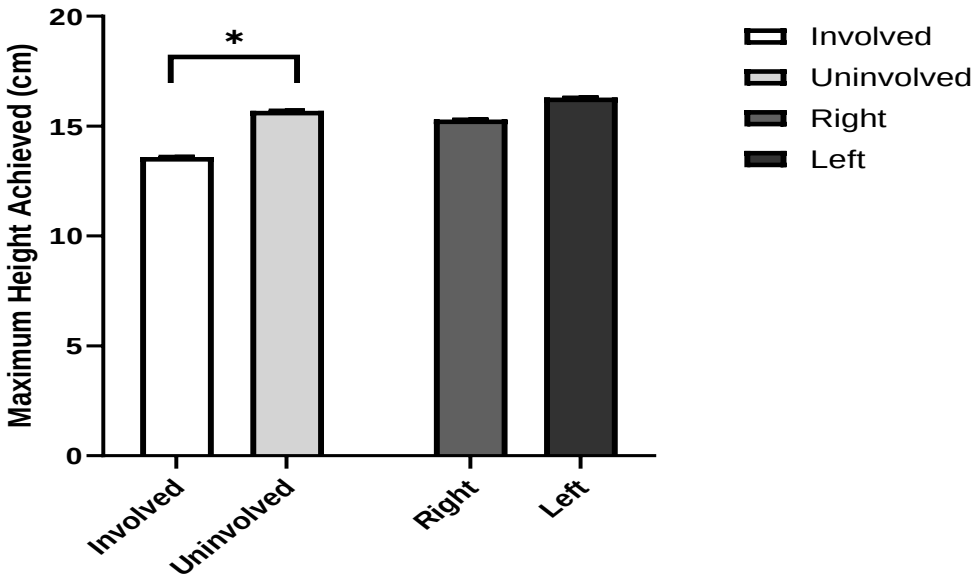
4.5 Single Leg Heel Rise (SLHR) Test

The results of the SLHR test are shown in Table 4.7. Using a non-parametric test, for the maximum height achieved, the involved leg (mean = 13.6 cm) had a significant ($p < 0.05$) 14% deficit compared to the uninvolved leg (mean = 15.7 cm) in the ACHL group. There was no significant difference ($p > 0.05$) between legs in the HEAL group. Figure 4.3 shows the maximum height achieved by the ACHL group and the HEAL group during the SLHR test.

Table 4.7 Results for the Single Leg Heel Rise (SLHR) Test for the Involved and the Uninvolved Legs in the Achilles Tendon Rupture (ACHL) Group and Right and Left Legs in the Control (HEAL) Group

	ACHL Group		HEAL Group	
	Involved	Uninvolved	Right	Left
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Height (cm)	13.6 (0.03) *	15.7 (0.03)	15.3 (0.02)	16.3 (0.02)

Note: * indicates significant difference ($p < 0.05$) across legs in the Achilles tendon rupture (ACHL) group.



Note: * indicates significant difference ($p < 0.05$) across legs in the Achilles tendon rupture (ACHL) group.

Figure 4.3 Maximum Height Achieved during the Single Leg Heel Rise (SLHR) Test for Both the Achilles Tendon Rupture (ACHL) and the Control (HEAL) Groups

4.6 Relationship between Peak Ankle Concentric Power (sprint) and Plantarflexor Isometric Strength, Power (leg press), and the Single Leg Heel Raise Test

The Pearson product moments were used to investigate relationships between peak ankle concentric power (sprint), PF muscle power (sprint), and total work achieved during the SLHR test. There was no significant relationship ($p > 0.05$) between peak PF isometric strength at both 0° and 20° and peak ankle joint concentric power during both the push-off phase and the first step of sprint acceleration.

For PF power, there was a significant positive correlation between PF power and peak ankle joint concentric power during the push-off phase ($r = 0.35$, $p < 0.05$) and during the first step ($r = 0.27$, $p < 0.05$) of sprint acceleration. There was no significant correlation ($p > 0.05$) between heel rise height achieved during the SLHR test and any of the sprint acceleration parameters.

Chapter 5 : Discussion

5.1 Introduction

The aim of the present study was to investigate sprint acceleration biomechanics during a five-metre (5 m) sprint test as well as plantarflexor (PF) strength and power in a cohort cleared for all activities post Achilles tendon rupture. It was hypothesized that there would be: (1) significantly reduced sprint acceleration performance in the ACHL group compared with the HEAL group, (2) significantly reduced concentric power of the involved ankle joint and potentially affected concentric power of the knee and hip joints during sprint acceleration. (3) a significant deficit in PF muscle strength/power and maximum height achieved during the Single Leg Heel Rise (SLHR) test in the involved leg of ACHL group may be associated with reduced ankle joint power during sprint acceleration.

The main findings of the study were: (1) No significant difference of the 5 m sprint time between the ACHL group and the HEAL group was observed. However, the ACHL group sprinted with a 16% lower horizontal impulse than the HEAL group during the push-off phase of sprint acceleration. (2) A 27% deficit in peak concentric ankle joint power was observed in the involved leg compared with the uninvolved leg in the ACHL group during the first step of sprint acceleration. No significant difference in peak concentric power at the knee and hip joints during sprint acceleration were observed. (3) Seven percent and 22% lower PF muscle strength in the ACHL group compared with the HEAL group was found at 0 and 20° PF range, respectively. No correlation was observed between PF isometric strength and sprint acceleration performance. A 17% deficit of PF power was observed in the involved leg compared with the uninvolved leg in the ACHL group and a small but significant positive correlation ($r = 0.03$) was observed between PF power and peak ankle concentric power during the push-off phase and the first step of sprint acceleration phase. Fourteen percent deficits in the maximum height achieved during the single leg heel rise (SLHR) test were found in the involved leg compared to the uninvolved leg. No significant correlation was found between the maximum height achieved during the SLHR test and any of the parameters during the sprint test. These findings are discussed in further detail below.

Firstly, the participants and their impairments such as Achilles Tendon Resting Angle (ATRA), the Weight Bearing Lunge Test (WBLT), PF muscles isometric strength and power were discussed as these findings provide some possible mechanisms which may have influenced the variables during sprint acceleration that are presented thereafter. The analysis of sprint

performance was divided into the push-off phase and the first step. The limitation and clinical implications are then presented.

5.2 Analysis of Participants

The present study consisted of participants with a mean age of 33 years in the ACHL group. The mean age in this study was younger than the mean ages of participants in the previous review studies following Achilles tendon rupture: 43 years (Lantto et al., 2015b), 37 years (Lemme et al., 2018) and 41 years (Westin et al., 2020). The younger participants in the current study were associated with the inclusion criteria of age (25 - 39 years old). This criterion was in place to reduce the possibility of age effects being apparent in the maximum effort sprinting. A mean height (1.78 meters) in the ACHL group of the current study was similar to the mean height (1.74 meters) of the cohort in Jandacka et al. (2017) who investigated the biomechanics of lower limbs during steady pace running following Achilles tendon rupture. A mean mass (86.8 kg) in the ACHL group was heavier than a mean mass of the cohort from the other studies in the similar research area (De la Fuente et al., 2022; Jandacka et al., 2017; Silbernagel et al., 2010). However, our data where appropriate were normalized to body weight for analyses. When comparing the gender ratio of participants, the current study had a ratio of 44% female to 56% male, while review papers with large cohorts identified male participants (88% (Lantto et al., 2015b) and 77.1% (Lemme et al., 2018)). Apart from our small sample size, there were no obvious reasons for the different gender ratio in our cohort. A mean time of the testing since an Achilles tendon rupture was 29.4 months in the current study, ranging from 13 - 58 months. The common timeframe investigating biomechanics of lower limbs during functional tasks following Achilles tendon rupture can range from 1 - 14 years (Brorsson et al., 2017; Carmont et al., 2015; Heikkinen et al., 2017a; Horstmann et al., 2012; Jandacka et al., 2017). Rehabilitation from the injury is often completed between 9 – 12 months with no major improvement observed in biomechanic variables of lower limbs during functional tasks and biomechanical properties of the tendons after these times (Lemme et al., 2018).

