# THE ROLE OF INFRARED THERMAL IMAGING IN THE ASSESSMENT OF CHRONIC MIDPORTION ACHILLES TENDINOPATHY

By

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List of abbreviations

| Term | Abbreviation |
|---|---|
| Achilles Tendon | AT |
| Analysis of Variance | ANOVA |
| Anterior-Posterior | A-P |
| Area Under Curve | AUC |
| Asymptomatic | ASX |
| Asymptomatic Achilles Tendon | ASX_AT |
| Baseline | BL |
| Beats per minute | BPM |
| Body Fat Percentage | BF% |
| Body Mass Index | BMI |
| Body Weight | BW |
| Change in Skin Temperature | ΔTSK |
| Comma Separated Value | CSV |
| Confidence Interval | CI |
| Consolidated Standards of Reporting Trials | CONSORT |
| Control Left Achilles Tendon | CL_AT |
| Control Right Achille Tendon | CR_AT |
| Cooldown | CD |
| Cross-Sectional Area | CSA |
| Electromyography | EMG |
| Field of View | FOV |
| Ground Contact Time | GCT |
| Ground Reaction Force | GRF |
| Heavy Slow Resistance | HSR |
| Infrared | IR |
| Infrared Thermal Imaging Camera | IRC |
| Instantaneous Field of View | IFOV |
| Intraclass Correlation Coefficient | ICC |
| Laser Speckle Contrast Imaging | LSCI |

| | |
|---|---|
| Limits of Agreement | LoA |
| Magnetic Resonance Imaging | MRI |
| Minimal Detectable Change | MDC |
| Multispectral Dynamic Imaging | MSX |
| Musculotendinous Junction | MTJ |
| Non-Uniformity Correction | NUC |
| Numerical Pain Rating Scale | NPRS |
| Osteoarthritis | OA |
| Physical Activity Readiness Questionnaire | PAR-Q |
| Rating of Perceived Exertion | RPE |
| Reactive Strength Index | RSI |
| Receiver Operating Characteristic | ROC |
| Region of Interest | ROI |
| Royal London Hospital | RLH |
| Single Leg Hop | SLH |
| Skin Temperature | TSK |
| Standard Deviation | SD |
| Standard Error of Measurement | SEM |
| Stretch Shortening Cycle | SSC |
| Superficial Digital Flexor Tendon | SDFT |
| Sympathetic Nervous System | SNS |
| Symptomatic | SX |
| Symptomatic Achilles Tendon | SX_AT |
| Thermographic Imaging in Sport and Exercise Medicine | TISEM |
| Ultrasound | US |
| Ultrasound Tissue Characterisation | UTC |
| Victorian Institute of Sports Assessment - Achilles | VISA-A |
| Visual Analogue Scale | VAS |

Infrared Thermal Imaging Camera Operational definitions

| | |
|---|---|
| IR resolution | The number of pixels contained within an image. One pixel is one temperature datum point. |
| MSX technology | The combination of an infrared thermal image and a digital image to create a single infrared thermal image with skeletonised digital detail |
| Accuracy | The manufacturer stated percentage difference in a measured temperature and the known temperature of a reference source |
| FOV | The largest area that an infrared thermal camera can detect |
| IFOV | Often termed spatial resolution. An angular projection of one single pixel in the infrared image |
| Thermal sensitivity | The smallest difference in temperature that an infrared thermal imaging camera can detect over temporal noise |
| Spectral range | The wavelength range that the infrared thermal imaging camera can detect |
| Minimum focus distance | The smallest distance from an object at which the lens of the camera is able to focus |

Abstract

Infrared thermal imaging cameras (IRC) are non-contact devices that allow the capture of radiation presented in the form of colour-coded images, therefore they may provide an effective method of assessment for chronic midportion Achilles tendinopathy. Some of the features of the condition point towards regional heat change and could be reflected through surface skin temperature (TSK) change.

This thesis firstly investigated the methodological aspects of IRC's and created a robust method of Achilles tendon (AT) assessment (chapter 3). The first experimental study (chapter 4) assessed the baseline differences in TSK of the AT midportion in symptomatic (SX) and asymptomatic (ASX) individuals. It was found that no differences existed between the two. There were no differences between the symptomatic AT's (SX_AT) or ASX AT's (ASX_AT) or between the left and right limbs of control participants.

Chapter 5 assessed the TSK responses of SX and ASX individuals in response to a 15-minute treadmill running task. Significant TSK elevations were found in all groups following the task, with the control group presenting with statistically significantly hotter absolute TSK values compared to the SX_AT and the ASX_AT groups. The SX participants then completed a 12-week heavy slow resistance (HSR) rehabilitation programme before conducting a repeat of the running task. No significant differences were found between the SX_AT and the control AT's which appeared to show a normalisation of TSK response. Significant differences still existed between the ASX_AT's and the control group. The 12-week HSR programme resulted in significant improvement in symptom scores in SX individuals.

Chapter 6 assessed the TSK responses of SX and ASX individuals to a single leg hopping (SLH) task. Statistically insignificant TSK decreases were seen post-SLH task and there were no significant differences between groups. There were statistically significant between-group differences in some kinematic and kinetic variables associated with SLH. The SX participants then underwent a 12-week HSR rehabilitation programme before conducting a repeat of the SLH task. There were no between-group differences in TSK or kinematic or kinetic variables. There were statistically significant improvements in symptom, effort and pain scores following the 12-week HSR programme.

Overall, this thesis demonstrated that the FLIR ONE is an acceptable objective measurement tool for the assessment of TSK. Some thermal responses to loading tasks were

noted in the midportion of the AT in those suffering from chronic midportion Achilles tendinopathy, however the lack of differences between SX and ASX ATs meant that it would be difficult to objectively measure the progress of pathology based on TSK. Due to the success in detecting some thermal responses from the chronic AT, the tool may be used at other joints for the assessment of more reactive or acute pathologies that may display greater regional heat change, however, this warrants further investigation. HSR rehabilitation has proved successful for the management of chronic midportion Achilles tendinopathy alongside normal recreational running training regimes.

Key words: Achilles Tendon; Achilles tendinopathy; Infrared thermal imaging; Heavy slow resistance

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## Research Output

Oliver, B, Munro, A., Gerald, S., & Herrington, L. (2019). The reliability of an Achilles tendon infrared image analysis method. Thermology International, 29(4), 136–145.

Oliver, Ben, Munro, A., & Herrington, L. (2020). The effect of distance and angle of a smartphone-compatible infrared thermal imaging camera on skin temperature at the midportion of the Achilles tendon. Thermology International, 30(2), 51–57.

COVID-19 impact statement

The emergence of the COVID-19 global pandemic has had a profound effect on the data collection aspect of my PhD. As a direct result of the pandemic, I lost a total of 14 participants from the prospective studies, 6 symptomatic and 8 control. The symptomatic participants were at various stages of the 12-week heavy slow resistance programme. These participants were unable to continue the rehabilitation during the initial national lockdown due to the closure of gym facilities and the restrictions placed upon movement. Unfortunately, due to the initiation and cessation of a rehabilitation programme, these participants could not resume the rehabilitation programme as part of the study once the national lockdown was lifted due to the possible pathophysiological changes that could have occurred during that time. The control participants were either scheduled to attend for testing, or between assessment and thermal sessions. By the time national lockdown was lifted and the risk assessments had been completed for the return of post-graduate research, data analysis had already been completed due to the time limits of the PhD project. The likelihood is that the prospective studies are underpowered due to this.

# Chapter ONE

# Introduction

Achilles tendinopathy is a complex condition referring to the disorder of the Achilles tendon (AT), characterised by swelling, pain and reduced performance (D'Addona, Maffulli, Formisano, & Rosa., 2017; Kragsnaes et al., 2014; Maffulli, Sharma, & Luscombe., 2004). Epidemiological research in UK running populations has shown a lifetime Achilles tendinopathy prevalence of 57% (O'Neill, 2016), which is comparable to the 52% found in a study by Kujala et al. (2005) in male Finnish endurance athletes. O'Neill (2016) found that 69% of the symptoms affected the midportion of the tendon, compared to only 16% insertional and 15% affecting both sites. Another study reported that 13.6% of Dutch marathon runners had an AT injury in the year before a marathon, with 7.7% having pain or dysfunction 1 month prior to the run and 7.6% sustaining a new injury of their AT during the marathon itself (Van Middelkoop et al., 2008).

The anatomical orientation of the AT allows efficient dissipation of force and efficient elastic recoil capabilities to optimise movement efficiency (Benjamin et al., 2004; Pierre-Jerome et al., 2010). Studies have suggested that during running, these peak AT forces can exceed 5 times body weight (BW) per foot contact (Willy et al., 2016). Almonroeder, Willson, & Kernozek (2013) estimated that similar peak AT forces up to 6.6 times BW pass through the tendon per foot contact at a speed of approximately 3.7m/s. Lagas et al. (2020) reported that the incidence of Achilles tendinopathy increased from 4.0% to 7.4% from 10 km to full marathon participants. As recreational running athletes typically cover moderately large weekly distances, sometimes in excess of 30 km per week (Rasmussen et al., 2013), their ATs are likely to be subjected to high amounts of peak force and subsequent accumulative load, with little time to recover.

Repetitive loading has been linked to architectural tendon damage, particularly to collagenous structures (Galloway, Lalley, & Shearn, 2013; Maffulli et al., 2004). With little time to recover, the repetitive excessive load may cause negative pathological change to the structure of the AT and can leave the athlete with chronic tendon pain, a condition known as Achilles tendinopathy (Cook et al., 2016; Dakin et al., 2018; Klatte-Schulz et al., 2018).

Achilles tendinopathy is not just a cause for concern in distance runners. It is prevalent in sports other than long-distance running. In track and field, it accounted for the most severe Victorian Institute of Sports Assessment (VISA-A - a questionnaire measuring Achilles tendinopathy symptoms) scores in one masters event, affecting 5/7 (71.4%) jumping athletes (Longo et al., 2009). In basketball, Achilles tendinopathy incidence was found to be 19.7%

(Florit et al., 2019). It accounted for 96% of all AT disorders in elite male football (Gajhede-Knudsen et al., 2013). Achilles tendinopathy incidence was found to spike during pre-season, which typically includes a rapid increase in loading, following a period of de-loading. Cumulatively, Achilles tendinopathy led to a higher total absence from matches and training than any other ankle injury in rugby union (Sankey et al., 2008). In particular, front row forwards were found to have the highest prevalence and it is possible that the high cumulative loads that they experience could account for this. Front row forwards may weigh in excess of 130kg and could be exposed to loads in excess of 7000N per stride, per leg during sprinting. This is in addition to controlling or assisting with the generation of the 9090N generated by a scrummaging pack of rugby union forwards, in a plantarflexed position mimicking explosive movements of plyometric jumping activity (Flavell et al., 2013)

An incidence of Achilles tendinopathy of 5.63 per 1000 has been reported in United States military personnel (Owens et al., 2013). Of these, 91.3% were not deployed overseas due to the condition and the highest percentage of those to suffer from the injury were over the age of 50.

The condition affects only 2.16-2.35 per 1000 people across general practices (Albers et al., 2016; De Jonge et al., 2011). 34.6% of these cases were related to sports activity with no further explanation as to whether this was due to a specific mechanism of injury, or if the remaining 65.4% of people did not engage in regular exercise. This equated to an approximate 2.5% of people suffering from the condition compared to 57% identified in a running population Kujala et al. (2005), which could suggest that load exposure is a large factor in prevalence.

As mentioned previously, the high loading forces caused by long-distance running have been shown to exceed 5 times BW (Willy et al., 2016). In long or high jump athletes, AT load can be as high as 2578 ± 633N during a static vertical jump (approx. 3.4xBW) (Bayliss et al., 2016). This would not account for the loads experienced in the run-up to their competitive efforts. Basketball specific movements have been shown to produce force as high as 6.6 ± 1.2xBW (Sinclair & Sant, 2017). In contrast to the high AT loads seen in athletic activity, walking at 1m/s has been shown to produce AT forces between 1.7 and 3.4xBW per stride (Finni et al., 2013; Keuler et al., 2019)

Based on these statistics, it is reasonable to hypothesise that a major risk factor for higher incidences of Achilles tendinopathy is excessive load, in activities that require repeated use of the stretch-shortening cycle (SSC) (Sobhani et al., 2013), but currently, the underlying biomechanical and physiological reasons for the condition are still debated.

The AT plays a vital role in the SSC, which is the pre-activation of a Gastrocnemius-Soleus musculotendinous unit to stiffen the musculotendinous junction (MTJ), followed by an eccentric phase, isometric transition and then a concentric phase of contraction (Debenham, Travers, Gibson, Campbell, & Allison, 2016; Turner & Jeffreys, 2010). The AT acts as a compression spring during impact activity where it compresses and stores energy before releasing this stored energy during the concentric phase of a movement (Hobara et al., 2008; Kummel et al., 2017; Obst et al., 2013).

However, unlike a true spring, it demonstrates a negative work loop (Zelik & Franz, 2017). Work refers to muscle performance in a single cycle of contraction and the work loop is represented by the area between the lengthening and shortening sections of a length vs force curve (Wilson & Lichtwark, 2011). A negative work loop refers to the active lengthening of the musculotendinous unit when absorbing force, to store elastic energy in the AT and reduce the positive work necessary for the muscle fibres, which overall generates a net negative work over the cycle of loading and unloading. This means more power and a more efficient musculotendinous unit (Wilson & Lichtwark, 2011; Zelik & Franz, 2017). The reason for this net negative work from the AT is due to hysteresis, defined as heat lost from the tendon divided by the energy stored in the tendon (Peltonen, 2014). The levels of hysteresis displayed by a tendon can be affected by changes to the mechanical properties, such as tendon stiffness, which in turn can change the metabolic requirements of local muscular tissue (Lichtwark & Wilson, 2005b). It is advantageous for the AT to display low hysteresis, as this would mean greater efficiency in reutilising stored energy, with less strain energy being lost through heat caused by internal friction during changes in the length of the tendon (Maganaris et al., 2008).

Variation exists within the literature on values of hysteresis for in vivo AT's depending on whether indirect or direct tendon estimates were used, ranging from 3-38% (Farris, Trewartha, & McGuigan, 2011; Lichtwark & Wilson, 2005a; Zelik & Franz, 2017). Higher values of hysteresis suggest that the AT is less efficient in returning elastic energy, as more energy from the tendon is being lost through heat. Wang et al. (2012) demonstrated that

symptomatic ATs demonstrated greater mechanical hysteresis combined with reduced tendon stiffness properties than healthy controls. Asymptomatic AT's demonstrated a significantly lower ($p=0.004$) hysteresis of 23.6 ± 5.3% compared to 28.0 ± 6.7% in symptomatic, a mean difference of 4.4% (95% CI 1.4-7.3%). The significantly ($p<0.001$) different stiffness values showed that the asymptomatic tendons had values of 132.7 ± 26.3N/mm vs 105.9 ± 19.8N/mm, a mean difference of 26.8N/mm (95% CI -35.0 to -18.5 N/mm).

Other studies investigating Achilles tendinopathy have also shown reduced tendon longitudinal and transverse stiffness properties (or increased compliance) (Arya & Kulig, 2010; Chang & Kulig, 2015; Karamanidis & Epro, 2020) and reductions in Gastrocnemius muscle stiffness properties (Morgan et al., 2019). Increased AT compliance has the potential to negatively affect the spring-like capabilities of the AT by placing more demand on the muscular component to generate force (Fletcher & MacIntosh, 2018) and thus expend more energy, creating a greater metabolic demand and reduced muscular efficiency (Ammer, 2017; Katayama & Saito, 2019; Lichtwark & Wilson, 2007). Lichtwark and Wilson (2007) demonstrated that changing the stiffness properties of the AT reduced muscular efficiency from 26% to 16% and increased the demand for muscular activation by as much as 140%. In contrast to this, work by Coombes et al. (2018) using shear wave elastography found that midportion AT stiffness was unchanged compared with healthy controls, but changes were present at the insertion. In a systematic review of tendon stiffness (Obst et al., 2018) reported that pathological AT's displayed reductions in stiffness at the muscle tendon junctions. It is clear from this research that stiffness changes can occur within the length of the AT and that it is possible that the relationship between stiffness and hysteresis may be complex.

The link between hysteresis and AT stiffness is further complicated by the complexity of the relationship between the tendon, the musculature and the aponeurosis with each of the mechanical components varying between individuals (Lichtwark & Wilson, 2005c). It is further complicated by the relationship between the plantar flexor muscles during locomotion, with the Soleus musculature generating force and working in isolation to the Gastrocnemius despite their shared insertion (Cronin et al., 2016; O'Neill, Barry, et al., 2019). Complications aside, it is possible based on the results from these studies that stiffness of the musculotendinous unit relates closely to the amount of hysteresis displayed by a tendon and may change the underlying physiological activity of the surrounding region.

If the mechanical properties of the tendon change due to tendinopathic symptoms, then changes to the physiological properties are likely to occur (Aubry et al., 2015). Histologically, tendinopathy is usually characterised by collagen fibre degradation, inflammatory cascades, increases in the non-collagen matrix, the proliferation of an excessive number of tenocytes, neovascularisation and fluid build-up between fibres (Aubry et al., 2015; D'Addona, Maffulli, Formisano, & Rosa, 2017; Li & Hua, 2016), all of which have the potential to cause local heat changes through increased metabolic demand (Snedeker & Foolen, 2017). Further research has identified local blood flow changes in those with Achilles tendinopathy both locally and more regionally (Knobloch et al., 2006; Kubo et al., 2017).

Cook et al. (2016) proposed a series of pathoaetiological models of tendon pathology following on from the initial tendinopathy continuum which identified reactive and degenerative tendinopathy, as well as those in disrepair (Cook & Purdam, 2009). These models were collagenous disruption, inflammation or tendon cell response and each have their limitations, an area discussed in detail in section 2.6.1.

The work by Cook et al. (2016) highlights the complexity of the condition, particularly from a clinical perspective. Traditionally, to diagnose pathological change, Ultrasound (US) or Magnetic-resonance imaging (MRI) scans have been classed as the gold standard for diagnosis of Achilles tendinopathy, with sensitivity values of 0.72-0.87 being reported in the literature (Kainberger et al., 1990; Khan et al., 2003). US imaging is generally cheaper and easier to conduct than an MRI scan meaning that it is used more frequently for the assessment of AT disorder, however, there are limitations which are discussed in section 2.6.2.

Current evidence suggests US scan findings are not always accurate when compared with clinical symptoms (Hullfish et al., 2018). As US images are difficult to interpret and require specialised training and qualification for diagnostic purposes, and MRI scanners are too expensive, they are not often used clinically, leaving a void for a clinical tool to be developed to assess the presence of Achilles tendinopathy.

One such device that may be suitable has recently emerged in the field of sports medicine for the assessment of musculoskeletal conditions, the infrared thermal imaging camera (IRC). IRC's are non-contact devices that allow the capture of a colour-coded image, through the capture of radiation that is not part of the visible spectrum and is undetectable to the human eye. Any object that is hotter than the absolute zero (0K/ -273.15°C) emits

energy, heat in the form of electromagnetic radiation. This radiation travels through a vacuum at the speed of light and is characterised by its wavelength. Infrared thermal imaging can detect energy from the infrared spectrum (0.75-100µm), with human skin measures falling into the long-infrared range of the electromagnetic spectrum, between 7-14µm (Langemo & Spahn, 2017). The camera detects the infrared radiation and generates an electrical signal which is converted into a thermal image. Each image is made up of several pixels, with each pixel representing a temperature data point. From this thermogram, it is possible to visualise an image by viewing a colour representation of temperature distribution, as seen in figure 1.1.

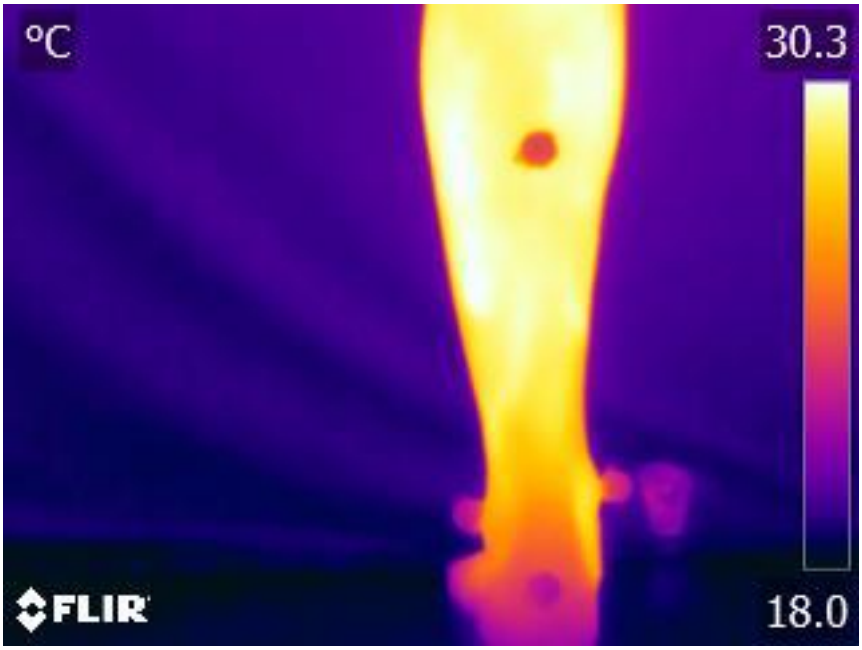



Figure 1.1: An infrared thermal image of the AT taken from a distance of 0.6m

When considering the pathophysiology and biomechanics of Achilles tendinopathy, certain characteristics of the pathology could be detected through the assessment of surface skin temperature (TSK). Inflammation, changes in intra-tendinous blood flow, neovascularisation and hysteresis have all been suggested as being linked to the condition (D'Addona et al., 2017; Knobloch et al., 2006; Wang, Lin, Su, Shih, & Huang, 2012). All of these factors could be associated with heat change. With that in mind, in the long-term IRC's may provide a novel and low-cost approach to the overall assessment and management of Achilles tendinopathy.