For a return to sports following an Achilles tendon rupture, the present study observed that 81% of the participants achieved a return to sports at any level. A result was comparable with the 77 - 80% return to sports rate by recreational athletes reported by Zellers et al. (2016). However, only 56% of our participants managed to return to sports at a pre-injury level, although the number was higher than the 20% return to sports at a pre-injury level for recreational athletes reported by De la Fuente et al. (2022). The low return to the pre-injury level of sports in the current study may be related to a lack of return to sports protocols or

activity modification post injury. Binkley et al. (2020) pointed out that there are no set criteria for a return to sports following Achilles tendon rupture in current literature. Unclear rehabilitation goals may affect the engagement of high intensity exercise or sports specific rehabilitation for many who sustained the injury (LaPrade et al., 2022; Lemme et al., 2018). Psychological factors can be one of the major barriers for return to sports following the injury (De la Fuente et al., 2022; Jonsdottir et al., 2023), although the current study showed the mean value of 56/60 on the Psychological Readiness to Return to Sport questionnaire. This score indicates high confidence in returning to sport (Slagers et al., 2019). Further qualitative analysis with a larger sample or establishing the return to sports criteria following an Achilles tendon rupture could assist in the return to sport process.

The rehabilitation programme of all participants was led by a physiotherapist. Although a Covid-19 related restriction disrupted the rehabilitation programme for some participants, a wide variation in the included elements was evident. As mentioned in the method section, specific questions with yes/no answers reduced the probability of recall errors. Relatedly, the findings were consistent with Zellers et al. (2019a) who reported notable differences in the intervention programme post injury. The large variation may be related to an uncertainty of the optimal management protocols. Even though some protocols are presented in the recent research papers (Massen et al., 2022; Saxena et al., 2022), a lack of details regarding the elements that require high intensities of muscle work is apparent. It can also be that physiotherapists are concerned and fearful of re-rupture if they implement exercises with high intensity.

Regarding perceived function, the participants scored a mean value of 90 out of 100 in the Foot and Ankle Outcome Score (FAOS) with subscale scores of 91 for (pain), 84 for (Symptoms), 98 for (ADLs), 84 for (Sports/Recreation), and 77 for (Quality of life). These scores indicate good to excellent levels and were consistent with mean scores reported in other studies (Akoh et al., 2021; Brorsson et al., 2017; Zellers et al., 2019b). For the ATRS, the mean score of 74/100 was lower than the 83 – 84 scores observed in review papers (Attia et al., 2023; Ochen et al., 2019). The difference in scores across these perceived function questionnaires likely reflects the emphasis of functional activities with small number of (a total of ten) items on the ATRS, while the FAOS is more extensive in the number of domains it covers.

5.3 Achilles Tendon Resting Angle (ATRA) and Weight Bearing Lunge Test (WBLT)

The involved legs had an 9° greater ankle resting angle towards dorsiflexion (DF) than the uninvolved leg in the ACHL group. Based on the equation described in by Hansen et al., (2020b), a mean of 3.4 mm elongation of the tendon was calculated in the involved legs. This finding was notably lower than the 12 - 18 mm mean tendon elongation, using an ultrasound image, reported in the review paper by Diniz et al. (2020), and hence may lead one to suggest that there was a small deficits across legs observed in tests such as the Weight Bearing Lunge Test (WBLT), PF muscle strength/power, and sprint acceleration performance.

For the WBLT, the involved legs had 30% shorter distance compared to the uninvolved legs. The similar result was observed by Bąkowski et al. (2017) and Kiedrowski et al. (2022) who reported 10 – 26% shorter distance in the involved legs than the uninvolved legs 2 - 3 years post injury. In the current study, a shorter distance with the WBLT and greater DF range in ATRA in the involved legs were observed. These findings suggest that the involved leg had a probable elongation of the Achilles tendon post rupture at rest but reduced ankle DF range in weight bearing position under load. Koshino et al. (2024) pointed out that the different structures in the ankle joint are being tested between weight bearing and non-weight bearing positions. The findings in the current study may suggest either a restriction of DF range due to other structural (bone, subtalar joint, ligaments, or capsule) limiting factors or stiffer MTU of the PF muscles under load, which was reported in previous studies (Barfod et al., 2015a) using an isokinetic dynamometer following an Achilles tendon rupture.

5.4 Analysis of Plantarflexor Muscle Isometric Strength and Power

The current study compared the peak PF isometric force following Achilles tendon rupture at 0° and 20° plantarflexion for both legs in the ACHL and the HEAL groups. No significant difference between the involved and the uninvolved legs in the ACHL group was observed at both plantarflexion angles. These findings were in contrast to the results from the literature (Don et al., 2007; Geremia et al., 2015; Horstmann et al., 2012; Jallageas et al., 2013; McNair et al., 2013; Möller et al., 2002; Mullaney et al., 2006; Orishimo et al., 2018; Porter et al., 2014; Talbot et al., 2012; Willits et al., 2010) which has shown a general trend of lower (10 - 34%) peak PF strength in the involved leg compared with the uninvolved legs following an Achilles tendon rupture. However, a direct comparison of the results can be challenging due to a large variability of study protocols (Backer et al., 2019). Of these testing protocols, Mullaney et al. (2006) and Orishimo et al. (2018) used a similar protocol to the one employed in the current

study by examining the peak isometric PF strength across legs at 20°, 10° of dorsiflexion (DF), neutral and 10°, 20° plantarflexion, but using an isokinetic dynamometer in a seated position. Both groups of authors reported no significant difference of peak PF torque across legs at 20° and 10° DF, and at neutral, whereas 17 - 20% and 27 - 34% deficits were observed in the involved legs at both 10° and 20° plantarflexion range, respectively. The findings of the current study agree with the results of Mullaney et al. (2006) and Orishimo et al. (2018) for the neutral ankle angle, but not at 20° plantarflexion position. Reduced peak PF force production at end (inner) range of plantarflexion was often reported following Achilles tendon rupture due to active insufficiency of the PF muscles, particularly in the presence of aforementioned elongation of the tendon coupled with shorter PF muscle fascicles post tendon rupture (Baxter et al., 2018; Khair et al., 2022; Orishimo et al., 2018). As mentioned above, the estimated tendon elongation observed in the involved leg of ACHL group was in the lower end of the range reported in a recent review (Diniz et al., 2020). Hence, a smaller structural remodeling of the PF muscles post injury may have contributed to little difference in maximal strength across legs.

A significant group effect indicated that the ACHL group performed significantly lower peak isometric PF strength than HEAL group both at 0° (7%) and 20° (22%). Mixed results have been reported for the difference in PF strength between the uninvolved leg of the Achilles tendon rupture group and a leg of the control group. For example, Lantto et al., (2015a) observed a 12% deficit in PF strength in the uninvolved leg of the tendon repaired group compared with the healthy group 14 months post Achilles repair surgery, although the deficit has reduced to 2.4% across legs when the test was repeated 10 years later. In contrast, no significant difference for peak isometric PF strength between the uninvolved leg of the Achilles tendon rupture group and the control group has been reported by De la Fuente et al. (2022). Reduced PF muscle strength of the uninvolved leg in the current study may be explained by a reduced general activity level. In the current study, 19% of the participants in the ACHL group had not returned to sporting activities and 44% of the participants have not returned to sports at pre-injury level. Reduced level of activities or inactivity has been correlated with PF muscle atrophy and strength (Manini et al., 2007).