The novel purpose of this thesis was to evaluate the utility of IRC assessment and management of Achilles tendinopathy, leading to the following aims:

- Investigate the reliability and construct validity of IRC for the assessment of the AT
- Assess TSK of the midportion of the AT in symptomatic and asymptomatic participants at rest and in response to exercise
- Assess the response of TSK and clinical symptoms of symptomatic AT's following a rehabilitation programme

# Chapter TWO

# Literature Review

## 2.1 Chapter overview

This chapter aims to provide a detailed overview of the available literature applicable to infrared thermal imaging and Achilles tendinopathy. Firstly, the current applications of infrared thermal imaging for tendons will be discussed. This will be followed by a review of the reliability and validity of the devices, to address issues surrounding accuracy and applicability in human TSK assessment. The next section of the chapter reviews the underlying physiological and biomechanical reasons that could affect TSK change around the region of the AT. An in-depth review of the clinical assessment of the AT will be conducted. Finally, the aims of the thesis will be outlined.

## 2.2 History of infrared thermal imaging as an assessment tool for pathology

IRC's were first utilised by the military in the mid-20$^{th}$ century (Szajewska, 2017). They were first used in the medical field in 1959 for the detection of heat over arthritic joints (Ring, 2004). According to the review by Ring (2004), infrared thermal imaging was first used with success for enthesopathy in the 1980s, in both the hand and at the tendons of the elbow. Infrared thermal imaging was not used to assess the AT until the 21$^{st}$ century, but it was utilised in the equine sciences with success for the Superficial Digital Flexor Tendon (SDFT) (Basile, Basile, Ferraz, Pereira, & Queiroz-Neto, 2010; Birch, Wilson, & Goodship, 1997; Çetinkaya & Demirutku, 2012; Eddy, Snyder, & Van Hoogmoed, 2001; Redaelli et al., 2014; Soroko, Henklewski, Filipowski, & Jodkowska, 2013; Soroko & Howell, 2018; Turner, 1998; Turner, Pansch, & Wilson, 2001). The SDFT is considered similar to the human AT due to its energy storage and release capabilities (Patterson-Kane & Rich, 2014).

Equine infrared thermography has been shown to have excellent specificity, with values of 0.95 being reported in the literature (Soroko et al., 2013). Studies have suggested that infrared thermal imaging can detect pathology in the SDFT in horses two weeks before any clinical symptoms being apparent (Eddy et al., 2001; Turner et al., 2001). Turner et al. (2001) identified an 88% agreement rate between infrared thermal imaging and trainer opinion regarding a pathological diagnosis of 45 horses, and a 95% agreement rate with veterinarian diagnosis. Çetinkaya and Demirutku (2012) found that infrared thermal imaging was able to detect 7 cases of acute SDFT tendonitis and 4 cases of chronic, with an overall conclusion that infrared thermography is a useful tool in the assessment of equine lameness, a view which is shared by Soroko et al., (2013).

## 2.3 Thermographic assessment of in vivo tendons

The success of infrared thermal imaging in detecting tendon pathology in the equine environment has lead to increased use in human TSK measurements. Infrared thermal imaging is an emerging tool in the musculoskeletal field of sports medicine for the assessment of tendons (Binder, Parr, Thomas, & Hazleman, 1983; Meknas, Al Hassoni, Odden-Miland, Castillejo, & Kartus, 2013; Meknas, Odden-Miland, Mercer, Castillejo, & Johansen, 2008; Quesada et al., 2016; Ratajczak & Boerner, 2015; Rodriguez-Sanz et al., 2018; Rodríguez-Sanz et al., 2017; Sanz-López, Martínez-Amat, Hita-Contreras, Valero-Campo, & Berzosa, 2016; Thomas, Siahamis, Marion, & Boyle, 1992; Tumilty, Adhia, Smoliga, & Gisselman, 2019).

Thermal profiles of asymptomatic runners AT's have been assessed recently in a cohort of collegiate athletes (Tumilty et al., 2019). Over 9 weeks during the running season, there were no significant changes in AT TSK either between limbs or between weeks. Despite no significant change being found, there was a mean temperature decrease over the 9-week period during the season. Any explanation into why this temperature decrease was seen would be purely speculative and requires further research to understand, however, it was suggested that the regional hypothermia may be attributed to changes sympathetic nervous activity resulting in local microcirculation alterations, a theory which is supported by the works of Tansey & Johnson (2015). However, it is important to note that the reductions in TSK that were seen were within the minimal detectable change (MDC) of their camera, therefore could be attributed to random error.

Tumilty et al. (2019) utilised the box analysis tool in FLIR tools analysis software (FLIR Systems Inc, Oregon, US) to measure the TSK of the AT, standardising each box using dimensions of 10x40 pixels. The distal border of the box was placed at the point where colour change existed between the calcaneus and the midportion of the tendon, as judged by the rater. This method may not be reproducible when assessing the TSK response of the tendon in response to exercise within-session or between-sessions, as changes in TSK would result in the defined border between the bone and the AT changing, leading to variations in box placement. This highlights the importance of having defined anatomical landmarks as opposed to post-hoc landmarks, to reduce the chance of erroneous region of interest (ROI) placement.

Rodriguez-Sanz et al., (2017) measured the TSK of the AT's in footballers suffering from functional ankle equinus. The results of their study suggested that AT TSK differed after

exercise in those suffering from the condition compared to those without. The change in TSK (ΔTSK) between post-exercise and pre-exercise in those with ankle equinus was 1.3°C (26.6°C ± 1.92°C to 27.9°C ± 2.1°C) in the left leg and 1.6°C (26.3°C ± 1.7°C to 27.9°C ± 1.7°C) in the right leg. In comparison, those without pathology saw a ΔTSK of 3°C (26.9°C ± 1.5°C to 29.9°C ± 1.3°C) in the left leg and 2.4°C (27.5°C ± 1.9°C to 29.9°C ± 1.2°C) in the right. These results evidence that there appears to be a substantially different response between pathological and non-pathological AT's in response to treadmill running. It is also apparent that those participants without pathology experienced greater ΔTSK than those with the condition.

Quesada et al. (2016) demonstrated that AT TSK was not significantly changed following a cycling intervention, despite other areas of the body such as the anterior thigh, posterior thigh and trunk displaying significant change. Unfortunately, there is no detail as to how the ROI's were selected and placed, therefore the results of the study should be interpreted with caution.

Ratajczak & Boerner (2015) also assessed TSK of the AT from a 2m distance following the application of 1MHz and 3MHz ultrasound. It appears from the figures provided that rather than being a measure of AT temperature specifically, the ROI encompasses the entire Gastrocnemius-Soleus complex from the proximal border of the midportion of the tendon. The authors reported that there was a significant alteration in TSK for up to 10- minutes post-3MHz procedure, with a 1.1°C ΔTSK. Again, caution should be drawn when interpreting the results as the authors used paraffin oil as a coupling agent, which may have altered the emissivity properties of the skin, without stating that they corrected for this in their analysis software.

Sanz-López et al. (2016), assessed AT TSK in response to running in a control versus eccentric intervention group and found no significant changes in AT TSK. The eccentric exercise chosen was a yo-yo squat which is predominantly a quadricep dominant exercise, raising a question as to whether this would induce significant TSK change in the region of the AT. Interestingly, in the eccentric intervention group, there were reductions in absolute baseline TSK on the second and third days of running, whereas there were no significant changes in the control group. It would be expected that these absolute values of TSK would increase on consecutive days following running interventions, as the activity is associated with collagenous disruption synthesis and inflammatory responses in the musculotendinous unit for up to 72 hours post-activity (Magnusson et al., 2010) The reduction in TSK values on the

second and third day of running may fit with the altered sympathetic nervous activity described by (Tansey & Johnson, 2015), with a vasoconstrictor response altering local circulation. It could also be the case that there was an increased metabolic demand from the musculotendinous unit to recover from the exercise-induced trauma, therefore local microcirculation could be reduced to redirect blood flow the deeper tissues to supply sufficient nutrients (Lenasi, 2014).

It is unknown whether these changes were more than the MDC values as these were not reported. No significant ΔTSK differences were found between the left and right limbs in the study, but there was a significant TSK increase post running activity on all of the days, which fits with the need for the body to increase its blood flow at the level of the skin to release heat and maintain thermal homeostasis (Lenasi, 2014).

Critically, Sanz-López et al. (2016) assessed the thermographic change of the Patella tendon and Achilles tendon in response to an eccentrically overloaded Yo-Yo squat. The effect of squat kinetics and kinematics on Achilles tendon function is debatable, as acknowledged within the paper, meaning that caution must be taken when interpreting the conclusion and applying it to exercise with a greater demand on the Gastrocnemius-Soleus complex such as running or single leg hopping (McMahon, 2015). Sinclair et al. (2015) suggested that the mean peak force on the Achilles tendon during 5 repetitions of a front squat is 2.37 times bodyweight, whereas during walking at a speed of 1.62m/s, Giddings et al. (2000) suggest that 3.9 times body weight is transmitted per step. In comparison, (Lichtwark & Wilson, 2005c) measured forces between 5-6.3 times BW during a single leg hop. With greater forces, there will be an increased metabolic demand on the Gastrocnemius-Soleus complex compared to a Yo-Yo squat and would likely cause a more varied TSK response. It is also worth considering here that a symptomatic AT could display increased compliance (Chang & Kulig, 2015; Karamanidis & Epro, 2020) and function less effectively as a compression spring by losing energy via hysteresis. This would increase the work demand from the muscle component, the Gastrocnemius and Soleus, and may again result in a more varied TSK response (Wiesinger et al., 2017).

There is limited research using infrared thermal imaging for tendinopathy. Much of the research that has been conducted using thermal imaging has focused on lateral epicondylopathy. Meknas et al. (2008) demonstrated in their prospective randomised study that clear hot spots were present in elbows with diagnosed lateral epicondylopathy, yet

following surgical correction, the last resort for resolution of symptomatic tendons, these hot spots had disappeared. Lateral epicondylopathy hot spots have also been seen versus healthy controls in previous works (Binder et al., 1983; Thomas et al., 1992). Thomas et al. (1992) suggested that the TSK of the hot spots seen with lateral epicondylopathy were due to increases in sympathetic nervous system activity, a theory which has since been suggested by Tansey & Johnson (2015) and Ammer (2017), which could explain heat increase despite the chronic nature of the pathology and the assumed lack of a traditional inflammatory response.

Mangine, Siqueland, & Noyes (1987) utilised computer-aided thermography to assess Patella tendinopathy and found abnormal thermal patterns in those who were symptomatic. A resultant rehabilitation period reduced the thermal asymmetry in all 6 of the follow-up patients, with 4 participants decreasing and 2 increasing. Caution should be drawn when generalising these findings due to the small sample size.

To the author's knowledge, there is no published research relating to infrared thermal imaging of Achilles tendinopathy. This, and the lack of overall literature relating to the use of infrared thermal imaging in tendinopathy, may be due to an existing debate as to whether infrared thermal imaging is valid or reliable enough to be used as a clinical tool. Therefore, the next section will review the available literature.

### 2.4 The validity and reliability of infrared thermal imaging using the FLIR ONE

TSK assessment has historically been conducted using wired temperature devices. With the emergence of new infrared technology that is affordable, easy to use, quick to set up and requires minimal training; it is being used to a much greater extent in the field of musculoskeletal assessment. There is conflicting evidence regarding the reliability and validity of the tool, and with devices varying greatly in specification and application, it is important to clarify if they are deemed both valid and reliable. This short narrative section will seek to identify the validity, followed by the reliability of the FLIR ONE smartphone-compatible IRC.

#### 2.4.1 Validity of infrared thermal imaging

Several studies have sought to identify the validity of the FLIR ONE smartphone-based thermal imaging device, as well as other handheld devices (Bach, Stewart, Disher, & Costello, 2015; Guirro et al., 2017; Fernandes et al., 2016; James, Richardson, Watt, & Maxwell, 2014; Jaspers, Carrière, Meij-de Vries, Klaessens, & van Zuijlen, 2017; Kanazawa et al., 2016; McFarlin, Venable, Williams, & Jackson, 2015; Quesada et al., 2015; Rodrigues-Bigaton, Dibai

Filho, Costa, Packer, & De Castro, 2013; Sanchis-Sanchez, Salvador-Palmer, Codoner-Franch, Martin, & Vergara-Hernandez, 2015; Sivanandam, Anburajan, Venkatraman, Menaka, & Sharath, 2012; Wilkinson et al., 2018) An overview of the validity studies using the FLIR ONE can be found in table 2.1. and other handheld devices in table 2.2.

Table 2.1: An overview of the validity studies using the FLIR ONE IRC

| Author | N | Camera | Pixel count | Comparison | Material measured | ROI selection | Temperature value | Validity |
|---|---|---|---|---|---|---|---|---|
| van Doramalen et al. (2019) | 32 | FLIR ONE (Android) | 160 x 120 | FLIR SC305 for Diabetic foot ulcer assessment | Diabetic foot ulcers | Manual selection (circle) | Absolute TSK | Excellent Intraclass Correlation Coefficient (ICC) values (>0.9), strong agreement with Bland Altman mean differences <0.15°, strong positive likelihood ratios (>5), small negative likelihood ratios (<0.1). Sensitivity 94%, specificity 86%. Strong concurrent validity. |
| Wilkinson et al. (2018) | 159 | FLIR ONE | 160 x 120 | Laser Speckle contrast imager (LSCI) & FLIR ONE vs clinician diagnosis | TSK hand and fingers | Manual selection (box) | Absolute TSK | Good to excellent convergent validity LSCI to handheld IRC latent correlation coefficient 0.65-0.94 (95% CI 0.50, 1.00) Excellent convergent validity handheld to mobile IRC latent correlation 0.90-0.98 (0.79, 1.00) |
| Jaspers et al. (2017) | 50 | FLIR ONE | 160 x 120 | Burn wound healing | TSK of burn wounds | Manual selection (circle) | ΔTSK | Moderate concurrent validity – AUC 0.69 (95% CI 0.54, 0.84), sensitivity 46%, specificity 82% |
| Kanazawa et al. (2016) | 16 | FLIR ONE | 160 x 120 | Thermotracer TH700N | TSK of pressure ulcers | Manual selection* | ΔTSK | Excellent criterion validity 1.00 (95% CI 1.00, 1.00) |

*Indicates that the manual ROI selection shape is unknown.

Table 2.2: An overview of the validity studies using handheld IRC's

| Author | N | Camera | Pixel count | Comparison | Material measured | ROI selection | Temperature value | Validity |
|---|---|---|---|---|---|---|---|---|
| Guirro et al. (2017) | 52 | FLIR T300 | 320 x 240 | Biopsy | Breast TSK | Manual selection (freehand) | Absolute TSK | Area under receiver operating characteristic curve (AUC) 0.57 (95% CI 0.47, 0.74) for affected and contralateral AUC 0.65 (95% CI 0.52, 0.78) for affected and control Mean sensitivity 71% & 86% for affected and contralateral & control respectively Mean specificity 49% & 38% for affected and contralateral & control respectively |
| Fernandes et al. (2016) | 12 | FLIR T420 | 320 X 240 | Thermal pill | Inner canthus temperature | Manual selection (circle) | Absolute TSK | Mean bias -0.61 (95% Limits of Agreement (LoA) -1.28, 0.05) |
| Bach et al. (2015) | 30 | FLIR A305sc | 320 x 240 | Thermistor, iButton & Infrared thermometer | TSK multiple locations | Manual selection (box) | Absolute TSK | Mean bias vs thermistor at rest 0.83 (± 95% LoA 0.77), outside of a |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | priori acceptable mean bias |
| McFarlin et al. (2015) | 30 | Razr-IR Max | 160 x 120 | Skin electrode | Multiple TSK locations | Unknown | Absolute TSK | Poor criterion validity – LoA ± 1.82 at bicep, LoA ± 3.43 at the abdomen |
| Quesada et al. (2015) | 14 | FLIR E60 | 320 x 240 | iButton | Multiple TSK locations | Manual selection* | Absolute TSK | Strong correlation r=0.92 (p<0.001) at rest and good agreement, post-cycling r=0.82 (p<0.001) and post cooling r-0.59 (p<0.001) |
| Sanchis-Sanchez et al. (2015) | 145 | FLIR E60 | 320 x 240 | X-ray for bone fracture | Multiple TSK locations | Manual selection (freehand) | ΔTSK between limbs | Sensitivity 91% (95% CI 79%, 98%)<br>Specificity 89% (95% CI 80%, 94%)<br>PPV 81% (95% CI 67%, 90%)<br>NPV 95% (95% CI 88%, 99%)<br>Area under curve 0.97 (95% CI 0.95, 0.99) |
| James et al. (2014) | 14 | FLIR e40BX | 160 x 120 | Wired thermistor | TSK multiple locations | Spot | Absolute TSK | Mean bias -0.87°C, standard error of measurement (SEM) 0.53°C, correlation (r-0.45) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rodrigues-Bigaton et al. (2013) | 26 | FLIR T360 | 320 x 240 | Research Diagnostic Criteria for Temporomandibular disorder | TSK over the Temporomandibular Joint (TMJ) | Manual selection (spot) | Absolute TSK | AUC left TMJ 0.68 (95% CI 0.56, 0.79), sensitivity 58%, specificity 78%<br>AUC right TMJ 0.65 (95% CI 0.54, 0.77), sensitivity 62%, specificity 76%<br>AUC TMJ asymmetry 0.60 (95% CI 0.48, 0.72), sensitivity 49%, specificity 73% |
| Sivanandam et al. (2012) | 62 | FLIR T400 | 320 x 240 | $HbA_{1c}$ blood sample for diabetes | Multiple TSK locations | Manual selection (box) | Absolute TSK | Sensitivity 70-90%<br>Specificity 40-62%<br>PPV 53-65%<br>NPV 62-85%<br>Accuracy 56-73% |

*Indicates that the manual ROI selection shape is unknown.

It is important to consider smartphone-compatible and handheld infrared thermal imaging devices separately as their specifications differ. The limitations of other TSK measurement devices will be discussed in relation to the use of both the FLIR ONE and other handheld IRC's.

In a recent study, the FLIR ONE was found to have excellent concurrent validity when compared to a FLIR SC305 high specification handheld infrared thermal imaging camera (van Doremalen et al., 2019). The researchers found that there excellent intraclass correlation coefficient values alongside strong agreement, with values not exceeding a difference of 0.15°C. Critically, the authors did not report values for standard error of measurement (SEM) or MDC, nor were they calculable as standard deviations (SD) of absolute TSK were not reported. Whilst 0.15°C is a small deviation in human TSK, these values would truly outline whether the differences lay within measurement error of the devices.

Kanazawa et al. (2016) demonstrated that the criterion-validity of the FLIR ONE infrared thermal imaging camera was excellent, (k=1.00, 95% CI 1.00-1.00) when relative temperature difference was assessed against a Thermo Tracer TH700N. The Thermo Tracer TH700N is a 320x240 pixel infrared thermal imaging device which is routinely used in the medical field. The researcher focused on relative temperature difference which is the difference between the two values of absolute TSK, similar to ΔTSK except the values are not specifically related to baseline. It is acknowledged that the FLIR ONE cannot measure absolute TSK values accurately against other devices but assessing the relative TSK change is a valid and reliable way of tracking temperature. The results also demonstrated that using the automatic temperature scale, where the camera automatically detects the range of temperatures within FOV, is as reliable and valid as manually selecting the temperature range, making the device easier to use.

A study by Wilkinson et al. (2018) furthered the evidence for acceptable validity of the FLIR ONE when assessing relative TSK change. They assessed the test-retest reliability and convergent validity of the FLIR ONE against LSCI in the assessment of Systemic Sclerosis. There was a high latent correlation for the AUC (0.86, 95%CI 0.74,0.97). Wilkinson et al. (2018) also report excellent convergent validity between handheld and mobile thermography, with an AUC of 0.98 (95% CI 0.94, 1.00).

Overall, there appears to be excellent concurrent validity for the FLIR ONE smartphone-compatible IRC. There is a lack of evidence for criterion validity, with only one study reporting excellent findings. Clinically, as gold standard measures are complex and expensive to operate, excellent concurrent validity may be more appropriate but it should be acknowledged that the devices cannot be directly compared to gold-standard measures.

Other studies have assessed the validity of handheld devices for the use of human TSK assessment. Guirro et al. (2017) found that the FLIR T300 did not have acceptable sensitivity (71-86%), or specificity (38-49%) to be used as a diagnostic tool for the assessment of breast cancer but concluded that the device was acceptable for clinical assessment due to its high intra-rater and inter-rater reliability values, meaning that the device can track TSK consistently when compared against itself. It is important to acknowledge here that these values of sensitivity and specificity applied only to the diagnosis of breast cancer and cannot be applied to other musculoskeletal conditions where accuracy requirements may differ.

Quesada et al. (2015) assessed the validity of the FLIR E60 against an iButton for measuring skin temperature before and after cycling. Before cycling, no significant differences in skin temperature existed between the devices, however, post-cycling the infrared thermal camera under-read values of skin temperature compared to the iButtons. However, linear regression analysis revealed a strong correlation between the two methods ($r=0.92$, $p<0.001$). The Bland-Altman plots revealed that there was strong agreement between the devices pre-cycling, but the LoA were excessive post-cycling, Similarly, a strong correlation between an IRC and an iButton were found by McFarlin et al. (2015) ($r=0.87$, $p<0.001$).

Quesada et al. (2015) also assessed the validity of the camera against an iButton on a hot plate. In a dry environment, a ΔTSK of 0.5°C existed between the IRC and the iButton when the microporous tape was applied to hold the iButton in place, however, when the sensors were left uncovered no ΔTSK existed between the devices. Much of the previous work that has reached conclusions about the poor validity of IRC's has been conducted against wired devices which are fixed using tape. It could be argued that the tape creates a local microclimate which may alter the local skin temperature and is likely not a true representation of local TSK. It is important to recognise that this is a limitation to the use of wired devices, and it emphasises the difficulty in measuring human TSK accurately, possibly highlighting the need for a non-contact alternative.

Bach et al. (2015) concluded that the FLIR A305sc infrared thermal imaging camera was not valid when compared to a range of other skin temperature devices, including wired thermistors, with a mean bias (+/- 95% LoA) of 0.83°C (+/- 0.77°C), measuring absolute TSK only. The criterion thermistor and the iButton were both secured to the skin by tape. Considering the areas for skin temperature measurement were 25mm x 25mm grids, there is the potential for this tape, with no specified dimensions, to influence the measures from the neighbouring grids. Further, anatomical variation can create substantial fluctuations of skin temperature close to each other (Taylor et al., 2014), therefore measuring skin temperature 25mm away from the site of thermistor attachment may result in substantially different readings, and again may not be a fair reflection of validity.

James et al. (2014) found poor validity between the FLIR e40BX IRC and both a hard-wired and telemetry thermistor. A large bias was recorded at rest (-0.87°C), with the SEM and LoA exceeding the predetermined limits throughout testing. The correlation between the two devices was also low (r=0.45).

When IRC's have been assessed against other criterion measures for pathology, excellent validity has been found. Sivanandam et al. (2012) concluded that infrared thermal imaging had criterion validity in the early detection of type 2 diabetes, demonstrating high sensitivity (90%) and high negative predictive values (85%) with an overall accuracy of 73%. This overall accuracy proved higher than the gold standard detection measure of HbA1c (Guo et al., 2014), which assesses the level of glucose within red blood cells.

Infrared thermal imaging has acceptable criterion validity for ruling out stress fractures in emergency departments (Sanchis-Sanchez et al., 2015). The researchers proved that in the assessment of 46 fractures, the AUC value was 0.97. The sensitivity was reported as 91%, the specificity as 89% and the negative predictive value as 95% (95% CI 0.79-0.99). Critically, the authors excluded 12 patients as their temperature values in the injured areas were less than the healthy areas which introduced selection bias into the study. The authors cite the fact that patients may have applied ice but did not report these statistics. The authors assume that there would be a temperature increase with fracture due to acute inflammation, but they may have overlooked the fact that there may be the potential for vascular compromise or reduced sympathetic neural activity, which may cool the local regions of skin around the fracture site (Clement & Goswami, 2009; McKenna et al., 2013; Pretorius & Stell, 2015; Tansey & Johnson,

2015). Based on this study, it is important to highlight the need to consider reductions of TSK as well as increases in TSK when assessing pathological areas to minimise selection bias.

Denoble et al. (2010) found moderate construct validity when comparing the Meditherm Med2000 Pro infrared thermal imaging camera to X-rays in the assessment of knee osteoarthritis (OA), with a Pearson correlation coefficient R=0.59 (p=0.02). Critically, patients who presented for thermal assessment were allowed to continue with anti-inflammatory medication, which may have reduced the inflammatory cascades and possibly heat production at the knee. It is possible that the results of the study may have shown stronger validity between infrared thermal imaging and X-ray diagnosis for knee OA had a washout period for the medication been included within the experimental design. However, ethically this may have been a dilemma as it would have likely increased patient symptoms and affected their activities of daily living.

### 2.4.2 Conclusion of the review of device validity

Based upon the narrative review of the literature, it would appear that the validity of the FLIR ONE is acceptable, however, there is only a limited amount of available literature. It is also apparent that the strength of the validity changes dependent on the devices compared, therefore the concurrent validity must be considered for each comparable device. It is not recommended based on results from handheld devices that they are utilised in conjunction with wired devices in the assessment of TSK. When assessed against wired devices agreement was unacceptable, and this may be due to methodological flaws when comparing contact versus non-contact devices. A more in-depth insight into the reliability of the devices is needed to establish whether they can be used as standalone assessment tools.

### 2.4.3 Reliability of infrared thermal imaging

Having acceptable reliability when using an assessment tool is an essential factor. Intra-rater reliability indicates the reproducibility of the devices under the same experimental conditions with the same rater (Gwet, 2008). When multiple raters are used this is referred to as inter-rater reliability (Gwet, 2014). From these values, it is possible to calculate the SEM and MDC which will allow an operator to understand the error involved with the measurements and to understand what values represent true change. An overview of the reliability studies using the FLIR ONE can be found in tables 2.3 and other handheld device in table 2.4.

Table 2.3: An overview of the reliability studies using the FLIR ONE infrared thermal imaging camera

| **Study** | **Design** | **Camera** | **Method** | **ROI selection** | **TSK reported** | **Reliability** |
|---|---|---|---|---|---|---|
| Cao et al. (2018) | Cross-sectional | FLIR ONE 160x120 pixels | n=30<br>TSK of the finger<br>Acclimatisation period unknown<br>Camera 1.0m from ROI<br>Ambient room temperature unknown<br>Relative humidity unknown | Manual selection (spot) | Absolute TSK & ΔT | Repeatability ICC 0.99 (95% CI 0.99-1.00) for dominant limb ΔTSK and non-dominant limb ΔTSK, SEM and MDC unknown<br>Repeatability ICC 0.97 (95% CI 0.96-0.99) for side-to-side ΔTSK, SEM and MDC unknown<br>Mean bias ΔTSK 0.56°C (LoA -1.09°C, 2.20°C)<br>Mean bias absolute TSK 2.64°C (LoA 0.96°C, 4.32°C) |
| Wilkinson et al. (2018) | Multi-centre observational | FLIR ONE 160x120 pixels | n=159<br>TSK of the hand and finger<br>20 mins acclimatisation period<br>Camera 1.0m from the ROI<br>Ambient room temperature of 23.0 (± 2.0) °C<br>Relative humidity unknown | Manual selection (box) | Absolute TSK | Test-retest ICC 0.61 (95% CI 0.51, 0.73), SEM and MDC unknown |
| Jaspers et al. (2017) | Observational | FLIR ONE 160x120 pixels | n=50<br>TSK of burn wounds<br>Acclimatisation period unknown<br>Camera 0.5-1.0m from ROI | Manual selection (circle) | ΔTSK | Inter-rater ICC 0.99, SEM 0.17-0.22°C, MDC unknown |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Ambient room temperature 23.3 (19.8-24.8) °C<br>Relative humidity 55.2 (42.2-64.3)% | | | |
| Kanazawa et al. (2016) | Observational cross-sectional | FLIR ONE 160x120 pixels | n=16<br>TSK of pressure ulcers<br>Acclimatisation period unknown<br>Camera distance from ROI unknown<br>Ambient room temperature unknown<br>Relative humidity unknown | Manual selection* | ΔTSK | Inter-rater ICC 1.00 (95% CI 1.00-1.00), SEM and MDC unknown<br>Intra-rater ICC 1.00 (95% CI 1.00-1.00), SEM and MDC unknown |

*Indicates that the manual ROI selection shape is unknown.

Table 2.4: An overview of the reliability studies using the handheld infrared thermal imaging cameras

| Study | Design | Camera | Method | ROI selection | TSK reported | Reliability |
|---|---|---|---|---|---|---|
| **Silva et al. (2018)** | Observational Cross-sectional | FLIR E60 320x240 pixels | n=51<br>TSK of the plantar surface of foot<br>15 mins acclimatisation period<br>Camera 0.98m from ROI<br>Ambient room temperature unknown<br>Relative humidity unknown | Spot | Absolute TSK | Intra-rater ICC 0.99-1.00 (95% CI 0.99, 1.00), SEM 0.00-0.23°C, MDC 0.00-0.64°C<br>Inter-rater ICC 0.94-0.99 (95% CI 0.89, 1.00), SEM 0.08-0.73°C, MDC 0.23-2.05°C |
| Guirro et al. (2017) | Blinded cross-sectional | FLIR T300 320x240 pixels | n=52<br>TSK of the breast<br>20 mins acclimatisation period<br>Camera 2.0m for ROI<br>Ambient room temperature 22.0 (± 1.0) °C<br>Relative humidity unknown | Manual selection (freehand) | Absolute TSK | Intra-rater ICC's on affected, contralateral and control breasts 0.998 (95% CI 0.997, 0.999), SEM 0.04-0.05°C, MDC 0.11-0.15°C<br>Inter-rater ICC's on affected and contralateral breasts 0.974-0.988 (95% CI's 0.948, 0.994), SEM 0.11-0.15°C, MDC 0.30-0.42°C |
| Dibai-Filho et al. (2015) | Observational Cross-sectional | FLIR T300 320x240 pixels | n=24<br>TSK Trapezius<br>15 mins acclimatisation period<br>Camera 1.0m from ROI<br>Ambient room temperature 22 (± 2.0) °C | Manual selection line, spot & box analysis | Absolute TSK | Intra-rater line analysis ICC 0.993 (95% CI 0.989, 0.996), SEM 0.13°C, MDC 0.36°C<br>Intra-rater spot analysis ICC 0.96 (95% CI 0.93, 0.97), SEM 0.34°C, MDC 0.94°C |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Relative humidity 50% | | | Intra-rater box analysis ICC 0.95 (95% CI 0.92, 0.97), SEM 0.16°C, MDC 0.44°C<br>Inter-rater line analysis ICC 0.92 (95% CI 0.87, 0.95), SEM 0.43°C, MDC 1.19°C<br>Inter-rater spot analysis ICC 0.91 (95% CI 0.85, 0.94), SEM 0.48°C, MDC 1.33°C<br>Inter-rater box analysis ICC 0.89 (95% CI 0.83, 0.93, SEM 0.44°C, MDC 1.22°C |
| Sanchis-Sanchez et al. (2015) | Observational cross-sectional | FLIR E60 320x240 pixels | n=145<br>TSK multiple locations<br>10 mins acclimatisation period<br>Camera 0.8m from ROI<br>Ambient room temperature 24.6 (± 1.4) °C<br>Relative humidity 40.6 (± 9.1)% | Manual selection (freehand) | ΔTSK | Intra-rater reliability ICC 0.92 (95% CI 0.83, 0.96), SEM and MDC unknown<br>Inter-rater reliability ICC 0.95 (95% CI 0.9, 0.97), SEM and MDC unknown |
| Rossignoli et al. (2015) | Observational cross-sectional | FLIR T335 | n= 24<br>TSK multiple locations<br>Acclimatisation period 10 mins<br>Camera 2-3m from ROI<br>Ambient room temperature unknown<br>Relative humidity unknown | Manual selection | Absolute TSK | ICC's 0.39-0.79 between 28 anatomical regions, ranging from fair to excellent<br>Reliability is dependent on the area needing to be analysed. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Fernandes et al. (2014) | Randomised crossover | FLIR T420 320x240 pixels | n=12<br>TSK multiple locations<br>Acclimatisation period unknown<br>Camera 3.0m from ROI<br>Ambient room temperature 24.9 (± 0.6) °C<br>Relative humidity 62.3 (± 5.7)% | Manual selection* | Absolute TSK | Intra-rater TSK method** ICC pre-exercise 0.75 (95% CI 0.12, 0.93), SEM and MDC unknown<br>Intra-rater TSK method** ICC during exercise 0.49 (95% CI -0.80, 0.85) SEM and MDC unknown<br>Intra-rater TSK method** ICC post-exercise 0.35 (95% CI -1.22, 0.81) SEM and MDC unknown |
| James et al. (2014) | Observational | FLIR e40BX 160x120 pixels | n=14<br>TSK multiple locations<br>Acclimatisation period 20 mins<br>Camera 1.0m for ROI<br>Ambient room temperature 31.9 (± 1.0) °C<br>Relative humidity 61.0 (± 8.9)% | Spot (live function) | Absolute TSK | Inter-device reliability ICC 0.52 (LoA 1.46 95% CI -1.08, 1.85), SEM 0.53°C, MDC unknown |
| Choi et al. (2013) | Observational cross-sectional | IRIS-5000 256x240 pixels | n=28<br>TSK at the site of complex regional pain syndrome<br>Acclimatisation period 20 mins<br>Camera 1.0m from ROI<br>Ambient room temperature 23°C<br>Relative humidity 50% | Manual selection* | ΔTSK | Inter-rater ICC 0.87 (95% CI 0.75, 0.93), SEM and MDC unknown |

| | | | | | | |
|---|---|---|---|---|---|---|
| Rodrigues-Bigaton et al. (2013) | Observational cross-sectional | FLIR T360 320x240 pixels | n=26<br>TSK of temporomandibular joint (TMJ)<br>20 mins acclimatisation period<br>Camera 1.0m from ROI<br>Ambient room temperature 22 (± 1.0) °C<br>Relative humidity unknown | Manual selection (spot) | Absolute TSK | Intra-rater ICC left TMJ 0.87<br>SEM and MDC unknown<br>Intra-rater ICC right TMJ 0.84<br>SEM and MDC unknown<br>Inter-rater ICC left TMJ 0.87<br>SEM and MDC unknown<br>Inter-rater ICC right TMJ 0.87<br>SEM and MDC unknown |
| Fernández-Cuevas et al. (2012) | Observational | FLIR T335 320x240 pixels | n=22<br>TSK multiple locations<br>Acclimatisation period unknown<br>Camera distance from ROI unknown **<br>Ambient room temperature of 23.6 (± 1.2) °C<br>Relative humidity 46.6 (± 4.1)% | Automated software | Absolute TSK & ΔTSK | Software ICC 0.999 (± 0.001), MDC and SEM unknown<br>Intra-rater ICC 0.997 (± 0.003) MDC and SEM unknown |

*Indicates that the manual ROI selection shape is unknown.

** indicates that the method of TSK analysis is unclear

Several authors, identified in table 2.5, have sought to identify the intra and inter-rater reliability of the FLIR ONE IRC in recent years. Jaspers et al. (2017) investigated the inter-rater reliability of the FLIR ONE iOS/Android compatible thermal imaging camera in the evaluation of burn wounds. The FLIR ONE plugs into the base of the iOS/Android device. It has a pixel count of 160x120 and an accuracy of ± 3°C but utilises multispectral imaging technology (MSX) to combine the infrared and digital image. The results demonstrated that the FLIR ONE had excellent inter-rater reliability (ICC 0.99, SEM 0.17-0.22°C) across three different time points when assessing ΔTSK.

The intra-rater and inter-rater reliability of the FLIR ONE was also excellent in a study by Kanazawa et al. (2016) in detecting subclinical inflammation in diabetic foot ulcer patients (ICC 1.00, 95% CI 1.00-1.00). They used a manual ROI selection to obtain their TSK values from diabetic foot ulcers, but it is unclear which function they used. The authors also assessed ΔTSK as opposed to absolute TSK. Unlike Jaspers et al. (2017), Kanazawa et al. (2016) did not provide any information within the paper on values of TSK, which meant that there were no figures available to be able to calculate the SEM and MDC values, therefore, it is not possible to understand what values constitute error.

Cao et al. (2018) demonstrated excellent reliability of the FLIR ONE, again using ΔTSK as an alternative to absolute TSK, but again no SEM or MDC values were reported. The authors used the spot function of the FLIR ONE to track their location for skin temperature and relied on user judgement for this.

Wilkinson et al. (2018) assessed the test-retest reliability of the FLIR ONE and found moderate (Koo & Li, 2016) ICC's (0.61, 95% CI 0.51, 0.73) in a multi-centre observational study. Wilkinson et al. (2018) utilised a manual box method to draw their ROI's retrospectively for various finger and hand locations. It could be possible that the ICC's may have been improved if there was an anatomical reference location for the box placement, as it is stated that the agreement between the main observer and one of the centres' observers was large.

Other authors have assessed the reliability of handheld infrared thermal imaging cameras, which were generally considered more reliable than their smartphone counterparts. Guirro et al. (2017) found that the FLIR T300, a 320x240 pixel device with thermal sensitivity of <0.05°C, had excellent reliability in the assessment of breast cancer. Mean intra-rater ICC's ranged from 0.998-0.999 (SEM 0.04-0.05°C, MDC 0.11-0.15°C) for the affected, contralateral

and control breasts. Mean inter-rater ICC's ranged from 0.974-0.988 (SEM 0.95-0.99, MDC 0.30-0.42°C) for the affected and contralateral breasts. Interestingly, the TSK measurements were taken from a distance of 2.0m, which exceeded the distances reported in other thermal imaging studies, yet the intra-rater and inter-rater reliability of the readings were still excellent. Guirro et al. (2017) used a freehand ROI analysis, traced around a ROI on a computer screen using examiner judgement of areas of the breast. This ROI analysis was conducted by two experienced physical therapists in the field of thermography.

Choi et al. (2013) found good inter-rater reliability (ICC 0.87, 95% CI 0.75-0.93) when exploring the diagnostic capability of infrared thermal imaging for complex regional pain syndrome. The infrared thermal imaging camera used in the study was an IRIS-5000, which had a pixel count of 256x240, which is below the recommended value for medical assessment outlined by Fernández-Cuevas et al. (2015).

Both Fernandes et al. (2014) and Fernández-Cuevas et al. (2012) assessed the reliability of the methods used as opposed to the reliability of the cameras themselves. Fernandes et al. (2014) retrospectively identified a $1cm^2$ ROI, but there was no description as to how these ROI's were located. Although there was a good overall ICC, this lack of standardised methodology may explain the variability in the 95% confidence intervals for the ICC's seen during resting conditions (0.75, 95% CI 0.12, 0.93). Fernández-Cuevas et al. (2012) assessed TSK using automated software to identify ROI's, with excellent reliability (ICC 0.999 ± 0.001). It is worth noting that the intra-rater reliability was also excellent without the use of the software (ICC 0.997 ± 0.003).

Dibai-Filho et al. (2015) assessed the reliability of line, spot and box analysis in the assessment of TSK over the Trapezius muscle. The strongest reliability coefficients were found when using the line analysis tool and can be seen in table 2.4. The SEM values were low for both intra-rater and inter-rater analysis (0.13°C and 0.43°C respectively). This indicated that when using the line analysis there was little variability between repeated measures (Kruse et al., 2017). The MDC value for intra-rater and inter-rater reliability using the line analysis tool were also low (0.36°C and 1.19°C respectively). The MDC is defined as the smallest amount of change required to detect a true change, opposed to measurement error or a change because of variability in the performance of the device (Nair & Behrman, 2012). In comparison the SEM's and MDC's for intra-rater and inter-rater reliability of the spot and box analysis tools were higher than the line tool, suggesting that a more accurate temperature value can be

obtained using line analysis. An issue when using SEM and MDC values when assessing the thermal response of a new body region is classifying whether the values are low or not. Preliminary work must be completed to understand what normal ΔTSK is of each region so that the error values can be contextualised.

As seen in table 2.3, none of the studies that assessed the reliability of the FLIR ONE IRC utilised line analysis (Cao et al., 2018; Jaspers, Carrière, Vries, et al., 2017; Kanazawa et al., 2016; Wilkinson, Leggett, Marjanovic, Moore, Allen, et al., 2018). These studies utilised the spot or manual selection functions, which Dibai-Filho et al. (2015) found to have lower reliability coefficients than the line function. Despite the studies demonstrating moderate to excellent reliability, it could be possible that utilising the line function may improve reliability reads for the FLIR ONE.

### 2.4.4 Conclusion of the review of device reliability

The review suggests that the intra and inter-rater reliability of infrared thermal imaging cameras is acceptable for the assessment of human TSK. However, both intra-rater and inter-rater reliability readings vary depending on the camera and the method of analysis used. It could be suggested that methodological consistency is of utmost importance to improve the ICC, SEM and MDC values which need to be obtained for each device.

The Thermographic imaging in sports and exercise medicine (TISEM) checklist was created (Moreira, Costello, et al., 2017) and was designed to improve the quality of infrared thermal imaging studies through standardised reporting of methods and results. Future studies should consult this checklist during the methodological design process, and factor in the points, which will make studies more comparable and repeatable. It is evident that no study has sought to assess the intra-rater or inter-rater reliability of a method of TSK assessment over the AT using the FLIR ONE, therefore this needs to be assessed. Based on the work conducted by Dibai-Filho et al. (2015), it is appropriate to consider that TSK is extracted from images using line analysis to reduce the SEM and MDC values.

This narrative review has highlighted that there is limited literature available specifically for the FLIR ONE, however, the validity and reliability results seem promising. It is evident that the validity and reliability values differ depending on the method of analysis, body region or condition assessed. It is also worth considering that factors other than the IRC's may impact the validity and reliability of the tool. With that in mind, it is important to consider

factors beyond the reliability and validity of the cameras that impact TSK readings. The next section will explore this.

## 2.5 Factors that affect skin temperature

Despite having acceptable validity and reliability for the measurements of TSK in humans, many physiological factors may influence data. These can be both intrinsic and extrinsic. These intrinsic and extrinsic factors for affecting TSK have been collated from the literature and they are presented in table 2.5 (Ammer, 2017; Arens & Hui, 2006; Blatteis, 2012; Chudecka & Lubkowska, 2015; Kenny & McGinn, 2017; Marins, Formenti, Costa, De Andrade Fernandes, & Sillero-Quintana, 2015; Neves, Salamunes, de Oliveira, & Stadnik, 2017; Neves, Vilaça-Alves, Nogueira, & Reis, 2015). Most of the evidence that surrounds these intrinsic and extrinsic risk factors is contradictory between anatomical regions, and there does not seem to be one TSK model for the whole body. The main intrinsic factors that affect TSK will be discussed. The extrinsic factors that are known to affect TSK can be controlled as part of the experimental procedures.

Table 2.5: Intrinsic and extrinsic factors that affect TSK

| **Intrinsic** | **Extrinsic** |
|---|---|
| Gender | Environmental ambient temperature |
| Ethnicity | Environmental humidity |
| Age | Clothing |
| Autonomic (Sympathetic) nervous system | Exercise intensity |
| Body Composition | Cooling/warming modalities |
| Aerobic fitness | Time of day (Circadian rhythm) |
| Skeletal muscle activation | |
| Emotion/stress | |
| Disease/Pathology | |
| Diet | |
| Hydration | |

### 2.5.1 Gender

Based on the available literature, it is suggested that absolute TSK differences exist between genders (Chudecka & Lubkowska, 2015; Marins et al., 2015; Neves et al., 2017). Neves et al. (2017) demonstrated that women have lower TSK than men in a sample of 94 participants (47m, 47f). Participants were banded into health risk classifications based on their percentage of body fat (%BF). Posterior lower leg TSK was different between genders in all risk classifications with women having a lower mean TSK by 2°C compared to their male counterparts. Similar results were found in an earlier study by Chudecka & Lubkowska (2015), with mean posterior shank TSK in women being significantly lower than the equivalent region in men.