Regarding the PF power utilizing the leg press, the results showed a significant interaction effect with the difference of 17% across legs in the ACHL group only. This finding was similar to 14 - 20% deficits of PF strength at higher joint angular velocities (180 - 240 deg/sec) using an isokinetic dynamometer in previous papers (Hurmeydan et al., 2020; McNair et al., 2013; Möller et al., 2002; Talbot et al., 2012; Willits et al., 2010). In addition to such deficits, Wang et al. (2013) reported 25% reduced rate of force development in the PF muscles of the involved

leg compared with the control group during a maximal isometric PF contraction following Achilles tendon rupture. It is possible that the rate of firing of motor units and atrophy of the anaerobic fibres in the PF muscles of the involved legs is responsible for the PF muscle power (Maffiuletti et al., 2016)

5.5 Analysis of 5 m Sprint Performance

To our knowledge, the present study was the first to investigate the performance of maximal five-meter (5 m) sprint following an Achilles tendon rupture. Therefore, no direct comparison of the results is available with the previous literature.

5.5.1 5 m Sprint Time

There was no significant difference for 5 m sprint time observed between the ACHL group and the HEAL group. The finding did not support the initial hypothesis of slower 5 m sprint time in the ACHL group compared to the HEAL group. The result was surprising as the literature stated that even 0.2 – 0.3 seconds (s) time difference between the groups can find a significant difference due to the nature of the maximum speed testing (Comfort et al., 2012; Macadam et al., 2019; Wild et al., 2018). No significant time difference between the two groups in the current study may be associated with the difficulty of identifying the difference in 5 - 10 m sprint time with the similar demographics and level of physical activities of the participants as previously reported by Comfort et al. (2012). However, these findings may not expose the potential underlying mechanical deficits described in the previous paragraphs following Achilles tendon rupture. The result highlights that the other kinetic or kinematic variables should be included to investigate the effect of the injury during the functional activities. In addition, future study with a longer sprint distance may find a difference in the sprint time.

5.5.2 During the Push-Off Phase of the 5 m Sprint Test

Horizontal impulse and RF were selected for further investigation of the performance of sprint acceleration due to a significant inverse correlation (r = - 0.61) with the 5 m sprint time (Slawinski et al., 2017). The ACHL group sprinted with 16% lower horizontal impulse than the HEAL group during the push-off phase, although there was no significant difference across legs in the ACHL groups. The findings supported our hypothesis of lower sprint acceleration performance in the ACHL group compared to the HEAL group. The horizontal impulse observed

in the HEAL group (mean = 2.09 Ns kg^{-1}) was comparable with the results by Slawinski et al. (2017), who reported values of 2.07 and 2.59 Ns kg^{-1} during the push-off phase from a three-point start and a false start, respectively. In contrast, Kraan et al. (2001) and Shinohara et al. (2018) reported higher horizontal impulse (3.41 - 3.57 Ns kg^{-1}) during the push-off phase from a standing start. The inconsistent values between the studies may be associated with the different demographics of participants. The current study consisted of recreational sports participants (mean age = 33 years) with mixed gender compared with young (mean = 21 - 22 years) males only participants (Kraan et al., 2001) and young male sprinters with the mean 100 m personal best time of 10.91s (Shinohara et al., 2018).

Regarding RF during the push-off phase, no significant differences across legs or the groups were observed with 40% and 42% in the ACHL and the HEAL group, respectively. This finding rejected our initial hypothesis. The proportion of horizontal force to resultant force were slightly higher in the current study than found in previous studies, which reported 38% from a split start (Bezodis et al., 2020), and 36% and 28% from a three-point start and a false start, respectively (Slawinski et al., 2017). The different values between studies may be attributed to the different calculation method for the RF value. The original method described by Morin et al. (2011) averaged the GRF over multiple steps throughout sprint acceleration phase. However, in the current study, GRF data were collected during the push-off phase and the first step only; due to the limited number of built-in force plates in the testing lab. The RF values have been shown to linearly decrease with each step throughout the sprint acceleration phase due to a gradual decrease in horizontal force production (Bezodis et al., 2019b). Therefore, higher RF values were expected in the current study compared to previous studies which used the original calculation method. Another reason for the different values between the studies may be associated with the different testing protocols. Both Bezodis et al. (2017) and Slawinski et al. (2017) instructed the unfamiliar sprint start techniques on the testing day, whereas in the current study, no specific instructions were given other than using a split start, which was a familiar technique to the participants. The adverse effects of providing new cues or skills in short notice on the RF values has been previously acknowledged (Bezodis et al., 2017).

During the push-off phase, the ACHL group sprinted using reduced horizontal impulse compared with the HEAL group but the RF values between the groups were similar. The respective findings suggests that the ACHL group either produced reduced resultant GRF or had a shorter foot contact time compared with the HEAL group. The finding of the current study may suggest an inferior acceleration performance during the push-off phase in the ACHL group compared to the HEAL group based on the studies (Ciacci et al., 2017; Čoh et al., 2017; Slawinski et al., 2010) which have reported a superior sprint acceleration performance by elite

sprinters was associated with increasing foot contact time to develop a large force during the push-off phase. However, further kinetic, and spatio-temporal analysis will be required to understand the exact reason for the reduced horizontal impulse observed in the current study. As previously mentioned, the production of GRF can depend on starting posture, and technical ability, and the force production capacity of lower limbs (Frost & Cronin, 2011). It is possible that the reduced horizontal impulse in the ACHL group may be associated with the starting posture or technical ability of the push-off phase. The influence of starting posture on force production during the push-off phase has been previously reported by Kugler and Janshen (2010) who noted lower and more forward leaning starting body posture can improve orientation and output of horizontal force during the push-off phase. Several other studies (Macadam et al., 2019; Salo & Bezodis, 2004; Slawinski et al., 2017) have reported a larger horizontal impulse from a lower centre of mass (COM) from a crouching start compared with a standing start. In addition to body positions, foot placement can influence horizontal force production and RF during the push-off phase. Cronin et al. (2007) and Slawinski et al. (2017) both observed a larger force production from a split and a false start compared with a parallel start. Placing the back leg away from the COM would increase the ankle joint plantarflexion angles to produce more horizontally orientated force (Bezodis et al., 2019b). It is also logical to consider that increased distance between feet during a split or a false standing start would support the lower COM and a forward leaning posture, and therefore an increased orientation of horizontal force. Unfortunately, no studies to date have examined the optimal starting posture or foot placement for sprint acceleration from a standing start. The lack of research in this area may be related to a large variance of starting postures between individuals (Macadam et al., 2019). The large variance of starting postures was qualitatively observed in the current study. For example, a few participants with an ice hockey background placed the back legs in an externally rotate like an ice skate sprint start. Others placed their back foot far from the COM, nearly outside of the built-in force plates boundary. One participant leant forward nearly to the level of their pelvis. Future studies on the optimal starting posture from a standing start may assist further understanding of biomechanics of a standing start and its association with optimal force production.