Marins et al. (2015) investigated the circadian differences in absolute TSK between males and females and found that significant differences in absolute TSK existed between the genders in the morning at all locations measured throughout the body. These differences then became insignificant by the evening in all locations other than the posterior thigh and posterior lower limb. Posterior lower limb TSK in the morning for males was 1.4°C hotter both limbs when compared to females, and this reduced to 1.2°C by the evening. This suggests that despite absolute TSK values differing, the ΔTSK throughout the normal day exhibits a similar response.

It is postulated that these gender differences exist due to three reasons; higher metabolic activity, increased lean body mass and a decreased percentage of body fat in males compared to females, all of which are other intrinsic risk factors (Chudecka & Lubkowska, 2015; Iyoho et al., 2017; Marins et al., 2015; Neves et al., 2017). Physical characteristics alone may not fully explain why differences in TSK exist between genders.

It is possible that differences in physiological characteristics may also be partly responsible. Males exhibited a significantly larger gross sweat loss and metabolic heat production compared to females during exercise (Hazelhurst & Claassen, 2006; Smith & Havenith, 2012). However, Smith and Havenith (2012) demonstrated that sweat production did not significantly increase between genders in the posterior lower leg or the heel between exercise of different intensities. Importantly, there was no correlation between sweat rate and TSK in either gender.

Further changes in the sympathetic nervous system activity may be responsible for gender differences in absolute TSK (Dart et al., 2002). In females, the menstrual cycle is known to cause changes in resting body temperature by up to 0.8°C, and the menopause has been shown to increase vasomotor activity which in turn causes changes in skin blood flow (Charkoudian & Stachenfeld, 2016). What is not known, is whether the ΔTSK response is affected by the absolute TSK rise during the cycle.

Due to the possible differences in absolute TSK between the genders, it should be advised that direct gender comparisons are not made. Future work may investigate whether the ΔTSK response differs between genders, or whether the thermal response is proportional at the region of the AT.

### 2.5.2 Ethnicity

There are a limited number of studies that discuss the relationship between TSK and ethnicity (Maley et al., 2014, 2015; Muia et al., 2019; Yim et al., 2012). Before reviewing these, it is important to understand that multiple physiological factors may be responsible for variations in TSK between ethnicities, such as skin pigmentation, diet variations, hydration, skin thickness, gland size, vascular resistance and chemical secretion (Dąbrowska et al., 2018; Diridollou et al., 2007; Vashi et al., 2016), therefore it may not be possible to truly understand the reasons why TSK differences exist between ethnicities.

Maley et al. (2014) and Maley et al. (2015) both assessed the differences between males of African and Caucasian descent. In both studies, it was found that Africans had attenuated skin blood flow readings and TSK compared to Caucasians. In response to cold exposure, vasoconstrictor responses were worse in Africans, as were the vasodilatory responses following cold exposure.

Despite some differences in TSK and cutaneous vasodilatory responses between ethnicities in response to passive temperature change, Muia et al. (2019) showed that there were no differences in nitric oxide-induced vasodilatory responses or sweating between African and Caucasian males in response to exercise. Nitric oxide is considered an important regulator of cutaneous vasodilation (Charkoudian, 2003).

Yim et al. (2012) suggested that endothelial function, the balance between relaxation and contraction elements of vascular homeostasis, differed between Korean and Caucasians. Skin blood flow was measured using Laser Doppler Flow in response to passive tissue heating

and vascular occlusion. Peak flux in Caucasians was found to be significantly higher, suggesting better endothelial function.

There is not enough evidence to draw a meaningful conclusion regarding differences in TSK between the ethnicities and this would require further investigation. There are likely many physiological reasons why absolute TSK differences exist between people of different ethnicities as highlighted previously, which fall way beyond the scope of this review. Until these reasons are understood, caution should be drawn when grouping people of varying ethnicities for TSK assessment.

### 2.5.3 Age

It is known that with advancing age there are many changes to the skin such as decreasing hydration, elasticity, thickness and secretion rate (Dąbrowska et al., 2018). It is also known that thermal perception decreases with age which may impact the control of skin blood flow (Shibasaki et al., 2012), which is important in the regulation of core temperature (Blatteis, 2012). Stapleton et al. (2015) found that older men (65 ± 3 yrs) had significantly ($p<0.05$) greater heat loss than younger men (aged 21 ± 1yr) in response to a 30-minute running intervention. There were no significant differences found between middle-aged (49 ± 5 years) trained individuals and the younger participants, but there were between middle-aged (48 ± 5 years) untrained individuals. Similarly, Moreira et al., (2017) found absolute TSK differences between younger (21.8 ± 2.3 years) and older (71.0 ± 7.5 years) physically active females, with the latter group having a higher mean TSK of 1.7°C and 1.9°C in the left and right legs respectively.

Recent research has contradicted this (Schlader et al., 2018). The researchers found that skin blood flow did not differ between young and older adults when transitioning from a cold to warm environment, in the fingertips and forearms. Changes in metabolic heat production were also similar between the two groups. However, there were differences in some sympathetic nervous system components, with sweat rate being increased in the older population.

The body of evidence relating to TSK change with age is not sufficient enough to draw a full conclusion. Caution should be drawn when making direct comparisons between TSK responses in populations with varying age. Based on available literature from Stapleton et al.,

(2015) and Moreira et al., (2017), the maximum age for TSK comparison will be capped at 61 years old for the current studies.

### 2.5.4 Sympathetic nervous system activation

The sympathetic nervous system (SNS) is important for the distribution and regulation of blood flow during exercise (Katayama & Saito, 2019). One of its main roles is to automatically regulate skin blood flow through the vasodilator and vasoconstrictor systems (Greaney et al., 2016; Simmons et al., 2011; Tansey & Johnson, 2015). Changes in blood flow to a region will result in alterations in TSK as the blood is circulated to the musculotendinous regions to meet their metabolic demands during movement (Joyner & Casey, 2015). The SNS has the potential to alter blood flow to musculotendinous tissue which has the potential to cause pathological alterations, although there is limited evidence to suggest this (Jewson et al., 2015). TSK is known to differ from the core temperature of the body and is heterogeneous throughout regions, with this distribution being poorly understood (Ammer, 2017).

The region of the AT is covered by non-glabrous skin, meaning that its surface is covered by hair, and results in a more stable temperature than glabrous skin. However, during activity, TSK of the region has been known to change. The body attempts to maintain thermal homeostasis, which requires heat dissipation at times when the core temperature rises, and heat conservation or generation and times when the core temperature declines (Greaney et al., 2016). The SNS, part of the autonomic nervous system, can respond to maintain thermal homeostasis, by causing piloerection, sweating and vasodilation to cool the body via convection, and shivering and vasoconstriction to attempt to raise core temperature (Ammer & Formenti, 2016; Kenny & McGinn, 2017; Simmons et al., 2011).

During exercise, blood flow to the skin generally increases to dissipate heat, however, the body must regulate this with the metabolic demand needed for the skeletal muscles to function optimally dependent on the task (Ammer, 2017; Arens & Hui, 2006; Joyner & Casey, 2015; Kenny & McGinn, 2017). Johnson (2010) suggested that with exercise that requires high levels of muscular vasodilation, there is an initial TSK decrease due to the redirection of cutaneous blood flow to meet the metabolic demand of the muscles. The heat flow in the dermis and epidermis is not controlled by blood flow in the capillaries but is dependent on the resistance of the individual tissues to temperature change, whereas in the subcutaneous regions there are vascular components which control heat transfer (Arens & Hui, 2006a). Small

variations in the diameter of these blood vessels result in large increases in blood volume, which has the potential to alter the temperature within the tissues significantly. Previous research has shown that skin blood flow is less during dynamic activity, than it is in passive heat stress (Crandall & Wilson, 2015; González-Alonso, Crandall, & Johnson, 2008). The review by González-Alonso et al. (2008) highlighted that skin blood flow plateaus as core temperature continues to rise during dynamic activity, to meet the need for the skeletal muscle blood flow. Crandall & Wilson (2015) suggested that skin blood flow during passive heat stress continues to rise with core temperature.

In a pathological Achilles tendon, whereby there is increased compliance and increased demand on the Gastrocnemius-Soleus muscles (Wang et al., 2012), it would be interesting to see whether this TSK response differs from a healthy tendon. A previous systematic review suggested that there could be a link between the upregulation of the SNS and tendinopathy (Jewson et al., 2015). It would be hypothesised that in a healthy tendon during activities whereby the core temperature of the body begins to rise, TSK would increase as core temperature increases, due to cutaneous vasodilation, to a point where it would plateau due to a balance between thermoregulation and skeletal muscle output (González-Alonso et al., 2008; Simmons et al., 2011). In a pathological tendon where there is an increased metabolic demand from the muscles, it may be that the cutaneous ΔTSK response is less, due to the redirection of blood to the muscles. Infrared thermal imaging may play a role in detecting this differing thermal response.

### 2.5.5 Body Composition

Several authors have suggested that there is a strong link between differing body compositions and TSK (Chudecka & Lubkowska, 2012, 2015; Epishev et al., 2019; Galan-Carracedo et al., 2019; Jalil et al., 2019; Neves et al., 2015b, 2017; Nirengi et al., 2019; Weigert et al., 2018).

Body fat percentage (BF%) has been suggested to influence TSK due to its insulating properties. Jalil et al. (2019) used infrared thermal imaging to assess TSK in overweight (Body Mass Index (BMI) >24.9kg/$m^2$) and lean women (BMI < 24.9 kg/$m^2$) at the abdomen and the hand. BF% was also measured and there were considerable differences between the groups (40% vs 25%). The results demonstrated that mean abdominal TSK was significantly greater in the group of lean women when compared to the overweight women (34.1 ± 0.7°C vs 32.9 ±

1.2°C, $p<0.05$). Conversely, mean TSK at the hand was significantly greater in the group of overweight women compared with the lean women (31.9 ± 3.1 °C vs 28.2 ± 3.1°C). These results suggest that areas of high BF% and high BMI are associated with lower surface TSK.

These results were similar to those of (Neves et al., 2017) who found that women had lower TSK than men with lower shank TSK showing decreases in subjects with increased BF%. The median 31.8% BF% in women vs the 17.1% median BF% found in men was suggested to be the cause. In another study before this Neves et al. (2015) found that BF% negatively correlated with TSK in the subscapular region ($r= -0.64$, $p<0.05$).

Similarly, Chudecka & Lubkowska (2015) showed a significant ($p<0.05$) negative correlation between BMI and TSK in the chest, upper back, abdomen and lower back between genders. Correlation between the two variables in the posterior shank was not statistically significant ($r=0.14$, $p>0.05$) which seemed to contradict the results obtained by Neves et al. (2017). However, the BMI mean values for women vs men were 21.7kg/m$^2$ and 23.2kg/m$^2$ respectively, but the BF% values were much less (women 22.8 ± 3.8% and men 13.8 ± 2.2%) than in previous studies which may help to explain why a negative association between TSK and the posterior shank was not found. A limitation of BMI for infrared thermal image classification is highlighted with these results, as the difference in BMI between the genders is 1.5kg/m$^2$, yet the difference in BF% is 9%, indicating the possibility that BMI is not accounting for muscle mass in the male counterparts. It could also indicate that the posterior shank is an area of low BF%, which may make it a suitable area for infrared thermal imaging, as suggested by Chudecka & Lubkowska (2012) and Quesada et al. (2015).

The evidence that exists relating to body composition and TSK variations may not apply to the region of the AT. Recent studies have shown that there are large variations in skin thickness characteristics between anatomical locations, which have a significant effect on TSK responses of the region (Maiti et al., 2020; Nedelec et al., 2016). Further, it is not known if individual variations of the number of skin thermoreceptors or cutaneous blood vessels cause different TSK responses between individuals or between anatomical regions. Based on existing evidence for body composition, people with high BMI or high BF% should not be compared for the assessment of AT TSK, until the effects of Gastrocnemius-Soleus composition are studied.

### 2.5.6 Aerobic Fitness

It is thought that individuals with a higher level of aerobic fitness display better skin thermoregulatory responses than those with a lower level of fitness based on the SNS vasoconstrictor and vasodilator responses to exercise which were discussed in section 2.5.4.

Galan-Carracedo et al. (2019) measured Pectoral absolute TSK of high and moderately fit individuals. They found that baseline TSK was significantly higher in highly fit individuals (34.2 ± 0.8°C vs 33.9 ± 0.7°C, $p<0.05$). Absolute TSK remained higher during the exercise intervention but was not statistically significantly different (36.2 ± 0.6°C vs 35.9 ± 0.8°C, $p>0.05$). The ΔTSK values from baseline to final were within 0.1°C between the groups, indicating that the ΔTSK response is the same regardless of aerobic fitness levels. However, the time it took for the groups to reach their peak absolute TSK values differed significantly, 910 ± 201s in the moderately fit and 1105 ± 244s in the highly fit. Interestingly, TSK was shown to drop in both groups at 80-90% of peak workload, with the hypothesis of sweating, cutaneous vasodilation and decreased skin blood flow to cool the body temperature down being the cause.

TSK decreases were also found by Abate et al. (2013) in trained individuals during a phased warm-up procedure. The decrease in TSK may fit with the initial vasoconstrictor response outlined in section 2.5.4. that the demand for blood flow from the muscles during the phased warm-up redirects blood away from the cutaneous regions, or it may be as a result of sweat cooling the skin surface. There was a differing response in untrained individuals, who did not display any significant TSK change. A speculative theory suggested that the initial vasoconstrictor response, directing blood towards the working muscles, was more efficient in trained individuals, but the reasons why this decrease occurred were not fully understood.

In contrast to both of these studies, Fernandes et al. (2016) demonstrated that physically active males produced a steady TSK rise in the posterior lower limb throughout 60 minutes of aerobic exercise, with no initial drop in TSK. However, all upper body regions including the chest and back demonstrated an initial TSK decrease suggesting an initial vasoconstrictor response (Abate et al., 2013; Galan-Carracedo et al., 2019; Johnson, 2010; Simmons et al., 2011).

No study has sought to compare the TSK response in individuals with different aerobic fitness but matched physical characteristics. It is known that higher BF% seems to correlate

inversely with TSK, yet in the studies by Galan-Carracedo et al. (2019) and Abate et al. (2013), significant differences in weight, BMI, fat mass percentage and muscle mass percentage exist. It is therefore difficult to conclude that aerobic fitness has any significant effect on TSK response to exercise in isolation.

### 2.5.7 Skeletal muscle activation

The level of skeletal muscle activation has been suggested to be a contributor to changes in TSK (Ammer, 2017; Arens & Hui, 2006; Escamilla-Galindo et al., 2017; Quesada et al., (2015); Rodriguez-Sanz et al., 2018; Rodríguez-Sanz et al., 2017; Rodriguez-Sanz et al., 2019).

Quesada et al. (2015) assessed the skeletal muscle activation of the Vastus Lateralis, Rectus Femoris, Biceps Femoris and Gastrocnemius and their relationship to TSK during a cycling intervention. It was concluded that participants who demonstrated a higher overall and lower frequency neuromuscular activation in the Vastus Lateralis presented lower TSK increases, which was considered to be a better thermal response, with the authors citing better heat dissipation as the reason. There was a strong correlation between overall neuromuscular variation and changes in TSK for the Vastus Lateralis. Interestingly, there was a weak correlation for the Rectus Femoris, despite its electromyographical (EMG) activation increasing with high cyclic workloads to a similar level compared to the Vastus Lateralis (da Silva et al., 2018).

A study by Rodriguez-Sanz et al. (2019) was the first to attempt to measure TSK alongside EMG in the Gastrocnemius-Soleus region. Their study on recreational runners found a strong correlation between increases in TSK alongside and EMG activity. However, the interpretation of the results is limited, as only the medial Gastrocnemius was assessed, and no detail is provided around the method of ROI analysis from a thermal perspective. There is scope for future work to assess this. Further, it would be beneficial to measure these changes in conjunction with cutaneous and skeletal muscle blood flow changes to truly understand the effect that physiological variables can have on skeletal muscle activation and TSK.

Results by Escamilla-Galindo et al. (2017) may provide some degree of contradiction to the claims by Rodriguez-Sanz et al. (2019). They found that there were TSK increases in the contralateral leg following a strength intervention 30 minutes after the activity had concluded. The contralateral leg had remained at rest during the activity, with the authors citing possible

cross-adaptation of the motor neurones as a reason for TSK increase. As the skeletal muscles on the contralateral limb had been at rest, it is possible that central mechanisms, beyond their activation, could have played a role in TSK change in response to activity.

Coletta, Mallette, Gabriel, Tyler, & Cheung (2018) found that during hyperthermic conditions, neuromuscular activation was dependent on the task, core temperature and skin temperature. Their study saw reductions in TSK combined with elevations in surface EMG in the Flexors of the hand during an isotonic task. Conversely, during an isometric task, there were no alterations in TSK, but alterations in core temperature were found to affect surface EMG readings. This highlights the complexity of attempting to determine whether skeletal muscle activation affects TSK, as the changes may occur due to many underlying physiological reasons. Implying that skeletal muscle activation alone is responsible for TSK changes may be an oversimplification of the physiology involved.

### 2.5.8 Clinical implications of factors that affect skin temperature

The review into factors that affect TSK has revealed points for consideration when considering TSK measurement studies. When considering gender, the evidence would suggest that absolute TSK values should not be compared between males and females due to varying physical and physiological differences that affect absolute TSK. However, how ΔTSK is affected is unknown. It should be noted that in studies where males and females are both included, there may be a greater range of absolute TSK values before and in response to activity.

For the effect of age and ethnicity, there is some evidence to suggest that absolute TSK differs between variants, however, this is not robust. Clinically, caution should be assumed when making direct comparisons between variants until the research can conclusively determine whether TSK differences exist.

Comparing absolute TSK between individuals with different body compositions should be avoided, as evidence suggests that there is a negative correlation between high BF% and TSK. Studies that include participants of varying body compositions may see a wide range of TSK values within the data. The effect of this at the region of the AT is unknown and warrants further investigation.

There is limited evidence to suggest that aerobic fitness affects TSK. For the clinical assessment of TSK, individuals should currently be compared against those who have similar fitness levels. Future research could explore this link further.

Differences in SNS activity and skeletal muscle activation between individuals is challenging to establish clinically, due to the complexity of the equipment required to measure this. The SNS may play a role in the development of Achilles tendinopathy, so it could be hypothesised that pathological tendons could display more extreme TSK values due to the lack of physiological homeostasis (Ackermann et al., 2014).

Based on these findings from the review, it is recommended that for comparison of AT TSK between symptomatic individuals and asymptomatic individuals, that matched controls are found where possible based upon age, gender, ethnicity, body composition and aerobic fitness where possible. All of these clinical implications may vary when pathology is introduced, as the potential adaptational responses between participants that differ in the aforementioned variables may also change. Therefore, it is important to understand the thermal reaction to pathology in depth.

## 2.6 Achilles tendinopathy

### 2.6.1 Pathophysiology

Achilles tendinopathy is a complex condition referring to the disorder of the tendon, characterised by swelling, pain and reduced performance (D'Addona, Maffulli, Formisano, & Rosa., 2017; Kragsnaes et al., 2014; Maffulli, Sharma, & Luscombe., 2004). Historically, tendinopathy was termed tendinitis referring to an inflammatory condition, however, the term tendinosis was adopted due to the degenerative nature of most pathologies (Maffulli, Khan, & Puddu, 1998). However, Cook et al. (2016) proposed a series of models expanding on the initial tendinopathy continuum (Cook & Purdam, 2009) which attempted to categorise tendinopathy. However, there were some issues with this.

One category, collagenous disruption, refers to the tearing of collagen fibres within the tendon, but it seems unlikely that this occurs in isolation, as tearing of collagen would result in inflammatory cascades and changes to the non-collagenous matrix to maintain homeostasis (Screen et al., 2015). This idea may overlap into the inflammatory model that was also proposed by Cook et al. (2016). It is more likely that as a result of excessive loading, fibre kinking and collagenous denaturation occur which ultimately leads to chronic tendon degeneration (Szczesny et al., 2018). Secondly, the collagenous disruption would not explain the physiology behind reactive tendinopathies caused by compressive load, direct impact or

acute overload, in which there is a large cellular response but little change to the collagenous organisation of tendon (Docking, Samiric, Scase, Purdam, & Cook, 2013).

It is unlikely that the inflammatory model occurs in isolation in acute or chronic tendinopathy. As previously mentioned, for a traditional inflammatory response to occur, there would have to be substantial collagenous disruption in response to high load (Cook et al., 2016). It was previously assumed that inflammatory responses did not occur in chronic tendinopathy, hence the term tendinosis (Alfredson, Ljung, Thorsen, & Lorentzon, 2000; Maffulli, Khan, & Puddu, 1998). However, more recent histological research has emerged suggesting that inflammation plays a role in the chronic conditions, hence the term tendinopathy (Abate et al., 2009; D'Addona et al., 2017; Rees et al., 2014). Inflammatory proteins are normal within tendons in response to mechanical loading, however, elevated levels may occur when there is a homeostatic imbalance (Magnusson et al., 2010). Elevated levels of inflammatory proteins have been found in both tendinopathic and ruptured AT's, with some proteins such as IRF1, IRF5 and CXCL10 distinguishing the chronic response (Dakin et al., 2018).

The midportion of the AT is poorly vascularised with less than half the number of blood vessels in comparison to the proximal and distal sections making the maintenance of homeostasis difficult (Chen et al., 2009; Tran et al., 2020; Zantop et al., 2003). This poor vascularisation leads to almost no tissue turnover from the region in non-pathological AT's (Järvinen, 2020). However, research has found that pathological AT's have increased tissue turnover but it is disorganised (Järvinen, 2020; Tran et al., 2020).

The body may attempt to combat this lack of homeostasis through the creation of new blood vessels from existing ones (anastomoses), termed neovascularisation (Hucthison et al., 2020). Other research has suggested that 72-92% of symptomatic AT's display increased intra-tendinous blood flow in comparison to the asymptomatic 33-50%. For tissue repair to occur and maintain homeostasis, the tissues would require a sufficient supply of nutrients (Järvinen, 2020). Therefore the chronic nature of the pathology combined with the neovascularisation, arterial anastomoses and increased blood flow found within pathological AT's may suggest that this is the body's attempt at healing the region (Chen et al., 2009). The role of the interfascicular matrix must be considered in relation to this disorganised tissue turnover as the AT has to cope with large strain, supported by (Thorpe et al., 2015) who demonstrated that interfascicular matrix can recover from repeated bouts of cyclic loading.

The final model proposed by Cook et al. (2016) is the tendon cell response, where tenocytes act in response to a mechanical stimulus to maintain homeostasis within the extracellular matrix of the tendon. The role of the tenocyte is to produce materials such as type 1 collagen to assist with the growth and repair of the damaged tendon (Lipman et al., 2018). Tenocytes have been shown to respond to tensile strain, which is defined as the force per unit area that elongates the tendon, under load (Chimenti et al., 2014) and are thought to alter elastic properties of the tendon (Lavagnino et al., 2015; Patel et al., 2017).

The models proposed by Cook et al. (2016) and recent research looking at neovascularisation (De Marchi et al., 2018; Järvinen, 2020; Tran et al., 2020) suggest that there are complex physiological processes that occur within the Achilles tendon. Rather than attempting to understand the complex differences in the physiological responses in all tendinopathy categories, it may be advantageous from a clinical perspective to attempt to understand the similarities between them. Physiologically, it is possible these mechanisms that attempt to maintain homeostasis within the region may change the temperature of a region as the metabolic activity is likely to change (Snedeker & Foolen, 2017), an area that needs investigating further.

Another similarity that is present in each of the categories is tendon load as identified by Cook et al. (2016), which may be an important factor in how the tendon becomes pathological and how it adapts to pathology. Load response to activity has recently been highlighted in a tendinopathy consensus as an essential reporting factor for clinicians (Scott et al., 2020). Numerous risk factors may contribute to changing load responses of the AT.

### 2.6.2 Biomechanical risk factors for Achilles tendinopathy

When considering load, it is important to understand stress and strain which are vital to the normal function of the AT. Longitudinal stress refers to the ratio of force that is acting perpendicular to the tendon fibres, whereas strain is defined as the ratio of deformation of the tendon (Lima et al., 2018). The ratio of stress and strain of a tendon is universally summarised using a stress-strain graph, as seen in figure 2.1.

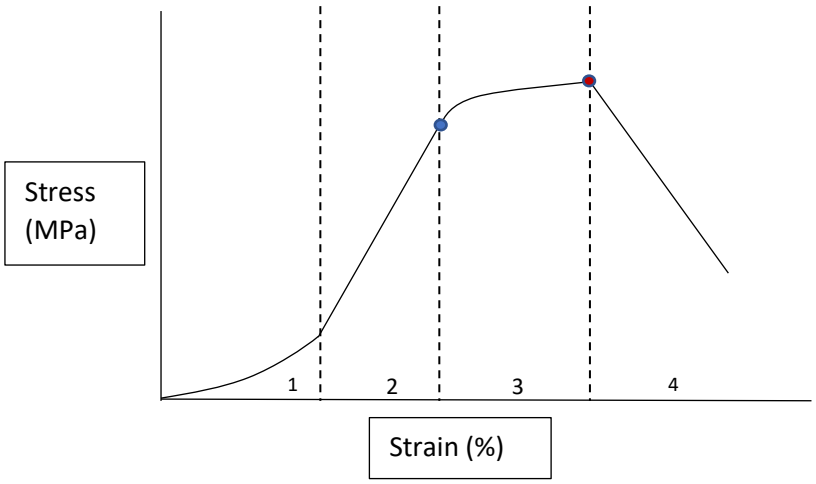



Fig 2.1 - Stress-strain curve. The blue dot represents the Yield Point. The red dot represents the failure point

The graph is divided into four regions; toe, elastic, plastic and failure (Maganaris et al., 2008). During the toe region (1), there is minimal crimping of the tendon fibres with no permanent length change. During the elastic region (2), the tendon fibres are stretched, however, they can return to their original resting length. At the end of the elastic region of the graph sits the yield point, which is defined as the point at which there is plastic tendon deformation or permanent shape change in response to high stress. This point is followed by the plastic region on the graph (3). The failure point occurs at the end of the plastic region, referring to the complete failure of the tendon (4) in response to the stress applied to it.

Excessive loading, taking the tendon past the yield point, will alter tendon stress-strain relationships, as previously seen in both insertional and midportion tendinopathies (Arya & Kulig, 2010; Child, Bryant, Clark, & Crossley, 2010; Chimenti et al., 2014; Obst et al., 2013). Tendons taken past the yield point will typically have a lower Young's modulus, defined as the slope of the stress-strain curve in the tendons linear region, representing the ratio of longitudinal stress to the longitudinal strain on the tendon (Arya & Kulig, 2010; Lima et al., 2018). A lower Young's modulus would result in a less stiffened or more compliant Achilles tendon, meaning that the efficiency in returning stored elastic energy is possibly reduced in a stretch-recoil movement (Wilson & Lichtwark, 2011).

The AT acts as a compression spring and a more compliant spring could lead to less efficiency, as energy could be lost due to hysteresis. Higher values of hysteresis suggest that the Achilles tendon is less efficient in returning elastic energy, as more energy from the tendon

is being lost through heat (Peltonen, 2014). Wang et al. (2012) demonstrated that symptomatic Achilles tendons demonstrated greater mechanical hysteresis than healthy controls in a population of 17 healthy males. Variation exists within the literature on values of hysteresis for in vivo non-pathological Achilles tendons, ranging from 3-38% (Farris et al., 2011; Lichtwark & Wilson, 2005a). It could be speculated that there is such variation due to the methodology employed, with the MTJ tracked via ultrasound motion analysis, with linear distances between the origin and insertion being calculated. This is a simplistic approach to the measurement of the AT and does not account for differences in the material properties of the tendon such as thickness or cross-sectional area, both of which may affect the elastic modulus of the tendon and thus the rate of hysteresis (Finni et al., 2013; Obst et al., 2013)

Many biomechanical risk factors exist that are thought to contribute to the development of Achilles tendinopathy through altering load on the AT, and these can be seen in table 2.6.

Table 2.6: Biomechanical risk factors for Achilles tendinopathy identified from the literature

| **Authors** | **Causal column (Prospective/Retrospective)** | **Biomechanical risk factors** |
|---|---|---|
| Bramah, Preece, Gill, & Herrington (2018) | Retrospective | Increased contralateral pelvic drop at foot contact during running |
| Bramah et al. (2018) | Retrospective | Increased forward trunk lean at foot contact during running |
| Bramah et al. (2018); Hein, Janssen, Wagner-Fritz, Haupt, & Grau (2014) | Retrospective<br>Prospective | Landing with increased knee extension during running |
| Bramah et al. (2018); Creaby, Honeywill, Franettovich Smith, Schache, & Crossley (2017); Kulig, Loudon, Popovich, Pollard, & Winder (2011) | Retrospective<br>Retrospective<br><br><br><br>Retrospective | Increased peak hip adduction |
| Bramah et al. (2018); Rabin, Kozol, & Finestone (2014); Mahieu, Witvrouw, Stevens, Van Tiggelen, & Roget (2006) | Retrospective<br>Prospective<br><br>Prospective | Altered ankle dorsiflexion |
| Becker, James, Wayner, Osternig, & Chou (2017); Lersch et al. (2012) | Retrospective<br><br>Retrospective | Increased rearfoot eversion |
| Becker et al. (2017) | Retrospective | Increased tibial varus angle |
| Bramah et al. (2018); Grigg, Wearing, & | Retrospective<br>Retrospective | Altered AT strain |

| | | |
|---|---|---|
| Smeathers (2012); Joseph et al. (2014); Lersch et al. (2012) | Retrospective<br>Retrospective | |
| Debenham, Travers, Gibson, Campbell, & Allison (2015); Joseph et al. (2014); Maquirriain (2012) | Retrospective<br>Retrospective<br>Retrospective | Decreased AT stiffness |
| Hein et al. (2014) | Prospective | Decreased knee flexor strength |
| Debenham et al. (2015); Masood, Kalliokoski, Bojsen-Møller, Magnusson, & Finni (2014) | Retrospective<br>Retrospective | Altered lower limb muscle activity |
| O'Neill et al. (2019); Mahieu et al. (2006) | Retrospective<br>Prospective | Decreased plantar flexor torque |

*Retrospective refers to studies that assessed patients with pre-diagnosed Achilles tendinopathy, therefore the factors as a cause or effect cannot be established.

Several authors have suggested that alterations in lower limb joint angles are associated with Achilles tendinopathy (Becker et al., 2017; Bramah et al., 2018; Creaby et al., 2017; Hein et al., 2014; Kulig et al., 2011; Rabin et al., 2014). Bramah et al. (2018) suggested that runners who suffer from Achilles tendinopathy land with greater knee extension than asymptomatic controls. Landing with increased knee extension would theoretically help to maintain stiffness of the AT in those who suffer from Achilles tendinopathy (Jandacka et al., 2017), who are likely to have greater AT compliance (Karamanidis & Epro, 2020; Wang et al., 2012) and decreased Gastrocnemius-Soleus muscle strength (Joseph et al., 2014; Masood et al., 2014) in their symptomatic tendon.

Rabin et al. (2014) used logistic regression to predict the likelihood of reduced ankle dorsiflexion causing Achilles tendinopathy in a military cohort. The odds ratio revealed that for every 1° of ankle joint dorsiflexion gained, the chance of suffering from Achilles tendinopathy reduced by 0.23. The ankle joints were assessed passively in a non-weight bearing position and the ankle joint range of movement cut off value for prediction was 22°

(sensitivity 80%, specificity 86%). This is in agreement with findings by Bramah et al. (2018) and Grigg et al. (2012).

Becker et al. (2017) suggested that eversion angle of the rearfoot was associated with Achilles tendinopathy, which in turn affected standing tibial angle. It is thought that this biomechanical alteration would increase stress and strain on the AT which have both been implicated in the development of the pathology (Munteanu & Barton, 2011). Lersch et al. (2012) demonstrated that an increase in eversion of the calcaneus resulted in an increased AT strain medially, with an angle of 15° increasing the strain by 5.6%, however, the strain was decreased laterally by 9.4%. This finding may highlight the complexity of the biomechanics of the AT, with force being dissipated unevenly through the tendon, which could be explained by the spiralled anatomical arrangement of the AT distally (Pekala et al., 2017). Alterations in both stress and strain, as well as anatomical variations, may coincide with physiological changes such as reductions in blood flow (Järvinen, 2020; Kubo et al., 2017), which could indicate that the onset of midportion tendinopathy is multi-faceted and not solely caused by biomechanical factors alone.

Joseph et al. (2014) found a contradictory AT strain response in males and females following a loaded jump. The mean AT strain in men decreased from 9.4% (± 3.1%) to 8.4% (±3.4%), whereas in woman the AT strain increased from 11.0% (±2.9%) to 15.0% (± 3.5%). The mean AT stiffness in men increased from 835.4 ± 233.8 N/mm to 853.3 ± 266.2 N/mm, whereas AT stiffness in females decreased from 530.6 ± 111.8 N/mm to 369.7 ± 91.7 N/mm. This result indicated an increase in AT compliance in women after a loaded jump, which is known to be detrimental to AT efficiency and could therefore be a contributing factor to the onset of Achilles tendinopathy in females and begin to explain large gaps in Achilles tendon pathology between genders (Joseph et al., 2014). Further research is necessary to fully understand why this response differs between genders.

Karamanidis and Epro (2020) have recently observed higher AT strain in jumping athletes suffering from Achilles tendinopathy compared with healthy controls. It was suggested that this was a direct result of decreased AT stiffness. Several other authors have also suggested that alterations in AT stiffness may play a role in the development of clinical symptoms of Achilles tendinopathy (Debenham, Travers, Gibson, Campbell, & Allison, 2015; Joseph et al., 2014; Maquirriain, 2012). However, it was not clear whether these changes in stiffness were as a direct result of training error, which has been suggested to be a risk factor

for the development of AT pathology (Alfredson & Lorentzon, 2000). Debenham et al. (2015) did not provide detail on the normal training loads of their participants, whilst Joseph et al. (2014) only stated that participants were moderately active, without specifying the type of activity. Those in the study by Maquirriain (2012) were high performance athletes across multiple sports training greater than 15 hours per week, therefore they were exposed to greater cumulative load than normal with the chosen activity of maximal hops and jumps. Each of the studies lacked control groups, thus, it is difficult to exclude that these changes in load and volume of activity may have influenced stiffness readings of the AT's rather than just the pathology itself. Pathological changes to the structure of the AT are thought to lead to alterations in the compliance of the AT and reduce the SSC performance (Martin et al., 2018; Uchida, Hicks, Dembia, & Delp, 2016; Wang et al., 2012).

In contrast, Intziegianni et al. (2016) found no significant changes in AT compliance in those with Achilles tendinopathy. There is no clear consensus within the literature on how pathological AT's respond to stiffness changes and it warrants further investigation, however, it is highly likely that increased strain as a direct result of this would lead to a maladaptive response by increasing mechanical demands on the AT (Karamanidis & Epro, 2020).

Some research has found that AT stiffness properties do not change with repeated SSC activity and that alterations in the Gastrocnemius and Soleus muscle stiffness properties could have an impact on performance, albeit these were in non-pathological AT's (Farris, Trewartha, & McGuigan, 2012; Kubo & Ikebukuro, 2019; Morgan et al., 2019). In contrast, Abdelsattar, Konrad, & Tilp (2018) found that stiffer AT's resulted in a shorter ground contact time (GCT) during jumping, which could indicate a greater movement efficiency, however, again the study was conducted on non-pathological individuals. The optimal stiffness values for individuals likely vary depending on their type and level of activity, as suggested by Kubo et al. (2010) and it may change based upon altered movement strategies to account for symptoms in pathological individuals.

Recent research has highlighted the possible link between reduced plantar flexor torque, specifically decreased Soleus force-generating capacity, and Achilles tendinopathy (Mahieu et al., 2006; O'Neill, Barry, et al., 2019). Mahieu et al. (2006) conducted a prospective study that assessed the differences in plantar flexor torque between symptomatic and asymptomatic AT's and found that there were significant deficits. The conclusion reached

after AUC analysis was that a deficit of 50Nm of force reflects a predisposition to Achilles tendinopathy.

O'Neill et al. (2019) investigated plantar flexor torque in both a straight and bent-knee position, with the latter allowing the Soleus to function and creating a biomechanical disadvantage for the Gastrocnemius due to its anatomical locations. The difference between symptomatic and asymptomatic limbs was not significant, however, the differences between symptomatic and control participants were significant, and these differences exceeded the MDC value. As there were large deficits between symptomatic and control participants in knee flexion, it was concluded that the Soleus must play a larger role in generating plantar flexor torque than first anticipated and that deficits of up to 36% in the muscle must be a by-product of Achilles tendinopathy.

Many biomechanical factors have been associated with Achilles tendinopathy, yet the exact aetiology of the condition is still unclear. Whether these risk factors are causative or consequential is still unknown. It is likely that biomechanical risk factors link closely with physiological risk factors and that there is no single cause of the pathology. Whilst complex laboratory work is ongoing into the physiological and biomechanical risk factors associated with Achilles tendinopathy, much of this is not transferrable to a clinical scenario due to the complexity of the equipment and the intensity of the tasks required in sport. This highlights the need for an assessment tool that can be used in conjunction with a clinical assessment that may help to identify Achilles tendon pathology objectively and track whether intervention measures influence the condition. Infrared thermal imaging will allow an objective measure of skin surface temperature and may help to provide a new angle of approach in the assessment of the condition based on the known physiology and biomechanics of the condition.

### 2.6.3 Clinical assessment of Achilles tendinopathy

A combination of a subjective and an objective assessment is utilised to assess the severity of Achilles tendinopathy. Typically, the most common onset of the condition described by a patient is gradual, over a prolonged time period, and in the midportion of the AT, with chronic midportion tendinopathy being the most prevalent condition (O'Neill, 2016). However, descriptions can vary depending on the type of tendinopathy, as some can be reactive, or have reactive components on existing degenerative areas, or some could be

present at the insertion onto the calcaneus (Cook et al., 2016; Nicola Maffulli et al., 2020). It is therefore important not to assume chronic midportion Achilles tendinopathy solely based on time, although this may help to understand whether the symptoms are reactive, degenerative, or hybrid. Key to clinical assessments are the terms sensitivity and specificity. With clinical testing, sensitivity refers to the test correctly identifying those with the condition in question, whereas specificity refers to correctly identifying those without the condition (Swift et al., 2020).

Patients often describe chronic midportion Achilles tendinopathy as focal pain and stiffness located 2-6cm proximal to the insertion on the calcaneus, with associated difficulty on the initiation of loading activities (Hutchison et al., 2013; Kountouris & Cook, 2007; Reiman et al., 2014; Rio et al., 2014). Characteristically, the pain and stiffness ease as the activity progresses, leaving the patient with a residual aching after cessation of the exercise.

Self-reported pain, scored on the numerical pain rating scale (NPRS), can indicate the severity of the symptoms that the patient has, with high sensitivity (0.78, 95% CI 0.58, 0.94) and specificity (0.77, 95% CI 0.60, 0.91) (Hutchison et al., 2013). Hutchison et al. (2013) evidenced that the NPRS has very good intra-rater reliability ($k=0.81$, $p<0.001$) and good inter-rater reliability ($k=0.75$, $p<0.001$). The NPRS has excellent correlation ($r=0.93$, $p<0.05$) with the visual analogue scale (VAS) (Thong et al., 2018), and is easier and quicker to obtain from a patient mid-way through a subjective examination.

Another clinical symptom that the patient may report during the subjective assessment is AT morning stiffness. Often patients will elude to symptoms that are present in the midportion of the AT during the first few steps when they get out of bed in the morning. AT morning stiffness has high sensitivity (0.89, 95% CI 0.75, 0.98), however, the specificity values are lower (0.58, 95% CI 0.38-0.77) (Hutchison et al., 2013). Hutchison et al. (2013) evidence that AT morning stiffness has very good intra-rater reliability ($k=0.88$, $p<0.001$) and good inter-rater reliability ($k=0.79$, $p<0.001$).

A useful outcome measure that can be used for assessing the severity of chronic midportion Achilles tendinopathy is the VISA-A questionnaire. The VISA-A is self-administered, allowing the patient to grade their level of symptoms, which allows a clinician to determine the clinical severity and response to load. The progress of the condition can then be monitored throughout a treatment regime. It is a reliable measure of pain levels and function in a clinical

setting for an athletic population (Dogramaci et al., 2011; Lohrer & Nauck, 2009; Maffulli et al., 2008; Murphy et al., 2018; Robinson et al., 2001; Sierevelt et al., 2018; Silbernagel, Thomeé, & Karlsson, 2005). The questionnaire has also been shown to have good face, content, concurrent, construct and criterion validity (Lohrer & Nauck, 2009; Robinson et al., 2001; Silbernagel et al., 2005).

From the subjective assessment, the clinician will often have a differential diagnostics list, a list of potential conditions that share similar symptoms. These could include the following: paratendinopathy, tendon tear, Achilles tendon ossification, retrocalcaneal bursitis, superficial calcaneal bursitis, tibialis posterior tendinopathy, flexor tendon tendinopathy, peroneal tendinopathy, sural neuropathy, calcaneal traction apophysitis, dysfunctions of the talocrural or subtalar joints, arthritic changes, posterior ankle Impingement, plantar fasciopathy, lower leg muscle injury and referred pain (Cook et al., 2002; Nicola Maffulli et al., 2020; O'Neill, 2016; Reiman et al., 2014; Webborn et al., 2015). Some of the conditions may be ruled out based on signs, symptoms, or location, but for those that are not, the objective assessment may help to exclude them.

Much of the objective examination is formed from a standard musculoskeletal assessment, observing the site of injury and assessing posture, range of movement, flexibility, strength, and general function. However, certain tests are specific to ruling in or ruling out the presence of midportion tendinopathy. Objective tests specific to midportion Achilles tendinopathy are outlined by Hutchison et al. (2013). It is important to consider that one objective test alone is not sufficient for diagnosis as they are not 100% sensitive or specific. However, there is also a question as to whether a triangulation of tests leads to a more accurate clinical impression with both Hutchison et al. (2013) and Maffulli et al. (2003) suggesting that a combination of tests did not improve sensitivity or specificity values. This emphasises the difficulty of reaching a truly accurate diagnosis from an objective perspective and highlights the importance of combining findings with subjective information.

The most sensitive objective test is palpation of the midportion of the AT (0.84, 95% CI 0.68, 0.98) (Hutchison et al., 2013; Trevethan, 2017). Hutchison et al. (2013) also found that palpation had good specificity (0.73, 95% CI 0.53, 0.92), a finding consistent with results by Maffulli et al. (2003)(0.84, 95% CI 0.75, 0.91). The test had excellent intra-reliability (k=0.96) and very good inter-rater reliability (k=0.74) (Hutchison et al., 2013). De Vos, Van Der Vlist,

Winters, Van Der Giesen, and Weir (2020) recently highlighted in an editorial painful palpation was the most used diagnostic criteria in Achilles tendinopathy.

Crepitus in the midportion of the tendon during passive ankle movement had perfect specificity (1.00, 95% CI 1.00, 1.00) however, its sensitivity was poor (0.03, 95% CI 0.03, 0.08) (Hutchison et al., 2013). This clinical test is conducted by gently squeezing the AT in the midportion and feeling for crepitus during passive ankle joint movement, and it is based upon the subjective opinion of the examiner. Despite the excellent specificity in ruling out midportion tendinopathy, the intra-rater reliability is only classified as good (k=0.66) and the inter-rater reliability of the test is poor (k=-0.02), meaning that the test may not be reproducible between clinicians and may be dependent on the experience of the examiner.

The Royal London Hospital (RLH) test had excellent specificity (0.93, 95% CI 0.83, 1.00), a result comparable to those found by Maffulli et al. (2003)(0.91, 95% CI 0.86, 0.95). The RLH test is conducted by initially palpating the midportion of the AT with the foot in neutral, then again in maximum dorsiflexion, with a positive test being a significant reduction or complete resolution of symptoms. The sensitivity of the RLH test was 0.51 (95% CI 0.33, 0.70). The RLH test had good intra-rater reliability (k=0.70) and fair inter-rater reliability (k=0.37), indicating that the agreement between clinicians can lack accuracy and may again be dependent on the clinical experience of the examiner.