From the force production point of view, no significant differences in peak concentric power at the ankle, knee, and hip joints across legs and between the two groups were observed during the push-off phase of sprint acceleration. These findings rejected our second hypothesis of significant different peak joint concentric power in the lower limb joints across legs, particularly at the ankle joint. The absence of difference in peak concentric power may be explained by a large variance of lower limb joint power production between individuals

(Cavedon et al., 2019). Cavedon et al. (2019) reported up to 55% variance of the ratio of power generation across these lower limb joints between individuals from a block start. Even larger variance of the ratio of power generation across lower limb joints can be assumed from a standing start where starting posture can be more variable compared with a block start with a more consistent foot placement (Debaere et al., 2015; Macadam et al., 2019). Hence, the deficit of ankle joint power production may not have been evident during the push-off phase of sprint acceleration in the current study. The kinematics of the ankle joint may explain another possible reason for no deficits in power output across legs during the push-off phase. A compensatory mechanism of adjusting ankle joint range due to a shifted operating length-tension curve has been previously reported during walking and running following the Achilles tendon rupture (Jandacka et al., 2017; Staudle et al., 2022). These studies reported a smaller deficit of PF peak strength in a more dorsiflexed range following the injury compared with the strength deficit at plantarflexion range. Therefore, it is possible for the involved leg to produce a similar amount of ankle joint power by adjusting ankle joint range to a new optimal operating range at the start of sprint acceleration. These thoughts are speculative as kinematics and spatiotemporal parameters were outside the scope of the current study. Further analyses of these parameters to investigate the mechanism of reduced horizontal impulse during the push-off phase of sprint acceleration is recommended.

5.5.3 During the First Step of 5 m Sprint Test

The current study observed no significant difference for horizontal impulse during the first step between the involved and uninvolved legs in the ACHL group and between the ACHL and the HEAL groups. The current study showed a mean of 0.83 and 0.86 Ns kg^{-1} in the ACHL and the HEAL group, respectively. These findings were lower than the results reported by Frost and Cronin (2011) and Kawamori et al. (2013), but in line with 0.77 Ns kg^{-1} reported by Macadam et al. (2019). As previously acknowledged, differences in participant demographics and starting techniques may explain the discrepancies between studies. The participants in the current study consisted of recreational athletes with a mean age of 32 years, while Frost and Cronin (2011) included younger (mean = 22.1 years) participants. A split standing start in the current study was likely to be associated with the lower horizontal impulse than a parallel standing start used in Kawamori et al. (2013). Approximately 24% higher horizontal impulse from a parallel start compared with a split start due to extended foot contact time during the first step to compensate for lower horizontal force produced during the push-off phase (Frost & Cronin, 2011).

For the RF values, no significant differences across legs or between the two groups were observed in the current study. The current study showed 31% and 32% of the RF values in the ACHL and the HEAL group, respectively. These values were lower than the RF of 46% during the first step of sprint acceleration reported by Lockie et al. (2012) and Stavridis et al. (2019), although young (mean = 22.6 years) competitive team sports athletes and high-level sprinters in these studies may explain the higher RF values compared with the current study.

A possible reason for no significant difference in the sprint acceleration parameters during the first step across the legs in the ACHL group and between the two groups may be related to the kinematic compensatory mechanisms. For example, Bezodis et al. (2015) identified a positive relationship between horizontal force and touchdown distance of foot in relation to the COM. A similar correlation ($r = 0.54$) between these two variables were also observed by Wild et al. (2018) who compared the biomechanics of a sprint start between sprinters and rugby union players. These authors found the superior horizontal force production and the increased touchdown distance in relation to the COM from sprinters during the initial three steps of sprint acceleration compared with rugby players (Wild et al., 2018). Furthermore, a significant positive correlation ($r = 0.73$) between the RF values and ankle dorsiflexion during the first step of sprint acceleration was reported by King et al. (2022). The kinematics of lower limb joints or spatiotemporal parameters during the first step were outside the scope of the current study. As for the first step of the sprint start, additional kinematic analyses are recommended to further understand the potential compensatory mechanism of restoration of horizontal impulse and RF during the first step of sprint acceleration following an Achilles tendon rupture.

Despite no difference in horizontal impulse and RF during the first step, the current study observed that the involved leg of ACHL group had a 27% deficit ($p < 0.05$) of peak ankle joint concentric power compared with the uninvolved leg during the first step. This finding supports the second hypothesis of the current study for during the first step of sprint acceleration. A deficit of peak ankle joint concentric power during the first step was expected and was generally comparable with the previous findings during other functional tasks following an Achilles tendon rupture. For example, Willy et al. (2017) and Sun et al. (2020) observed a similar deficit (12 - 16%) of peak ankle joint concentric power and joint reaction force at the ankle joint during running (2.4 - 3.2 ms^{-1}) following an Achilles tendon rupture. Similarly, Brorsson et al. (2017) and Powell et al. (2018) found between 15 - 20% deficit of ankle joint concentric power in the involved leg during a countermovement jump (CMJ) and hopping tasks post injury. The different deficits in ankle joint power between these studies and current study may be related to the difference in physical demand and joint angular velocity required at the ankle joint during the tasks (Powell et al., 2018; Sun et al., 2020). The concentric ankle joint

power observed in this study (5.5 - 9.8 W kg^{-1}) during the sprint test was higher than the ankle joint power output (5.2 - 7.1 W kg^{-1}) reported during a drop CMJ by Powell et al. (2018). Such difference of power output between the tasks may explain the larger deficit of ankle concentric power in the current study compared with the others (Brorsson et al., 2017; Jandacka et al., 2017; Powell et al., 2018; Sun et al., 2020; Willy et al., 2017).

A deficit of ankle joint power during sprint acceleration following an Achilles tendon rupture may be associated with a structural remodelling of the PF muscles to compensate for the elongated tendon post injury (Baxter et al., 2018; Khair et al., 2022). The greater ATRA angles observed in the involved leg in the current study would suggest the presence of probable tendon elongation in the ACHL group, although the elongation was likely to be small. As a result, the injury may have shortened fascicles of PF muscles and compromised the overall PF power output (Khair et al., 2022). Furthermore, high demand at the ankle joint during the first step of sprint acceleration has been previously reported from a block start (Aeles et al., 2018; Debaere et al., 2015; Lai et al., 2016; Pandy et al., 2021; Schache et al., 2014; Schache et al., 2019). The ankle joint has been reported to contribute to 67% and 50% of the entire COM acceleration in a horizontal and vertical direction, respectively, during the first step of sprint acceleration (Debaere et al., 2015). To produce such high power at the ankle joint, gastrocnemius and soleus muscles were found to undergo a significant shortening of their muscle fibres during the first step of sprint acceleration (Lai et al., 2016). However, it should be considered that the PF MTU undergoes a stretch-shortening cycle during the first step of sprint acceleration to amplify the force production (Aeles et al., 2018; Lai et al., 2016). Other studies reported reduced stiffness (20 - 80%) of the tendon and reduced capacity of energy storage (11 – 27 %) of the PF MTU following Achilles tendon rupture (Barfod et al., 2015a; Ivanac et al., 2021; McNair et al., 2013), which would significantly compromise the total force production during the first step of sprint acceleration.

Peak concentric power at the knee and hip joints during the first step were not significantly difference across legs and between the two groups. Increased knee joint power has been reported in the presence of reduced ankle concentric power in the involved legs during hopping and running following an Achilles tendon rupture (Powell et al., 2018; Sun et al., 2020; Willy et al., 2017). No significant difference in peak concentric power in the lower limb joints during the first step may be associated with the ratio of power output across lower limb joints. The current study observed an approximately 2.5 to 3 times larger peak concentric power production at the hip joint than the ankle joint during the first step from a standing start. The similar findings were observed by Slawinski et al. (2022) who reported higher contribution by thigh segments to kinetic energy of the COM compared to leg/foot segments from a standing

start. However, the findings were significantly different from the biomechanics of a block start where ankle joint contributes over a half of the entire COM acceleration during the first step (Debaere et al., 2015). One of the key differences between a standing and a block start is the position of the COM during the first step. The higher COM from a standing start, may reduce the torque required at the ankle joint during the first step of sprint acceleration, particularly in a vertical direction, compared to a block start (Johnson et al., 2010; Kraan et al., 2001; Macadam et al., 2019; Wild et al., 2018). Therefore, the hip joint may have contributed more to the propulsive force of the COM than the ankle joint in a similar biomechanical pattern of the mid to end phase of sprint acceleration when body is in a more upright position (Morin et al., 2015; Pandy et al., 2021).

5.6 Analysis of Relationship between Plantarflexor Strength/Power (leg press) and Peak Ankle Joint Concentric Power (sprint)

Concerning the correlation between PF muscle strength and peak ankle joint power during sprint acceleration, no relationship was observed between these two variables. This rejected our hypothesis of the correlation between PF muscles strength and peak ankle joint power during the 5 m sprint test. The different types of PF muscle actions, dynamic and isometric contraction, during the 5 m sprint and the PF muscle strength test, respectively, may explain the absence of the correlation between the two variables. James et al. (2024) reported a lack of agreement between dynamic and isometric testing to quantify maximal muscle strength with functional movement. These authors stated that the difference between dynamic and isometric muscle actions may be related to separate neuromuscular domains, a presence/absence of the stretch-shortening cycle and connective tissue stiffness during the two forms of testing. Although an isometric maximal muscle strength test has been shown to be reliable (James et al., 2024), dynamic maximal muscle strength test may have demonstrated a correlation between the PF muscle strength and peak ankle joint power during the 5 m sprint test.

A low to moderate correlation ($r = 0.27 - 0.37$) was found between PF muscle power (leg press) and peak ankle joint concentric power during the push-off phase and the first step. The findings supported our final hypothesis of a significant correlation between these variables. The findings matched a significant correlation ($r = - 0.63$) between PF power in the calf raise test and a 10 m sprint time found in a previous study (Hebert-Losier et al., 2023). However, the calculated small correlation coefficient indicates a low level of variance associated with the respective variables. Hence, their contribution is questionable. Despite a significant correlation

and a difference across legs in the ACHL for PF power (leg press) and peak ankle joint concentric power (sprint) during sprint acceleration, there was no difference for overall sprint acceleration performance across legs in the ACHL and between the two groups except in the horizontal impulse during the push-off phase. These findings may indicate that the ACHL groups have adopted different compensatory strategies to maintain the horizontal force production during the push-off and the first step, and rectified the loss of joint ankle joint power after the first step of sprint acceleration before reaching 5 m. Further kinetic and kinematic analysis of full 5 m length will assist the understandings of compensatory mechanism for reduced ankle joint power.

5.7 Analysis of the Single Leg Heel Rise Test and its Association with Peak Ankle Joint Concentric Power (sprint)

The current study observed a 14% deficit in the maximum height achieved in the involved leg compared to the uninvolved leg. Similar deficits of 16 - 24% in the maximum height achieved were reported in previous literature (Carmont et al., 2017; Powell et al., 2018; Silbernagel et al., 2010; Willy et al., 2017). The probable tendon elongation observed with the ATRA in this study may explain the deficit with the maximum height achieved in the involved leg due to probable shortening of fascicles in the PF muscles following the tendon rupture (Khair et al., 2022).

The current study found no significant correlation between maximum height achieved during the SLHR test and any of parameters during the 5 m sprint test. This was not a surprising finding as the energy systems associated with the SLHR test are likely different to the speed of muscle contraction required during sprint acceleration (Sara et al., 2021). It may be logical to believe that the reduced height achieved in the involved leg during the SLHR test affects the kinematics at the ankle joint during the 5 m sprint test. Future kinematic analysis during the 5 m sprint test may show a relationship with the deficit observed in the SLHR test following Achilles tendon rupture.

5.8 Limitation of the study

There are several limitations to be considered. Firstly, due to the availability of equipment such as force plates and the space in the testing lab, the analysis of sprint acceleration was limited to kinetics during the push-off and the first step from a static position. The biomechanics of the lower limbs will be different beyond the second step of sprint acceleration or from

different standing start techniques. An additional study on kinematics during the same phase as well as beyond the second step of sprint acceleration may highlight compensatory mechanisms following Achilles tendon rupture. The testing environment was also different from the participants' normal sporting settings. Hence, the kinetic values during sprint acceleration would likely be different depending on the surface or footwear

Another limitation involved the PF strength test protocol. It is difficult to select the right testing method due to a wide range of published testing protocols utilized in studies on Achilles tendon rupture. An instrumented supine leg machine was used to measure strength, and an isometric protocol was chosen for its accuracy and ease. Therefore, it is acknowledged that dynamic concentric and eccentric muscle testing may have provided a more extensive assessment and a closer representation of muscle action during the 5 m sprint test. However, the equipment for these testing protocols is not generally available in clinics or commercial gym. Similarly, the SLHR test required a linear displacement transducer that was linked to a computerised data acquisition system. The cost of such equipment in the clinical setting can be an issue, although interestingly a recently developed app-based measurement system has been shown to be reliable and valid test (Fernandez et al., 2023).

The data analysis in the HEAL group in the current study was conducted with right and left leg as opposed to a more common comparison between dominant and non-dominant legs in other literatures. Moraux et al. (2013) showed a significant difference in PF muscle strength between dominant and non-dominant legs in healthy population. The current study acknowledged a possibility of different outcomes if the collected data was analysed with dominant and non-dominant legs. However, majority of studies (Haddad et al., 2023; Petrovic et al., 2021; Vaisman et al., 2017) showed no significant asymmetry in PF muscle strength and leg power between the legs. Furthermore, there was only one participant with left leg dominance in the HEAL group. Therefore, it is unlikely to yield different result from the findings in the current study.

Consideration must be given to the cohort assessed who were recreational athletes. Compared to elite athletes, such a cohort may have quite different motivation, intensity in their training and the games/sports that they play. It could be argued though that the recreational athlete needs more attention than they are given currently. They often do not have the resources nor the luxury of time to focus sufficiently on their rehabilitation compared to competitive/elite athletes. Another related limitation was the lack of uniformity in the initial hospital treatment and the rehabilitation program undertaken by participants. Regarding the latter, there were multiple physiotherapists from different private practices, hence programs had different elements (strength, ROM, functional exercises) that were focused upon in

varying degrees. Financial limitations restricted a standardised program being implemented, and it would also have lengthened the time for recruiting participants considerably.

5.9 Summary and Conclusions

The main purpose of this study was to investigate the effects of an Achilles tendon rupture on sprint acceleration performance post injury.

Firstly, Achilles tendon rupture did not affect the 5 m sprint time. The finding was surprising as a slower sprint time in the ACHL group was hypothesized. The hypothesis was based on well-documented changes related to PF muscle atrophy and insufficient healing of the tendon. Except for a 16% deficit in horizontal impulse during the push-off phase in the ACHL group compared to the HEAL group, there was no significant difference in kinetic parameters, horizontal impulse, and Ratio of Force (RF) observed between the involved and the uninvolved legs in the ACHL group and between the ACHL and the HEAL groups, except for a 16% deficit in horizontal impulse during the push-off phase in the ACHL group compared with the HEAL group. Although the ACHL group showed an inferior sprint performance during the push-off phase, the reduced performance was rectified beyond the first step to achieve the same mean 5 m sprint time. Kinetic analysis beyond the first step may provide a better understanding of biomechanical changes/compensations in the latter steps that were responsible.