The Arc sign test also had perfect specificity (1.00, 95% CI 1.00, 1.00) in ruling out midportion tendinopathy (Hutchison et al., 2013). Maffulli et al. (2003) found that the specificity of the test was 0.83 (95% CI 0.72, 0.91). These differences in results may have existed due to the variation in the defined methodology of the test. The Arc sign test is conducted by palpating the swelling at the midportion of the AT and asking the patient to actively plantarflex and dorsiflex the ankle. A positive test would be the swelling moving with the motion of the ankle joint, indicating that the swelling is contained within the tendon. Maffulli et al. (2003) stated that in the absence of swelling, the examiners would select an area 3cm proximal to the AT insertion and attempt to replicate the test, which seems confusing as a positive test was based upon swelling being present at the site. The sensitivity of the Arc sign test was 0.25 (95% CI 0.09, 0.44). The Arc sign test had very good intra-rater reliability (k=0.80) and good inter-rater reliability (k=0.77).

Maffulli et al. (2003) assessed the combined sensitivity of the palpation, RLH, and Arc sign test. They concluded that the overall sensitivity was 0.59 (95% CI 0.47, 0.74) and the specificity was 0.83 (95% CI 0.76, 0.89). This result indicates that when combined the tests are stronger at ruling out the presence of midportion Achilles tendinopathy. Critically, the process was repeated on each subject by three examiners consecutively. The tests can be provocative for symptomatic patients, which may have affected the individual and combined sensitivity, specificity, and inter-rater reliability values discussed above.

During the objective assessment, it is important not only to conduct hands-on assessments but to assess the level of function that the patient has in response to load. A single-leg heel raise test is an assessment method that has been shown to have high specificity (0.93, 95% CI 0.82, 1.00) (Hutchison et al., 2013). The aim of the test is for the patient to raise onto their toes concentrically and lower back to the ground eccentrically, with pain in the midportion of the tendon being a positive test.

Despite a battery of clinical tests being available for the detection of chronic midportion tendinopathy, in some instances, it may still be necessary to utilise imaging technology to diagnose symptoms. Traditionally, US and MRI scans have been classed as the gold standard for diagnosis of Achilles tendinopathy, with sensitivity values of 0.72-0.87 being reported in the literature however a clear consensus on the gold standard tool is still lacking (Docking, Ooi, et al., 2015; Kainberger et al., 1990; Khan et al., 2003). US imaging is generally cheaper and easier to conduct than an MRI scan and can often have a better spatial resolution, meaning that it is used more frequently for the assessment of Achilles tendon disorders (Sunding et al., 2016). It would typically present as a hypoechoic region on an image, which refers to a darker grey region. Accompanying this could be an increase in the cross-sectional area (CSA) within the midportion of the tendon or increases in anterior-posterior (A-P) thickening. Alterations in AT A-P thickness have recently been identified as indicators of clinical symptoms in moderately active adults (Corrigan et al., 2020). However, recent research suggests that it is not always accurate when compared with the assessment of clinical symptoms in elite runners (Hullfish et al., 2018). A limitation to greyscale US is the difficulty in quantifying pathological change as it presents a two-dimensional image of a three-dimensional structure.

However, Sunding et al. (2016) showed that identifying characteristics of pathology was possible, attempting to quantify these pathological changes using greyscale US and found

that there were significant differences in mean thickness structure as measured using the modified Öhberg scale. Neovascularisation was also measured using colour doppler, and differences were found to exist. Reliability readings for tendon thickness were excellent, but the quantification of structural changes between observers was variable dependent on observer experience, limiting its applicability.

Ultrasound tissue characterisation (UTC) is a method of assessing a tendon based on the categorisation of tissue echo types, derived from equine studies (van Schie et al., 2010). The tissue is categorised into four echo types; highly stable, medium stable, highly variable, and constantly low intensity and distribution. Van Schie et al. (2010) found that there were clear differences in echo type between symptomatic and asymptomatic participants, with a 25% difference in echo types I and II, with the overall accuracy for diagnosis was found to be 83%.

Similar results were found in a recent study by Rabello et al. (2020), with increased echo type I and decreased echo types III and IV in comparison to control tendons. Interestingly, it was also found that differences in echo types existed between the asymptomatic tendon and control participants, which suggested that there could be some cross-adaptational responses to chronic midportion tendinopathy. This finding was also confirmed in an earlier study by Docking, Rosengarten, Daffy, & Cook (2015).

The effectiveness of UTC as an assessment method for chronic midportion tendinopathy is still debated. Docking, Rio, Cook, Carey, & Fortington (2019) concluded that UTC used for the assessment of collagen integrity was not a useful measure for the prediction or severity of clinical symptoms. Similarly, Wezenbeek et al. (2018) found that UTC could not sufficiently identify structural predictive factors for tendinopathy development. They found contrasting results to Rabello et al. (2020) in that the presence of differences in echo types III and IV were marginal. This difference between Rabello et al. (2020) and Wezenbeek et al. (2018) could have been present due to differences in the mean ages of the samples, with the latter authors utilising University students (mean age 17.85 ± 0.53 years vs 47.8 ± 12.0) which are not representative of the normal age group at risk of tendinopathy (Jonge et al., 2011).

It is clear from the literature that there is variability in the results of objective tests and that there is no consensus regarding the gold standard assessment tool for Achilles tendinopathy. Due to the complexity and expense of the equipment, much of it is not often

used clinically. Clinicians often rely on the subjective and physical part of the objective assessment, which when combined provide high values of specificity, which helps them to rule out other pathology and arrive at a clinical diagnosis of chronic midportion Achilles tendinopathy (Silbernagel, Hanlon, & Sprague, 2020).

### 2.6.4 Exercise-based management of Achilles tendinopathy

The treatment with the highest level of evidence for chronic midportion tendinopathy is exercise-based rehabilitation (Pavone et al., 2019; Silbernagel & Crossley, 2015). Isometric exercises are often associated with acute pain relief for tendinopathy, based on studies that have been conducted in the patella tendon (Rio et al., 2015, 2017). However, this was not found to be the case in the AT (O'Neill, Radia, et al., 2019). It is difficult to consider isometrics as a standalone treatment technique for chronic midportion tendinopathy when there is evidence to suggest the use of loading programs are beneficial for the tendon physiologically, biomechanically, and clinically over a short time-period (Beyer et al., 2015; Geremia et al., 2018; Habets & Cingel, 2015; Habets et al., 2017; O'Neill, Watson, & Barry, 2015). Additionally, research by O'Neill et al. (2019) has suggested that the plantar flexors must be rehabilitated to cope with eccentric loads of two times BW which would not be achievable with isometrics alone.

It is known that tendons respond well to controlled load so that they can maintain their physiological and biomechanical properties and prevent maladaptation (Docking & Cook, 2019; Magnusson & Kjaer, 2019). Achilles tendinopathy has traditionally been successfully managed using the Alfredson protocol (Alfredson, Pietilä, Jonsson, & Lorentzon, 1998; Beyer et al., 2015; Habets, Van Cingel, Backx, & Huisstede, 2017). However, there are limitations to this protocol. Firstly, there is a lack of concentric resistance applied to the plantar flexors. Purely eccentric exercise has been shown to insufficiently rehabilitate symptomatic limbs to the same strength levels as healthy controls (O'Neill, 2016). Secondly, the Alfredson protocol is conducted twice daily, 7 days per week, for 12 weeks. It consists of 2 exercises, both performed for 3 sets of 15 repetitions. This amounts to 180 repetitions per day for 12 weeks. This equals a total volume of 1260 repetitions per week. Performing 180 repetitions of purely eccentric exercise is both time-consuming and likely to induce high levels of delayed-onset muscle soreness, which may explain why patient satisfaction scores are higher in a HSR training programme (Beyer et al., 2015). Patient satisfaction is an important consideration for any rehabilitation programme, as a lack of it may result in reduced patient adherence.

Additionally, from a physiological perspective, this high volume may leave little time for optimal tendon adaptation to occur and may lead to alterations in stiffness properties of the tendon which may impact recovery and performance (Bohm, Mersmann & Arampatzis, 2015; Docking & Cook, 2019). There is a lack of research surrounding Gastrocnemius-Soleus strength changes as a direct result of the Alfredson eccentric protocol, however, a recent review in strength training in distance runners would suggest that the loads required to facilitate strength gains would far exceed those of body weight exercise, and would likely be too high from a volume perspective to conduct in line with the Alfredson protocol (Trowell, Vincenzino, Saunders, Fox & Bonacci, 2020).

Recently, HSR training has shown promising results. It is a protocol consisting of three exercises, containing a 3-second concentric component and a 3-second eccentric component, but there is limited evidence for it (Beyer et al., 2015; Habets et al., 2017; Silbernagel & Crossley, 2015). Theoretically, the prolonged slow load should favour the tendon and allow positive adaptation to occur if the AT is worked at the mechanostat point (Docking & Cook, 2019; Magnusson & Kjaer, 2019; Silbernagel et al., 2020).

Beyer et al. (2015) are the only researchers, to the author's knowledge, that have investigated the effects of HSR training versus the Alfredson eccentric protocol and its effects on Achilles tendinopathy. Patient satisfaction was higher in the HSR training group at 12-week follow-up when compared to the Alfredson eccentric group, however, physiological characteristics did not differ between the HSR group and the eccentric group in the AT.

HSR has been shown to produce lower strain rates which are beneficial for chronic mid-portion Achilles tendinopathy and Patella tendinopathy (Bah et al., 2017; Beyer et al., 2015; Kongsgaard et al., 2010). HSR training has been shown to induce physiological changes in tendon structure in the Patella tendon, such as increasing the density of fibres and reducing their cross-sectional area in patients suffering from Patella tendinopathy, alongside 27% ± 7% improvement in Victorian Institute of Sports Assessment – Patella tendon scores (Kongsgaard et al., 2010). It may be possible that it causes physiological changes within the AT, such as reducing pathological compliance and improving neuromuscular control as has been demonstrated with plyometric training (Hirayama et al., 2017; Werkhausen et al., 2018, 2019), however, this would require further investigation and is an emerging research area.

Based on what is known about tendon adaptation, HSR training may be beneficial for chronic midportion tendinopathy, as the progressive nature of the load throughout the programme may help to shift the mechanostat point of the tendon (Docking & Cook, 2019). The mechanostat point has been defined as the level at which load induces positive or negative tendon responses and has been shown fluid based on long term load in tendon cells (Arnoczky et al., 2008; Lavagnino et al., 2015; Szczesny et al., 2018). However, it is not known how HSR and eccentric training differ with regards to altering the mechanostat point of the AT.

More recently, the Silbernagel protocol has emerged for the treatment of mid-portion Achilles tendinopathy (Silbernagel & Crossley, 2015). This is a progressive programme that consists of numerous loading exercises dependent on the phase. The exercises are performed once daily, with varying sets and repetitions, with phase 2 focusing on body weight and amounting to a large volume of 1680 repetitions per week. Phase 3 consists of a maximum of 585 repetitions and is performed 2-3 times per week and gradually introduces heavier load based on the numerical pain rating scale. This quantity is less than half of the Alfredson eccentric protocol but slightly more than the heavy slow resistance protocol. To date, there has been no study completed comparing the Silbernagel protocol to the Alfredson or HSR protocol, only Habets et al., (2017) have proposed a methodology for a randomised control trial.

Both the heavy slow resistance programme and the Silbernagel programme incorporate a concentric component to each exercise. The Silbernagel programme has a plyometric component, which arguably makes it the most sport-specific programme, but future controlled studies are needed to assess long term outcomes of the programme.

The reviewed research presented within this review suggests that the HSR programme is a promising programme as it allows sufficient recovery time for positive AT adaptation to occur, has lower strain rates, has had positive physiological effects on the Patella tendon and has greater patient satisfaction scores than previously utilised programmes (Docking & Cook, 2019; Magnusson & Kjaer, 2019; Silbernagel et al., 2020). However, more research is needed to assess the programme prior to advocating its use on a wider scale for the management of Achilles tendinopathy.

## 2.7 Summary

Pathological AT's are thought to display higher levels of hysteresis, lower levels of exercise-induced tendon blood flow, and a higher inflammatory response than symptomatic tendons (D'Addona et al., 2017; Wang et al., 2012; Wezenbeek et al., 2018), all of which point towards the possibility of local heat change. IRC's have been utilised successfully for a number of other pathologies to track local TSK changes (van Doremalen et al., 2019); Wilkinson et al. 2018); Jaspers et al. 2017; Kanazawa et al. 2016). There is a gap in the literature relating to the measurement of AT TSK for the assessment of chronic AT pathology.

Chronic midportion Achilles tendinopathy is a prevalent condition in runners that can lead to pain and reduced function (Beyer et al. 2015; Kujala et al. 2005; O'Neill, 2016). Three AT specific rehabilitation programmes are known to exist (Alfredson et al. 1998; Beyer et al. 2015; Silbernagel & Crossley, 2015). As identified in the literature review, the HSR programme appears promising due to the sufficient recovery time for positive AT adaptation to occur, lower strain rates, positive physiological effects and greater patient satisfaction scores than previously utilised programmes (Docking & Cook, 2019; Magnusson & Kjaer, 2019; Silbernagel et al., 2020). As exercise-based rehabilitation is known to lead to adaptational responses, both physiologically and biomechanically, and the equipment required to quantify these changes is complex and expensive, it could be possible that infrared thermal imaging cameras may play a role in measuring progress.

Therefore, the aims of this thesis are:

- To develop a reliable method of determining AT midportion TSK
- To establish the normal baseline TSK of symptomatic and asymptomatic individuals
- To establish the normal ΔTSK of symptomatic and asymptomatic individuals in response to running or hopping tasks
- To establish the effect of a 12-week HSR training programme on ΔTSK response in symptomatic individuals

# Chapter THREE

# Methodology

## 3.1 Chapter overview

Contained within this chapter are the individual studies that were undertaken to arrive at a robust reliable final methodology that was used to assess the TSK of the midportion of the AT. Study one investigated the reliability of the method of analysis used to assess the TSK of the midportion of the AT. Study two investigated the effect of distance and angle of the IRC on TSK at the midportion of the AT. Study three investigated the repeatability of the FLIR ONE IRC and calculated new intraclass correlation coefficients for reliability at a 0.6m distance. The final part of this section outlines the final methodology employed for the remainder of the thesis.

## 3.2 Chapter introduction

With recent improvements in technology, the introduction of smartphone-based IRC's has become increasingly popular due to their cost and ease of use. Smartphone-compatible devices are less expensive than handheld devices, meaning that they are more affordable for clinicians. However, questions have arisen around the reliability and validity of the devices for use in human TSK measurement as outlined in chapter 2 of this thesis. The FLIR ONE IRC is deemed to have a lower specification than most handheld devices (table 3.1), having lower properties for accuracy, infrared (IR) resolution, spatial resolution (instantaneous field of view (IFOV)) and thermal sensitivity. These terms are defined in table 3.2. Despite this, excellent criterion and convergent validity have been demonstrated for the FLIR ONE when compared against other TSK measurement devices, as discussed in chapter 2. The supervisory team also established that the FLIR ONE had excellent construct validity to provide proof of concept before the start of this PhD, which can be found in appendix 1.

Table 3.1: The specification of the FLIR ONE and FLIR E8 infrared thermal imaging cameras

| **Specification** | **FLIR E8** | **FLIR ONE** |
|---|---|---|
| Infrared resolution (IR) | 320x240 | 160x120 |
| Multi-spectral Dynamic Imaging resolution (MSX) | 320x240 | 640x480 |
| Accuracy | +/- 2% | +/-5% |
| Field of View (FOV) (Horizontal/Vertical) | 45°x°34 | 46°x35° |
| Spatial Resolution/Instantaneous Field of View (IFOV) | 2.6mrad | 11.6mrad |
| Thermal Sensitivity | <60mK | 150mK |
| Spectral Range | 7.5-13µm | 8-14µm |
| Minimum Focus Distance | 0.5m | 0.3m |

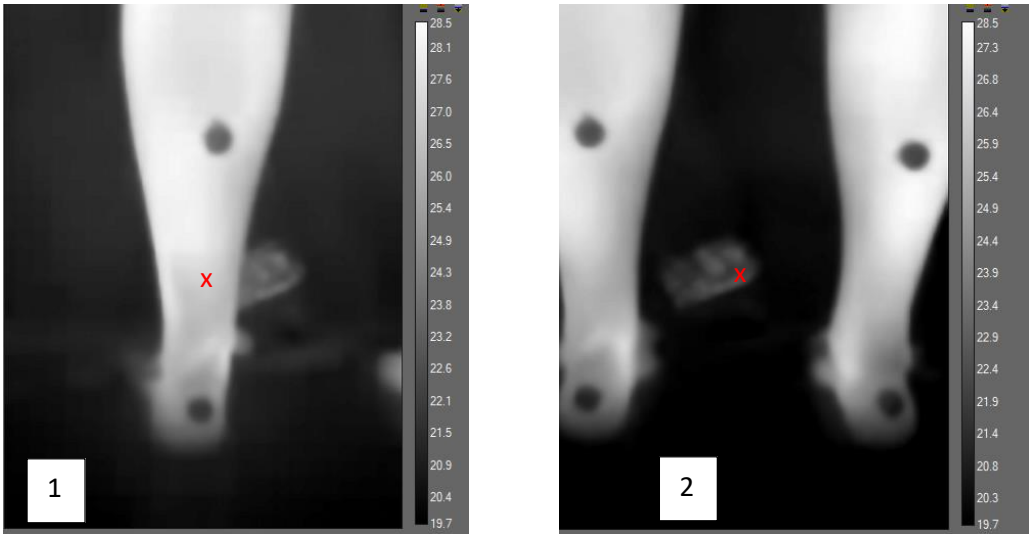
Table 3.2: Definitions of infrared thermal imaging terms

| | |
|---|---|
| IR resolution | The number of pixels contained within an image. One pixel is one temperature datum point. |
| MSX technology | The combination of an infrared thermal image and a digital image to create a single infrared thermal image with skeletonised digital detail |
| Accuracy | The manufacturer stated percentage difference in a measured temperature and the known temperature of a reference source |
| FOV | The largest area that an infrared thermal camera can detect |
| IFOV | Often termed spatial resolution. An angular projection of one single pixel in the infrared image |
| Thermal sensitivity | The smallest difference in temperature that an infrared thermal imaging camera can detect over temporal noise |
| Spectral range | The wavelength range that the infrared thermal imaging camera can detect |
| Minimum focus distance | The smallest distance from an object at which the lens of the camera is able to focus |

The improvement in technology in the IRC's has led to the introduction of multi-spectral dynamic imaging (MSX). The technology combines a digital and thermal image that are taken at the same instant, enhancing the thermal image with digital detail. It allows images from the visible spectrum to be seen interpolated with images from the long-infrared range of the electromagnetic spectrum (Langemo & Spahn, 2017). It is important to clarify that this does not enhance the thermal capabilities of the camera which remain at 120x160 pixels, but the 480x640 pixel digital camera allows image interpolation creating a temperature point every 4 pixels on the digital image.

The FLIR ONE has previously been shown to have excellent reliability, as discussed in chapter 2. Only one study has previously reported SEM values for the IRC (0.2°C) however none have reported MDC values. It is important to understand what these values are to understand the ΔTSK values that are required for statistically significant change that is not associated with random error. It is also important to understand the agreement between the FLIR ONE and handheld devices to know whether TSK values can be compared between the two. Agreement is defined as the level of concurrence between the two devices (Liu et al., 2016; Ranganathan et al., 2017)

It is apparent from existing literature that there is a lack of standardised methodology between studies which makes direct comparisons difficult (Quesada et al., 2016; Ratajczak & Boerner, 2015; Rodríguez-Sanz et al., 2017; Fernando Sanz-López et al., 2016; Tumilty et al., 2019). Differing ROI's are used as well as different IRC positions, with varying distances from the ROI and varying angles, with some perpendicular to the ROI on the measured limb (single-limb measure – ROI central on image), and some perpendicular to the area of interest (bilateral measure - both ROI's on the same image). An example of this can be seen in figure 3.1.




X = the focal point of the IRC

Figure 3.1: An example of a thermal image perpendicular to the ROI (1) and perpendicular to the area of interest in line with the midline of the body (2)

Grgić & Pušnik (2011) found that the size of the source effect led to decreasing camera signal when targets were measured that subtended smaller angles as a proportion of the IFOV. Placing the camera perpendicular to the ROI at a closer distance would capture more pixels than placing it perpendicular to the area of interest and capturing both limbs simultaneously. Distances exceeding 1m from the ROI would encompass other anatomical locations and reduced the overall pixel count within the AT ROI. Therefore, the effect of moving the camera placement backwards within this range, and between angular placements must be assessed to identify if this affects absolute TSK readings.

A 20° angular change was found to be equivalent to a 35cm variation in the horizontal distance at a fixed 1m position and did not influence TSK values (Westermann et al., 2013). However, the properties of equine and human skin are different, therefore the results from equine studies cannot be assumed for human TSK.

Ammer (2006) assessed how angular change of the participant from the camera affected TSK readings on the face. The total number of pixels that covered the face changed by as much as 3.7%, yet the repeatability of the measures remained high (ICC 0.84-0.86). This study focused on reliability and did not report the interaction between distance and angle on TSK.

The repeatability of smartphone-based IRC's has been questioned previously due to a principal called thermal drift, which is defined as deviations in temperature readings due to

instability of lens and internal camera temperatures, and not due deviations in radiation from the measured object (Strakowski & Wiecek, 2016). The FLIR ONE uses an uncooled microbolometer detector focal plane array for each pixel, the Lepton 3, which captures longwave infrared radiation and assigns the pixel a colour based on the level of infrared radiation captured (*FLIR LEPTON® 3 Long Wave Infrared (LWIR) Datasheet*, 2017).

To attempt to combat the issue of temperature drift, the FLIR ONE's Lepton 3 uncooled microbolometer has an automated system called scene-based non-uniformity correction (NUC), that uses a mechanical shutter to compensate for the effects of thermal drift (*FLIR LEPTON® 3 Long Wave Infrared (LWIR) Datasheet*, 2017; Strakowski & Wiecek, 2016). The mechanical shutter provides a momentary uniform scene, and the camera then automatically updates the NUC to provide a uniform output, a process that takes less than one second. It is important to understand whether this NUC affects TSK readings in humans over a period of time, to see whether there is a high degree of repeatability.