Secondly, a 27% deficit in peak ankle joint concentric power during the first step of sprint acceleration was observed in the involved leg compared with the uninvolved leg. Despite such a large deficit, no significant difference in peak concentric power at the knee and hip joints was observed across legs and between the two groups. These findings suggested that the ACHL group may have adopted a compensatory mechanism associated with kinematic or spatiotemporal parameters to maintain the horizontal force production and overall sprint acceleration performance. Further study including kinematics and spatiotemporal parameters is recommended. The results also highlighted limitations of performance-based measurement in research and perhaps the importance of including multiple variables to capture the full understanding of the effect of the injury on the biomechanics during the functional activities. In the current study, limited sample size did not allow a more complex modelling approach with multiple random and fixed effect variables to be undertaken.

A significant group difference showed that the ACHL group performed 7% and 22% lower PF strength at 0° and 20° plantarflexion range respectively, compared with the HEAL group. However, no association was found between these deficits and peak ankle concentric power

during sprint acceleration. These findings may suggest the potential contribution of general reduced activity level in the group leading to a bilateral deficit in the PF muscles. A significant interaction effect showed that the involved legs had 17% deficits in PF muscle power (leg press) compared to the uninvolved legs, and such deficit may have been partly responsible for the significant correlation with ankle joint peak concentric power during the push-off phase ($r = 0.35$), and during the first step ($r = 0.27$) of sprint acceleration. post injury. As these correlation coefficients were a low level, and hence contributed only a small portion of the total variance in the sprint variables.

Finally of note, a fourteen percent deficit in maximal height achieved during the single leg heel rise (SLHR) test was observed in the involved leg compared to the uninvolved leg. This finding provided further evidence that PF muscle function related properties remain affected long after the end of rehabilitation. There was no significant correlation found between the maximum height achieved in the SLHR test and any of the parameters during the 5 m sprint test.

5.10 Clinical Implications

Although an Achilles tendon rupture did not affect the overall sprint acceleration performance, peak ankle joint concentric power during the sprint test and PF muscle strength/power were significantly compromised post injury. Given a large deficit in ankle joint power observed during sprint acceleration and the leg press test, these findings may guide the healthcare providers to address an inclusion of power training or exercises with high intensity at the ankle joint during the rehabilitation process.

The present study highlighted a large variation in rehabilitation programmes despite the covid-19 related restrictions. This observation may be associated with a lack of consistency in published management protocols. Future studies focused on consensus statements and recommendations for the rehabilitation programme may improve the consistency of interventions post injury and potentially improve the overall outcome.

5.11 Future Research

Potential future research projects were found from the current study:

1. The inclusion of a kinematic analysis of lower limb joints during the sprint acceleration performance following an Achilles tendon rupture will be a valuable addition of the present study. A kinematic analysis would provide a deeper understanding of other potential compensatory mechanisms adopted during sprint acceleration by the Achilles tendon rupture group.

2. A study with the same protocol but over a longer distance with longer built-in force plates may capture a more complete picture of the biomechanics of lower limbs through the entire sprint acceleration phase following an Achilles tendon rupture.

3. The development of comprehensive rehabilitation protocol following Achilles tendon rupture may assist healthcare providers in improving the quality of service and to achieve better return to sports rate. Due to the larger deficit in ankle joint power observed, a rehabilitation programme involving power training of plantarflexor muscles may improve performance in high intensity activities. The development of the clear return to sports criteria following the injury may also lead to better pathways and goals for rehabilitation.

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Appendices

Appendix A: Ethics Approval

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

21 October 2021

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re Ethics Application: **21/318 The effect of Achilles tendon rupture on the ankle joint mechanics during an initial acceleration phase of sprinting from a split standing start**

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 21 October 2024.

Non-Standard Conditions of Approval

1. Update the Information Sheet from 7 days to 14

2. In the advert exchange to word 'subjects' to 'participants'

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

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.
8. 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: tomu.hiratsuka@gmail.com; hannah.wyatt@aut.ac.nz

Participant Information Sheet

The effect of Achilles tendon rupture on the ankle joint mechanics during an initial acceleration phase of sprinting from a split standing start

Date Information Sheet Produced:

19/8/2021

An Invitation

My name is Tomu Hiratsuka. I am a physiotherapist and Masters student at the Health and Rehabilitation Research Institute, Faculty of Health and Environmental Sciences, School of Clinical Sciences at AUT. I would like to invite you to participate in our project called "*The effect of Achilles tendon rupture on the ankle joint mechanics during an initial acceleration phase of sprinting from a split standing start*". This research project will help me achieve my qualification of a Masters in Health Science. Your participation in this study is voluntary and will not affect your ability to access healthcare service in future. You may withdraw from the study at any point without any consequences.

What is the purpose of this research?

The purpose of this project is to examine the effect of Achilles tendon ruptures (1-5 years post injury) on sprint acceleration performance using a 5-metre (5 m) running test. Calf muscle strength deficit has been commonly reported following the tendon ruptures and such deficit may affect the ability to sprint as the calf muscle group plays an important role during the activity. Therefore, it is important to understand how the injury may impact the sprint performance and the biomechanics of entire lower limbs. The findings of this research may be used for publication in an international journal. The results of the research may also be presented at national and international physiotherapy and sports medicine conferences. However, should you choose to participate, you will not be identifiable in any research outcomes.

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

You have responded to an advertisement or been informed verbally of this study which directed you to make contact with myself, Tomu Hiratsuka. You will have met either of the following criteria;

Achilles tendon rupture group:

You will have had an Achilles tendon rupture 1 – 5 years ago. You will have been discharged from medical care and have returned to activities involving running or sprinting without restrictions. You may be excluded from this study if you have any known neurological disorder, any current/previous injuries which may impact your ability to perform 5 m running safely, if you are currently receiving physiotherapy service for this injury, or if you have been taking oral steroid for over the last six months.

Control group:

You will have no history of significant lower limb injuries including Achilles tendinopathy and have been actively participating in activities involving running or sprinting. You may be excluded from this study if you

have any known neurological disorder, any current/previous injuries which may impact your ability to perform 5 m running safely or if you have been taking oral steroid for over the last six months.

How do I agree to participate in this research?

You will be required to complete a written consent form prior to your participation in this study on the testing day. The test session will be scheduled once you have agreed to participate in study.

Your participation in this research is voluntary (it is your choice). 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 you removed or allowing it to continue to be used. However, once the findings have been produced, a removal of your data may not be possible.

What will happen in this research?

If you agree to participate, you will be asked to attend one session at the Biomechanics Lab, Health and Rehabilitation Institute AUT North Shore Campus, Akoranga Drive, Northcote, Auckland (see the attached map). The testing consists of four sections: 1) 5 m running, 2) ankle range of motion assessment, 3) a single leg heel raise test, 4) calf muscle strength and power testing. The whole session will take approximately 60-90 minutes to complete. Before the test begins, you will be asked to complete a consent form for this study and written questionnaires relating to your lower limb function.

1) 5 m running - You will be asked to perform running for 5 m from a static standing start. After several attempts, you will be asked to progressively increase your running speed only if you feel comfortable to do so. Reflective markers will be placed on your body which will be tracked by motion capture cameras during the sprint start (Please see the figure 1). Two force plates and timing gates will additionally be used to data during your running performances. You will be asked to perform 5 m running for a minimum of five successful trials for each leg. Subsequently, the starting position will be relocated back by your leg length to assess your first step of your sprint on the force plate. A minimum of five successful trials will be recorded for each leg. Sufficient breaks will be provided between each sprint.