Vardasca, Magalhaes, Silva, Kluwe, & Mendes (2019) found that the FLIR ONE was prone to start-up drift, that is the drifting of temperature once the camera was switched on and adjusted to the environmental surroundings. There was a stabilisation period of between 15 and 20 minutes. Drift testing revealed an overestimation of absolute TSK when compared to a blackbody source, emphasising the caution that must be drawn when comparing absolute TSK agreement between devices differing in specification. It is therefore important to understand whether the FLIR ONE can measure absolute TSK values of the midportion of the AT accurately against itself over multiple time periods.

Therefore, the aims of this chapter were:

1. To determine the intra-rater and inter-rater reliability of the method of TSK analysis at 0.5m and 1m distances, with associated SEM's and MDC's for a smartphone-based IRC and a handheld IRC
2. To determine the agreement between the devices
3. To determine the repeatability of the FLIR ONE for measuring human midportion AT TSK
4. To determine the effects of distance and angle on absolute TSK values at the midportion of the AT.

To do this, the chapter will be split into sections and will contain individual hypotheses.

## 3.3 The reliability of an Achilles tendon infrared image analysis method

### 3.3.1 Aims

1. To determine the intra-rater and inter-rater reliability of the method of TSK analysis at 0.5m and 1m distances, with associated SEM's and MDC's for a smartphone-based IRC and a handheld IRC
2. To determine the agreement between the devices

### 3.3.2 Hypotheses

The section been broken down into a series of individual hypotheses in order to create transparency for the individual elements of the chapter that are being assessed. This has been conducted in each of the experimental chapters.

1. The method of analysis for the FLIR ONE would demonstrate excellent intra-rater reliability at 0.5m from the ROI
2. The method of analysis for the FLIR ONE would demonstrate excellent intra-rater reliability at 1m from the ROI
3. The method of analysis for the FLIR E8 would demonstrate excellent intra-rater reliability at 0.5m from the ROI
4. The method of analysis for the FLIR E8 would demonstrate excellent intra-rater reliability at 1m from the ROI
5. The method of analysis for the FLIR ONE would demonstrate excellent inter-rater reliability at 0.5m from the ROI
6. The method of analysis for the FLIR ONE would demonstrate excellent inter-rater reliability at 1m from the ROI
7. The method of analysis for the FLIR E8 would demonstrate excellent inter-rater reliability at 0.5m from the ROI
8. The method of analysis for the FLIR E8 would demonstrate excellent inter-rater reliability at 1m from the ROI
9. There would be excellent inter-device agreement between the FLIR ONE and the FLIR E8

### 3.3.3 Methods

#### 3.3.3.1 Ethical approval

Ethical approval was granted by the University of Salford Research, Enterprise and Engagement Ethical Approval Panel. The ethical approval number was HSR1718-032 and can be seen in appendix 2.

#### 3.3.3.2 Participant recruitment

Participant recruitment was conducted through poster and verbal advertisement at the University of Salford in the Sport Rehabilitation degree programme after consultation with the programme leader. An example of the recruitment poster can be seen in appendix 3.

Upon expressing their interest in taking part in the study, an information sheet was forwarded to participants (appendix 4). They were initially given the opportunity to respond via email or telephone to discuss any queries that they had regarding the study. They then attended for testing at the University of Salford human performance laboratory, whereupon attendance they were asked to read a copy of the information sheet and sign a consent form (appendix 5) once the procedures had been verbally explained.

Testing took place across two days. 7 participants were recruited in line with recommendations from Bujang & Baharum (2017)(4 male, 3 female, aged 18.6 ± 1.6 years, height 173.7 ± 6.3cm, mass 73.8 ± 8.kg).

#### 3.3.3.3 Inclusion and exclusion criteria

All participants were between the ages of 18-60, involved in a minimum of 3 hours of exercise per week, in good health and scored 100 in the VISA-A questionnaire section of the physical activity readiness questionnaire (PAR-Q) (appendix 6). Participants were required to adhere to strict pre-participation criterion in line with recommendations by Moreira et al. (2017). Before any of the testing sessions, participants were instructed to avoid consumption of alcoholic beverages, caffeine products and to avoid smoking on the day of testing. Participants were asked not to eat a large meal in the four hours before testing. Participants were asked not to apply any lotions or cosmetics to their skin on the day of testing and they were asked not to shower within 4 hours of testing. If any participant failed to adhere to any of these criteria, they were excluded from testing.

#### 3.3.3.4 Anthropometric measures

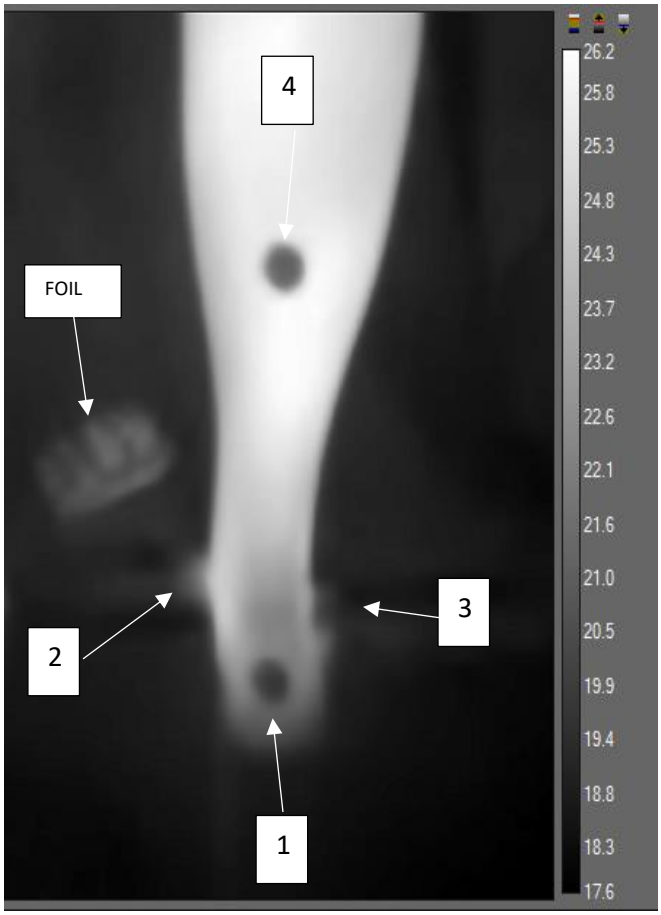
All participants who attended testing sessions underwent an anthropometric assessment which included standing height, sitting height and weight. Standing and sitting height were measured using a Leicester SECA 213 height measure (Seca Deutschland, Hamburg, Germany), to the nearest 0.1cm. For both, the participants were instructed to hold their head in the Frankfort plane, to take a deep breath in and hold it whilst the measurement headboard was placed onto the Vertex. Weight was measured using a Seca 769 (Seca Deutschland, Hamburg, Germany) digital scale to the nearest 0.1kg. All measurements were conducted in line with the International Standards for Anthropometric Assessment guidelines, which involved a mean of two measures for each variable (Marfell-Jones et al., 2011)

#### 3.3.3.5 Room temperature

Ambient temperature and room humidity were recorded for all testing sessions and between participants, using a digital weather station. These values were then applied individually to each thermal image in FLIR Research IR Max (v4.40.9.30, FLIR Systems, Oregon, US) so that the resultant temperature values were as accurate as possible. The experiments were conducted away from any external light sources and drafts so the environment remained constant.

#### 3.3.3.6 Anatomical markers

Thermally inert wooden markers were placed onto the following anatomical landmarks of each participant before the acclimatisation phase: calcaneus, medial and lateral malleolus, and at the joining point of the medial and lateral heads of the Gastrocnemius. These can be seen in figure 3.2.




1. Calcaneal marker
2. Medial Malleolus marker
3. Lateral Malleolus marker
4. Muscle tendon junction marker
5. FOIL – Reflective foil

Figure 3.2: An image obtained from the FLIR ONE with anatomical markers

#### 3.3.3.7 Acclimatisation procedure

Prior to any thermal data collection, participants underwent a 15-minute acclimatisation period in line with TISEM recommendations (Moreira, Costello, et al., 2017). Participants acclimatised in the standing anatomical position, stood in front of the thermal cameras, to minimise the transitional movement between that and the baseline thermal images being taken.

#### 3.3.3.8 Infrared thermal imaging cameras

Images were taken using the FLIR ONE smartphone-compatible IRC and the FLIR E8, a handheld device. The specifications of both devices can be seen in table 3.1. The FLIR ONE was switched on and allowed to stabilise from the beginning of the acclimatisation period and the FLIR E8 60 minutes before any data collection. The emissivity of each camera was set to 0.98 in line with human skin (Moreira, Costello, et al., 2017), done retrospectively for the FLIR ONE using FLIR Research IR MAX (v4.40.9.30, FLIR Systems, Oregon, US) software.

#### 3.3.3.9 Thermal data capture

A black polycotton sheet was suspended to provide a smooth and uniform background for the images, allowing a good thermal contrast. A piece of foil was placed into the image to allow the reflective temperature to be measured. A line of gaffer tape was placed parallel to this sheet, 40cm in front, which served as a line on the floor whereby participants heels could be placed, to standardise their position in from of the IRCs.

A grid of tape was then constructed using goniometer and string, to create six camera placement points at 0° perpendicular to the left and right heel markers, two at 0.5m (Figure 3.3 A and C) and two at 1m distances (Figure 3.3 D and F). Locations B and E were used in section 3.4.

Once the participants were stood barefoot in position, the IRC's were placed perpendicular to the ROI's, at locations A, B, C, D E and F on figure 3.3. This order was block randomised. Images were taken from all 6 locations but for this section, only images from positions A, C, D and F were used, so that the left and right AT's were captured at 0.5m and 1m distances.

The FLIR ONE was mounted to a clamp, with the lens being 0.21m from the ground, the lowest that it could be due to the dimensions of the device. It was connected via USB cable

to a laptop, which was used as a remote for image capture. Images were taken and stored on FLIR Research IR Max (v4.40.9.30, FLIR Systems, Oregon, US). The FLIR ONE was mounted to a tripod, with the lens 0.21m from the ground to replicate the placement of the FLIR E8.

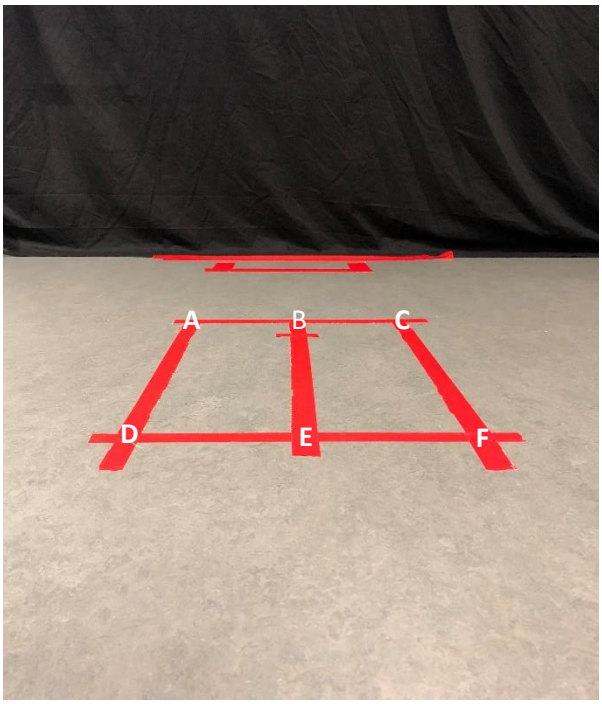



Figure 3.3 – Tape grid with camera locations (A= Left leg TSK measure at 0.5m, C = Right leg TSK measure at 0.5m, D = Left leg TSK measure at 1m, F = Right leg TSK measure at 1m)

#### 3.3.3.10 Thermal data analysis

Captured thermal images from the FLIR ONE were stored locally on the iPhone 6S. They were then transferred to Dropbox, where each file was given a coded name. From Dropbox, these files were downloaded immediately to a laptop for analysis and deleted from the Dropbox file. All images contained no identifying information relating to the participants involved.

Images captured using the FLIR E8 were stored on the laptop connected to the camera in a password-protected folder. Images were named using coding, and no identifying features or information were contained within the images.

Thermal images from both IRC's were analysed retrospectively by drawing a bendable ROI between the centre of the calcaneal marker and the marker at the MTJ through the centre of the AT, using FLIR Research IR Max (v4.40.9.30, FLIR Systems, Oregon, US).

Individual lines were then exported into Microsoft Excel (v16.0, Microsoft corporation, WA, US) as a comma-separated values (CSV) file. Two separate macros were created in Excel to automate the extraction of the mean AT TSK, one for each camera due to the different pixel dimensions. The diameter of the anatomical markers was known to be 2cm, therefore this was measured on images using both cameras. The macros then identified the respective number of pixels within the CSV file to reach a start point 2cm proximal to the insertion on the Calcaneus, the defined start of the midportion of the AT. The number of pixels that equated to a 6cm distance was followed from here, extending beyond the defined midportion of the AT to account for any anatomical variances or TSK differences that occur at the proximal border of the midportion. The mean AT TSK value was then automatically calculated by the macro based on these data points.

This method was repeated after one week to establish intra-rater reliability. One month after this a second-rater repeated the line analysis. Rater 2 had no experience in infrared thermal imaging as was provided with a written instruction sheet and visual demonstration of how to conduct the analysis.

#### 3.3.3.11 Statistical Analysis

SPSS for Windows (v24.0 SPSS Inc, Chicago, Illinois, USA) was utilised to conduct intra-rater and inter-rater reliability analyses. Assumptions of normality were assessed using the Shapiro-Wilk test and were not violated ($p>0.05$). Unless otherwise stated, data are presented as mean ± SD.

An ICC (3,1) two way-mixed effects, absolute agreement, single measurement model was used to assess intra-rater reliability, and a two-way random effects, absolute agreement, single measurement model was used to assess inter-rater reliability, in line with guidance from Koo & Li (2016). Values <0.5 were considered poor, values between 0.5 and 0.75 were considered moderate, values between 0.75 and 0.9 were considered good and values >0.9 were considered excellent.

SEM and MDC values were calculated using Microsoft Excel (v16.0, Microsoft corporation, WA, US). The formula used to calculate the SEM was $SD(pooled) * (\sqrt{1 - ICC})$ and the formula for the MDC was $1.96 * (\sqrt{2}) * SEM$. The pooled SD formula that was used was $\sqrt{\frac{(SDrating1 * SDrating1) + (SDrating2 * SDrating2)}{2}}$.

Agreement was assessed using Bland Altman analysis, the mean bias and 95% LoA in SPSS. The mean bias represented the mean difference between rating 1 and 2 for intra-rater agreement, rater 1 and rater 2 for inter-rater agreement and between the FLIR ONE and FLIR E8 for between device agreement. The 95% LoA represented the range of difference where 95% of data points would be expected to lie and was calculated using the equation $Mean\ Bias\ \pm 1.96 * SD$. The manufacturer stated accuracy of the FLIR ONE is ±5%, therefore a priori acceptable mean bias was defined as a value within 5% of the mean absolute TSK measurement. The manufacturer stated accuracy of the FLIR E8 is ±2%, therefore a priori acceptable mean bias was defined as a value within ±2% of the mean absolute TSK measurement. Proportional bias was assessed using linear regression (Doğan, 2018).

### 3.3.4 Results

The mean absolute TSK values, SD's and 95% CI's can be seen in table 3.3 for both IRCs.

Table 3.3: Mean, SD and 95% CI's for the TSK data from the FLIR ONE and FLIR E8 at 0.5m and 1m

| Camera | Distance (m) | Mean TSK (°C) | SD (°C) | 95% CI (°C) | |
|---|---|---|---|---|---|
| FLIR ONE | 0.5 | 27.7 | 1.8 | 26.8 | 28.6 |
| | 1 | 27.7 | 1.2 | 27.1 | 28.4 |
| FLIR E8 | 0.5 | 26.6 | 1.2 | 26.0 | 27.2 |
| | 1 | 26.3 | 1.4 | 25.6 | 27.1 |

#### 3.3.4.1 Intra-rater reliability

The method used to analyse TSK at the midportion of the AT demonstrated excellent intra-rater reliability at both 0.5m and 1m distances from the ROI for images captured by both IRCs. The ICC's, 95% CI's, SEM's and MDC's can be seen in table 3.4. Mean bias and LoA can be seen in table 3.5. Bland Altman plots can be seen for the FLIR ONE at 0.5m in figure 3.4, and for 1m in figure 3.5. The Bland Altman plots for the FLIR E8 can be seen in figures 3.6 and 3.7 for the respective distances.

Table 3.4: Intra-rater reliability ICC, 95% CI's, SEM's and SDD's for the FLIR ONE and FLIR E8 at 0.5m and 1m

| Camera | Distance (m) | ICC | 95% CI | | SEM (°C) | MDC (°C) |
|---|---|---|---|---|---|---|
| FLIR ONE | 0.5 | 0.99 | 0.96 | 1.00 | 0.2 | 0.5 |
| | 1 | 0.99 | 0.96 | 1.00 | 0.1 | 0.4 |
| FLIR E8 | 0.5 | 0.98 | 0.81 | 1.00 | 0.2 | 0.5 |
| | 1 | 0.95 | 0.27 | 0.99 | 0.3 | 0.9 |

Table 3.5: Intra-rater agreement of the FLIR ONE and FLIR E8

| Device | Distance (m) | Bias (°C) | Lower 95% LoA (°C) | Upper 95% LoA(°C) |
|---|---|---|---|---|
| FLIR ONE | 0.5 | 0.1 | -0.5 | 0.6 |
| | 1 | 0.1 | -0.3 | 0.5 |
| FLIR E8 | 0.5 | 0.2 | -0.1 | 0.5 |
| | 1 | 0.4 | -0.1 | 0.8 |