Figure 6.1 Placement of Reflective Markers

2) Achilles tendon resting angle and ankle range of motion assessment - Your ankle range of movement will be measured using a biometric electric goniometer and a standard goniometer while you are resting on plinth.

3) A single leg heel raise test – You will be asked to stand on a 10^{o} incline board on one leg with your knee straight and raise your heel as high as you can at a rate of 30 heel rises per minute. The test will be completed once you fail to keep up with the pace or to lift your heel more than 2cm. The maximum height raised and repetition will be recorded for each leg.

4) Calf muscle strength and power test - You will be asked to lie on a supine leg press machine (see figure 2 below) and perform isometric calf raise and toe jumps on the machine with one leg. A force plate will be attached to the leg plate to measure the force and power of your calf muscles. You will be asked to perform three attempts on each leg for each test.

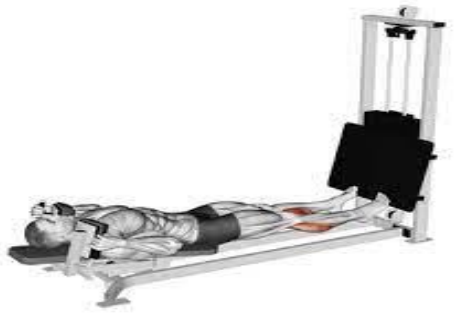

Figure 6.2 Supine Leg Press Machine

What are the discomforts and risks?

There are no significant risks associated with the tests. You may experience some discomfort with running test if you do not participate in physical activities or play sports on a regular basis. Sufficient time will be provided for a warm-up and familiarization of the test. The test is designed to replicate running performance during your sporting activities, and you should not experience anything greater than what you would experience when you play sports.

How will these discomforts and risks be alleviated?

You will be able to stop and/or withdraw yourself from this study at any point if you experience greater discomfort than anticipated. The primary researcher is a practising physiotherapist who has appropriate medical knowledge and skill to assess and manage any symptoms should you develop them and require any assistance during test.

What are the benefits?

Participating in this study will provide you with information regarding your running performance, your calf strength as well as your overall lower limb performance during sprinting. Any deficits in sprint performance, calf strength or ankle range of movement will be identified, and you could use this information to improve your lower limb function further. This information may also help to guide management and rehabilitation protocols in future. This study is a part of Masters thesis and your participation will help me to achieve a qualification of a Masters in Health Science.

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 (ACC), providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

When you enter the study, you will be given an identification code and your name will not be used on data/records collected. The consent form will contain both your name and identification code, and this will be stored securely under lock and key at the School of Clinical Sciences, AUT North Shore Campus. Only the primary researcher and his supervisors will have access to this form. Your identification will be concealed in any research outputs.

What are the costs of participating in this research?

There are no costs associated with participation in this study. The test session is up to 90 minutes and you will receive a small token of appreciation for your time and participation.

What opportunity do I have to consider this invitation?

You will have up to 4 weeks to consider this invitation. We will contact you 7 days after you receive this information sheet. If you require more time, please let us know.

Will I receive feedback on the results of this research?

A summary of the study results as well as a copy of individual test results will be sent to you via post or email upon completion of the study and data analysis unless you indicate otherwise on your consent form.

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, Peter McNair, *peter.mcnair@aut.ac.nz*, +64 9 921 9999 ext 7143

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

Tomu Hiratsuka, AUT University North Shore Campus

Ph: 0223960234

E: tomu.hiratsuka@gmail.com

Project Supervisor Contact Details:

Professor Peter McNair

Email: *peter.mcnair@aut.ac.nz*

Approved by the Auckland University of Technology Ethics Committee on 21 October 2021**, AUTEC Ethics Reference number 21/318.**

VOLUNTEERS REQUIRED!!

ACHILLES TENDON RUPTURE & HEALTHY SUBJECTS

A study to examine the effect of Achilles tendon ruptures on 5-metre running

- This is part of a physiotherapy research project to investigate the effect of Achilles tendon rupture on lower limb joint mechanics during 5-metre running.

For Achilles tendon ruptured participants

- Participants with Achilles tendon rupture on one side of leg within 1 – 5 years are required and invited to apply. Please do not hesitate to contact even if your injury is under 1 year but interested to participating in this study, we will be able to contact you again once you reach 1 year from your injury to see if you are still interested.
- Participants must have been cleared and returned to all the activities and discharged from all medical care and rehabilitation before participating in this study.
- Participants must be able to understand written and spoken English and must be aged 25-39 years.
- Participants **must not** have any known neurological conditions or over 6months of oral steroid use. Other than Achilles tendon ruptures, participants **must not** have any other known bone, joint or muscle conditions which may impact your ability to perform 5-metre running.

For healthy participants in the control group

- Healthy participants with no history of significant lower limb injuries and aged between 25-39 years are also required and invited to apply.

Please contact me for further information

Tomu Hiratsuka
Mobile: 0223960234
Email: tomu.hiratsuka@gmail.com

Appendix D: Consent Form (Achilles Tendon Rupture Group)

Consent Form (Achilles tendon group)

Project title: **The effect of Achilles tendon rupture on lower limb mechanics during sprint acceleration from standing split stance**

Project Supervisor: Professor Peter McNair and Dr Hannah Wyatt

Researcher: Tomu Hiratsuka

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 19/8/2021.
- ○ 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 do not suffer from previous notable lower limb injuries other than an Achilles tendon rupture, nor have neurological or cardiovascular conditions, or other injuries/conditions which may impair my physical performance in the activities indicated in the information sheet.
- ○ I am not currently taking oral steroids and have not ever taken them for longer than 6 months.
- ○ I agree to take part in this research.
- ○ I am happy to be contacted should another study related to Achilles tendon injury be undertaken in the future.
- ○ I wish to receive a summary of the research findings (please tick one): Yes○ No○
- ○ I wish to have a summary of the research findings sent to the clinic I received medical care for this injury (Please tick one): Yes ○ No ○ Name of the clinic: _____

Participant's signature: .....

Participant's name: .....

Participant's Contact Details (if appropriate):

.....

.....

.....

.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 21 October 2021, AUTEC Ethics Reference number 21/318.

Appendix E: Consent Form (Control Group)

Consent Form (control group)

Project title: **The effect of Achilles tendon rupture on lower limb mechanics during sprint acceleration from standing split stance**

Project Supervisor: Professor Peter McNair and Dr Hannah Wyatt

Researcher: Tomu Hiratsuka

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 19/8/2021.
- ○ 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 do not suffer from previous notable lower limb injuries in the past 12months, nor an Achilles tendon rupture, nor have neurological or cardiovascular conditions, or other injuries/conditions which may impair my physical performance in the activities indicated in the information sheet.
- ○ I am not currently taking oral steroids and have not ever taken them for longer than 6 months.
- ○ I agree to take part in this research.
- ○ I am happy to be contacted should another study related to Achilles tendon injury be undertaken in the future.
- ○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

Participant's signature: .....

Participant's name: .....

Participant's Contact Details (if appropriate):

……..

……..

……..

……..

Date:

Approved by the Auckland University of Technology Ethics Committee on 21 October 2021, AUTEC Ethics Reference number 21/318.

Appendix F: Achilles Tendon Rupture Score (ATRS)

Achilles Tendon Total Rupture Score

Today's Date: ____/____/_____ Date of Birth____/____/_____
Name:_____

All questions refer to your limitations/difficulties related to your injured Achilles tendon. Answer every question by grading your limitations/symptoms from 0-10. Remember (0= Major limitations and 10= No limitations). Please circle the number that matches your level of limitation

1. Are you limited due to decreased strength in the calf/Achilles tendon/foot?	0 1 2 3 4 5 6 7 8 9 10
2. Are you limited due to fatigue in the calf/Achilles tendon/foot?	0 1 2 3 4 5 6 7 8 9 10
3. Are you limited due to stiffness in the calf/Achilles tendon/foot?	0 1 2 3 4 5 6 7 8 9 10
4. Are you limited due to pain in the calf/Achilles tendon/foot?	0 1 2 3 4 5 6 7 8 9 10
5. Are you limited during activities of daily living?	0 1 2 3 4 5 6 7 8 9 10
6. Are you limited when walking on uneven surfaces?	0 1 2 3 4 5 6 7 8 9 10
7. Are you limited when walking quickly up the stairs or up a hill?	0 1 2 3 4 5 6 7 8 9 10
8. Are you limited during activities that include running?	0 1 2 3 4 5 6 7 8 9 10
9. Are you limited during activities that include jumping?	0 1 2 3 4 5 6 7 8 9 10
10. Are you limited in performing hard physical labour?	0 1 2 3 4 5 6 7 8 9 10

Appendix G: Foot and Ankle Outcome Score (FAOS)

Foot and Ankle Outcome Score (FAOS) Survey

Patient Name: _____
Date: _____ Affected Foot/Ankle: R L (Circle One)

Instructions: This survey asks for your opinion about your foot/ankle and helps us understand how well you are able to complete your usual activities. Answer each question by ticking the appropriate box (only one box for each question). If you are uncertain about how to answer a question, please give the best answer you can.

I. Symptoms
Answer these questions thinking of your knee symptoms during the last week.

S1. Do you have swelling in your foot/ankle?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

S2. Do you feel grinding, hear clicking, or any other type of noise when your foot/ankle moves?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

S3. Does your foot/ankle catch or hang up when moving?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

S4. Can you straighten your foot/ankle fully?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

S5. Can you bend your foot/ankle fully?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your foot/ankle joint stiffness after first wakening in the morning?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

S7. How severe is your foot/ankle joint stiffness after sitting, lying, or resting later in the day?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

II. Pain

P1. How often do you experience foot/ankle pain?
□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

What amount of foot/ankle pain have you experienced the last week during the following activities?

P2. Twisting/pivoting on your foot/ankle

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P3. Straightening foot/ankle fully

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P4. Bending foot/ankle fully

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4))

P5. Walking on a flat surface

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P6. Going up or down stairs

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P7. At night while in bed

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P8. Sitting or lying

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

P9. Standing upright

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

III. Function, daily living

This section describes 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 foot/ankle.

A1. Descending stairs

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A2. Ascending stairs

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A3. Rising from sitting

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A4. Standing

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A5. Bending to the floor/pick up an object

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A6. Walking on a flat surface

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A7. Getting in/out of car

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A8. Going shopping

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A9. Putting on socks/stockings

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A10. Rising from bed

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A11. Taking off socks/stockings

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A12. Lying in bed (turning over, maintaining foot/ankle position)

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A13. Getting in/out of bath

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A14. Sitting

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

A15. Getting on/off toilet

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

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

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

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

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

IV. Function, sports, and recreational activities

This section describes your ability to be active on a higher level. For each of the following activities, please indicate the degree of difficulty you have experienced in the last week due to your foot/ankle.

SP1. Squatting

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

SP2. Running

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

SP3. Jumping

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

SP4. Twisting/pivoting on your injured foot/ankle

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

SP5. Kneeling

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

V. Quality of Life

Q1. How often are you aware of your foot/ankle problem?

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

Q2. Have you modified your lifestyle to avoid activities potentially damaging to your foot/ankle?

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

Q3. How much are you troubled with lack of confidence in your foot/ankle?

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

Q4. In general, how much difficulty do you have with your foot/ankle?

□ Never (+0) □ Rarely (+1) □ Sometimes (+2) □ Often (+3) □ Always (+4)

Appendix H: Injury-Psychological Readiness to Return to Sport Scale

Injury-Psychological Readiness to Return to Sport Scale

INJURY-PSYCHOLOGICAL READINESS TO RETURN TO SPORT SCALE

Please rate your confidence to return to your sport on a scale from 0 – 100.

0 = no confidence at all
50 = moderate confidence
100 = complete confidence

1. My overall confidence to play is _____

2. My confidence to play without pain is _____

3. My confidence to give 100% effort is _____

4. My confidence to not concentrate on the injury is _____

5. My confidence in the injured body part to handle the demands of the situation is _____

6. My confidence in my skill level/ability is _____

Add total and divide by 10 = _____

Appendix I: Questions Regarding Rehabilitation Programme for Achilles Tendon Rupture Group

Questions Regarding Rehabilitation Programme for Achilles Tendon Rupture Group

a. Did you receive physiotherapy input for rehabilitation of Achilles tendon rupture? Y/N

b. Please state how many physiotherapy session you received per month in the first 6 months of rehabilitation ____ sessions per month
c. Has your rehabilitation been disrupted due to Covid-19 or any other reasons in the first 6 months from your injury? Y/N
d. Did you perform a significant amount of ankle range of movement exercises in the first 6 months of rehabilitation? Y/N
e. Did you perform a significant amount of body weight strengthening training in the first 6 months of rehabilitation? Y/N
f. Did you perform a significant amount of resisted (with weight) strengthening training in the first 6 months of rehabilitation? Y/N
g. Did you perform a significant amount of balance exercises in the first 6 months of rehabilitation? Y/N
h. Did you perform a significant amount of plyometric training (jumps, hops) in the first 12 months of rehabilitation? Y/N
i. Did you perform a significant amount of through sports specific trainings/return to sports training in the first 12 months of rehabilitation? Y/N
j. How satisfied we you with your physiotherapy rehabilitation programme? Please select one - (Not Satisfied/neutral/quite satisfied/very satisfied)

Appendix J: The Data Collection Sheet used during the Testing

Achilles Tendon Rupture Data Collection Sheet

Participant Information			
Alpha Code		Date	
Age		Ethinic group	
Height	cm	Dominant leg	
Weight	kg	Ruptured side	
Sports (if applicable)		Management:	Surgical or Conservative
Cast duration and Weight bearing commencement:			

Outcome Measure	
AFOS	/140 ( )%
ATRS	/100

Sprint test					
Marker checklist					
C7, Acromions, Manubrum, T8		PSIS, ASIS, Iliac crest			
Medial and lateral condyle of knees		Medial and lateral malleolus			
Heel, 5th base of metatarsal, 1st MTP joint, between 1st-2nd MTP					
Cluster thigh and Shank					
Procedure Checklist					
Force Plate Calibration					
Marker recognition					
Static T standing, Hip movement, Squat					
Familiarization and Suboptiomal test					
Sprint from force plates	1st	2nd	3rd	4th	5th
Dominant leg behind (time)					
Other leg behind (time)					
1st step on force plates					
Dominant leg behind (time)					
Other leg behind (time)					

Ankle ROM			
Dorsiflexion		Plantarflexion	
Restng angle in prone			

Single Leg Heel Rise Test			
Familiarization			
L	Height:	Rep:	Work:
R	Height:	Rep:	Work:

Supine leg press machine test			
Strength test	Trolley starting position:		
Familiarization			
	1st	2nd	3rd
L at Neutral			
L at 20 deg PF			
R at Neutral			
R at 20 deg PF			
Rate of force development test	Trolley starting position:		
Famiriarization			
	1st	2nd	3rd
L (W)			
R (W)			