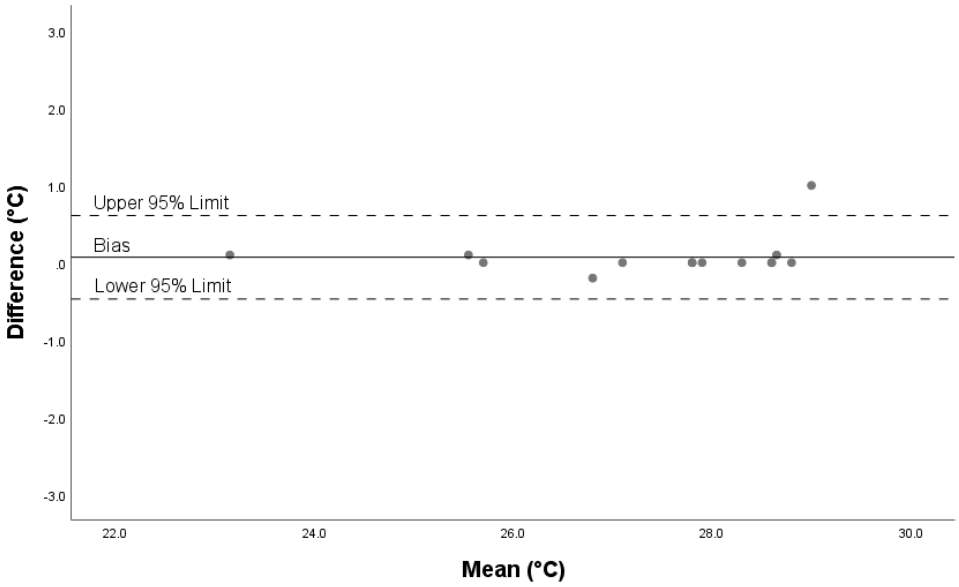



Figure 3.4: Bland Altman plot for intra-rater agreement for the FLIR ONE at 0.5m

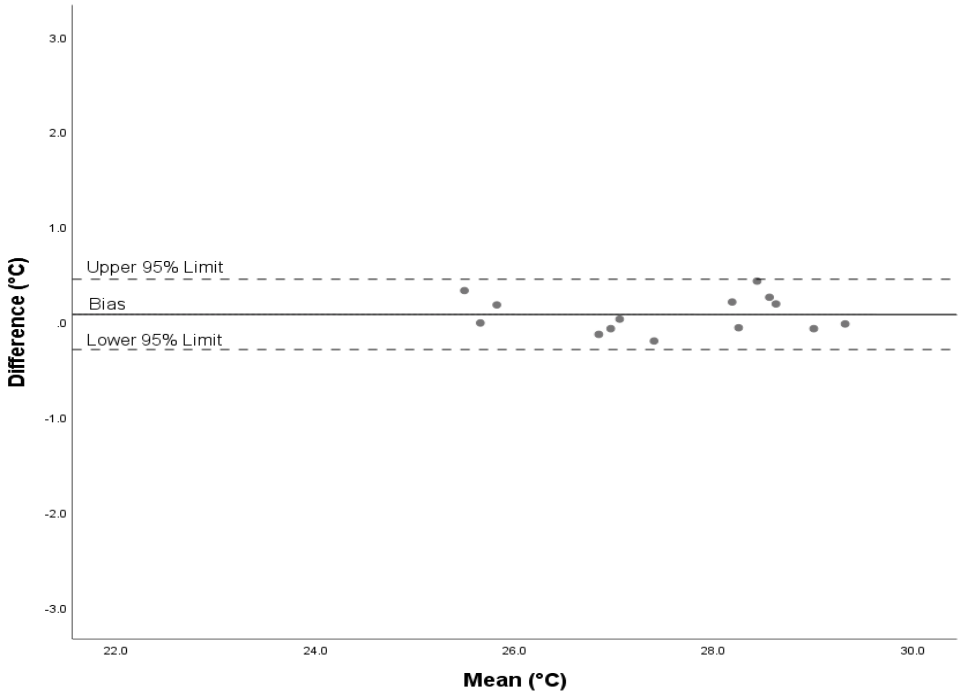



Figure 3.5: Bland Altman plot for intra-rater agreement for the FLIR ONE at 1m

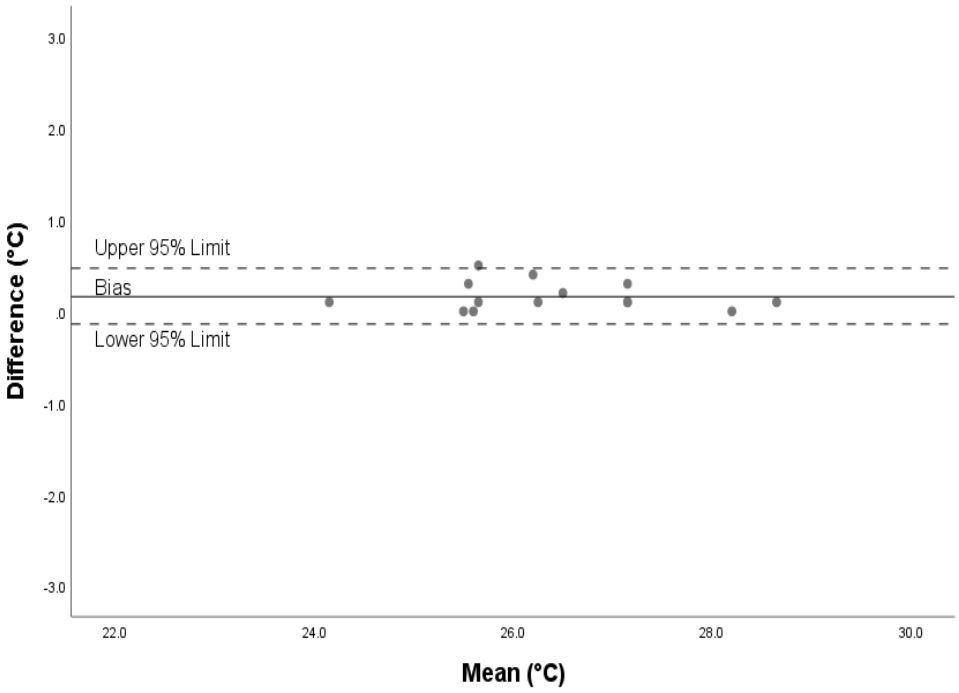



Figure 3.6: Bland Altman plot for intra-rater agreement for the FLIR E8 at 0.5m

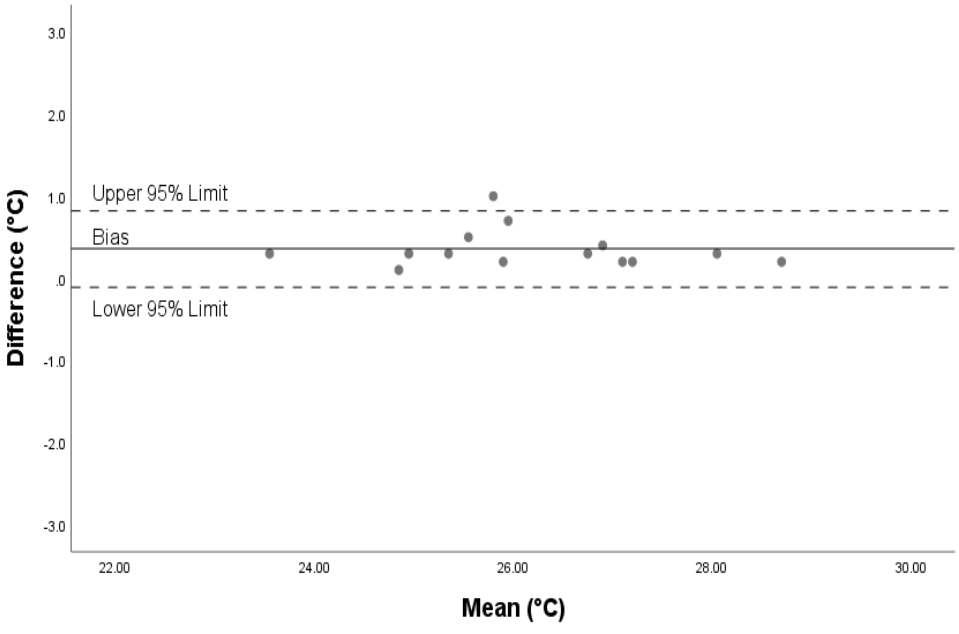



Figure 3.7: Bland Altman plot for intra-rater agreement for the FLIR E8 at 1m

#### 3.3.4.2 Inter-rater reliability

The method used to analyse TSK at the midportion of the AT demonstrated excellent inter-rater reliability for the FLIR ONE at 0.5m and the FLIR E8 at 0.5m and 1m distances from the ROI. At a 1m distance from the ROI, the method used to analyse TSK demonstrated good inter-rater reliability for data captured by the FLIR ONE. These results can be seen in table 3.6. Mean bias and LoA can be seen in table 3.7. Bland Altman plots can be seen for the FLIR ONE at 0.5m in figure 3.8, and for 1m in figure 3.9. The Bland Altman plots for the FLIR E8 can be seen in figures 3.10 and 3.11 for the respective distances.

Table 3.6: Inter-rater reliability ICC, 95% CI's, SEM's and SDD's for the FLIR ONE and FLIR E8 at 0.5m and 1m

| Camera | Distance (m) | ICC | 95% CI | | SEM (°C) | MDC (°C) |
|---|---|---|---|---|---|---|
| FLIR ONE | 0.5 | 0.97 | 0.54 | 0.99 | 0.3 | 0.9 |
| | 1 | 0.79 | 0.48 | 0.93 | 0.6 | 1.6 |
| FLIR E8 | 0.5 | 0.97 | 0.61 | 0.99 | 0.2 | 0.6 |
| | 1 | 0.99 | 0.97 | 1.00 | 0.1 | 0.4 |

Table 3.7: Inter-rater agreement of the FLIR ONE and FLIR E8

| Device | Distance (m) | Bias (°C) | Lower 95% LoA (°C) | Upper 95% LoA (°C) |
|---|---|---|---|---|
| FLIR ONE | 0.5 | -0.4 | -0.9 | 0.2 |
| | 1 | -0.3 | -1.8 | 1.3 |
| FLIR E8 | 0.5 | -0.2 | -0.6 | 0.2 |
| | 1 | 0.0 | -0.3 | 0.4 |

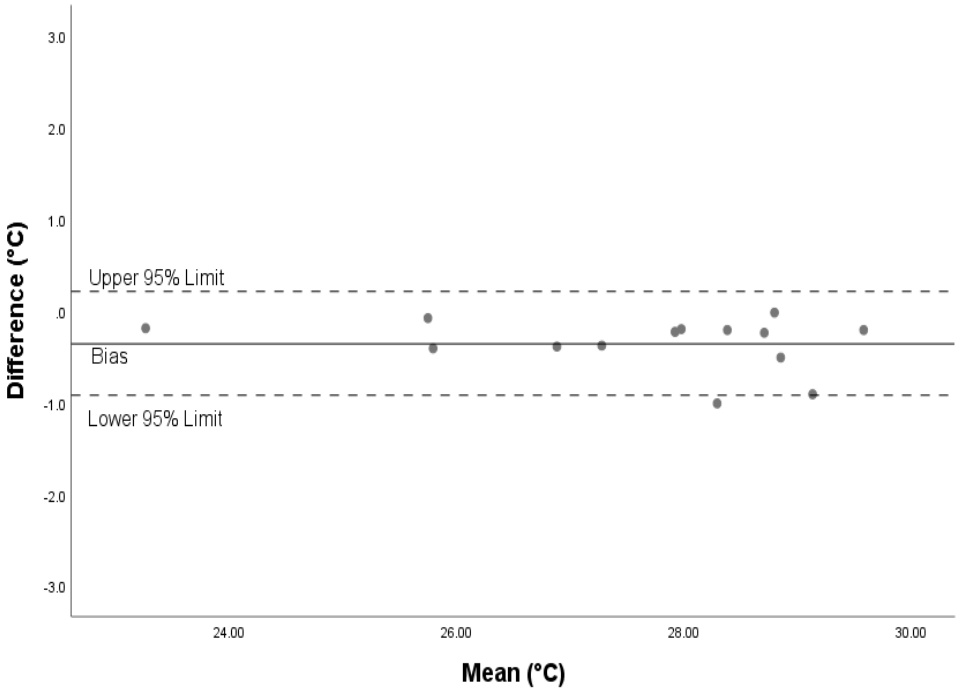



Figure 3.8: Bland Altman plot for inter-rater agreement for the FLIR ONE at 0.5m

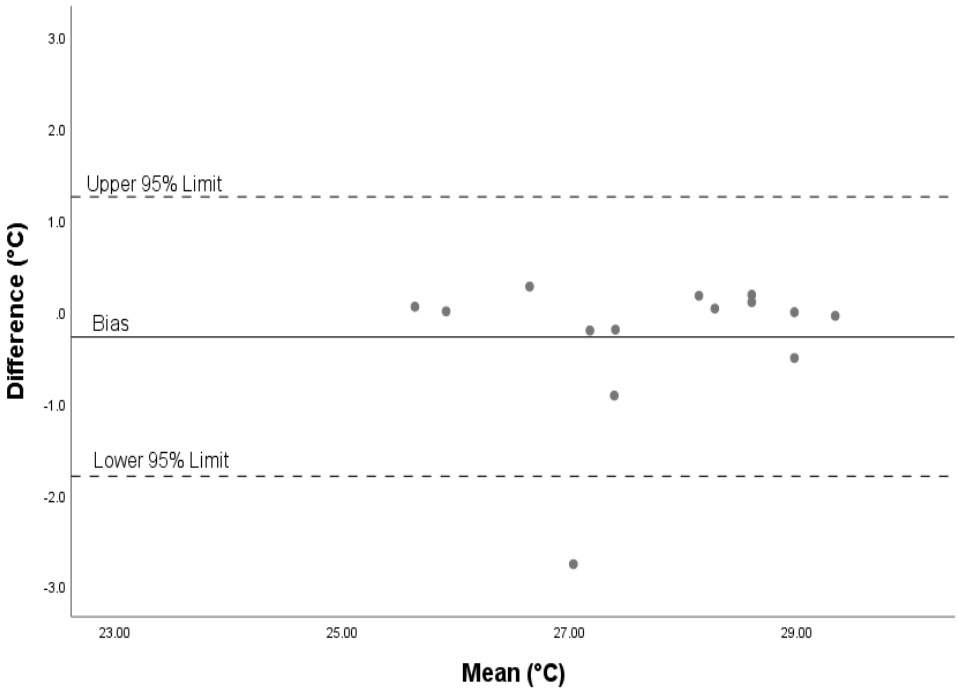



Figure 3.9: Bland Altman plot for inter-rater agreement for the FLIR ONE at 1m

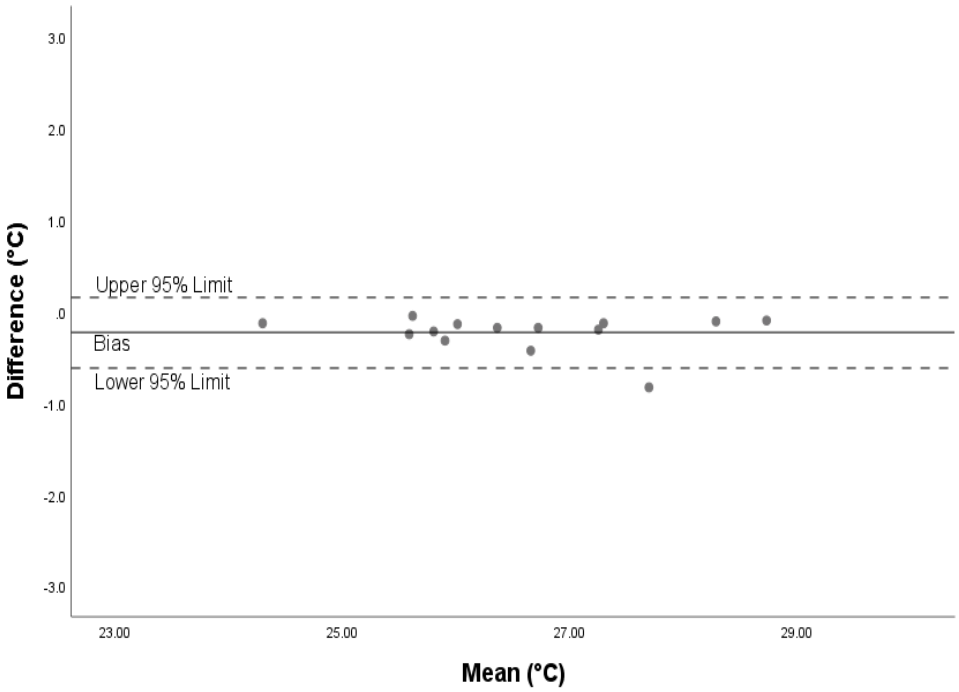



Figure 3.10: Bland Altman plot for inter-rater agreement for the FLIR E8 at 0.5m

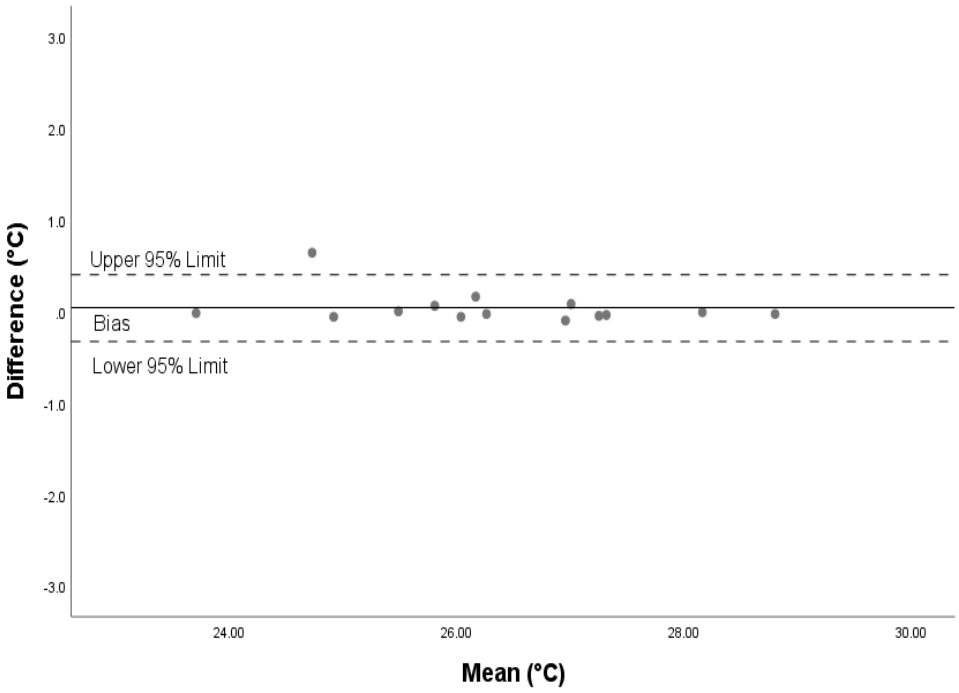



Figure 3.11: Bland Altman plot for inter-rater agreement for the FLIR E8 at 0.5m

#### 3.3.4.3 Inter-device agreement

The agreement between the two IRC's was not acceptable. The mean bias and the 95% LoA were high at both distances from the ROI and the confidence limits exceeded the a priori defined acceptable figures, which can be seen in table 3.8 and in figures 3.12 and 3.13. Linear regression revealed that there was proportional bias present at 0.5m ($p<0.001$) and at 1m ($p=0.002$).

Table 3.8: Inter Device Agreement FLIR ONE vs FLIR E8

| Distance (m) | Bias (°C) | Lower 95% LoA (°C) | Upper 95% LoA(°C) |
|---|---|---|---|
| 0.5 | 1.0 | -0.9 | 2.8 |
| 1 | 1.2 | -0.6 | 3.0 |

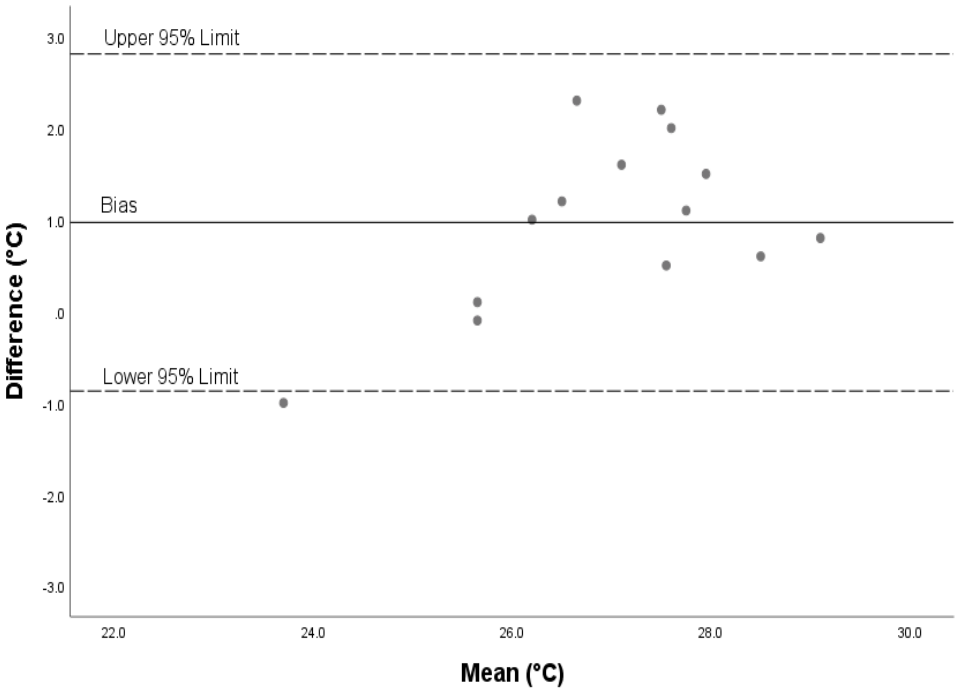



Figure 3.12: Bland Altman plots for inter-device agreement at 0.5m

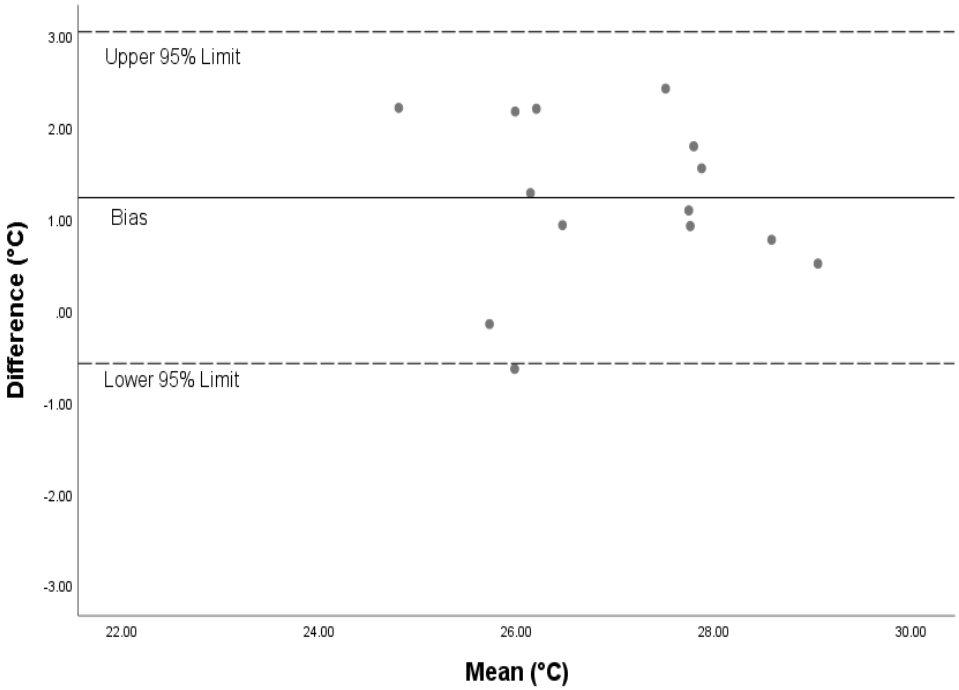



Figure 3.13: Bland Altman plots for inter-device agreement at 1m

### 3.3.5 Discussion

The first aim of this chapter was to determine the intra-rater and inter-rater reliability of the method of TSK analysis at 0.5m and 1m distances, with associated SEM's and MDC's for the FLIR ONE and FLIR E8 IRCs.

The method of analysis for both devices displayed excellent intra-rater reliability for assessing midportion AT TSK at a distance of 0.5m, as seen in table 3.4. This led to the acceptance of hypotheses 1 and 3. The associated SEM and MDC values were low (0.2°C and 0.5°C) and were similar between the two devices. The intra-rater reliability for the two devices was also excellent at a 1m distance from the ROI, leading to the acceptance of hypotheses 2 and 4. The SEM and MDC values for the FLIR ONE were slightly better at the 1m distance (0.1°C and 0.4°C), but for the FLIR E8, they had worsened to 0.3°C and 0.9°C respectively.

The higher SEM and MDC values obtained from the FLIR E8 suggested that the method of analysis resulted in more reliable readings from the FLIR ONE device when the same rater (rater one) analysed the images. It suggested that the consistency of custom ROI placement by rater one was excellent. A possible reason for this is the interpolation of the images using MSX technology, creating temperature points every 4x4 pixels. As the custom ROI line drawn in the software is only 1 pixel wide, there is scope for a slight deviation in the line placement within the image, as the temperature only changes every fifth pixel in each direction.

This same reason could potentially explain why there were lower SEM and MDC values from the FLIR E8 during the inter-rater interpretation of the images. When analysing the FLIR ONE images, there were 230,400 ((480x640) – (320x240)) more pixels available in the image, meaning that the pixels sizes were smaller, leading to more chance of variation when different raters were interpreting the path of the ROI through the centre of the AT. So, despite TSK change only occurring every fifth pixel, there were thousands more pixels available within the image suggesting that there may have been slight variation in how raters interpreted the ROI placement. The inter-rater reliability was still excellent for the FLIR ONE at 0.5m and the FLIR E8 at 0.5m and 1m, and good for the FLIR ONE at 1m.

As the distance increased from 0.5m to 1m, the clarity of the thermal image decreased, which made it harder to identify the borders of the AT, as seen in figure 3.14. A fewer number of pixels covered the ROI on the AT, which combined with the lack of clarity in the images at the 1m distance, it became much more difficult to identify the central midportion, which may

have explained why the inter-rater ICC values were lower, and the SEM and MDC values were higher.

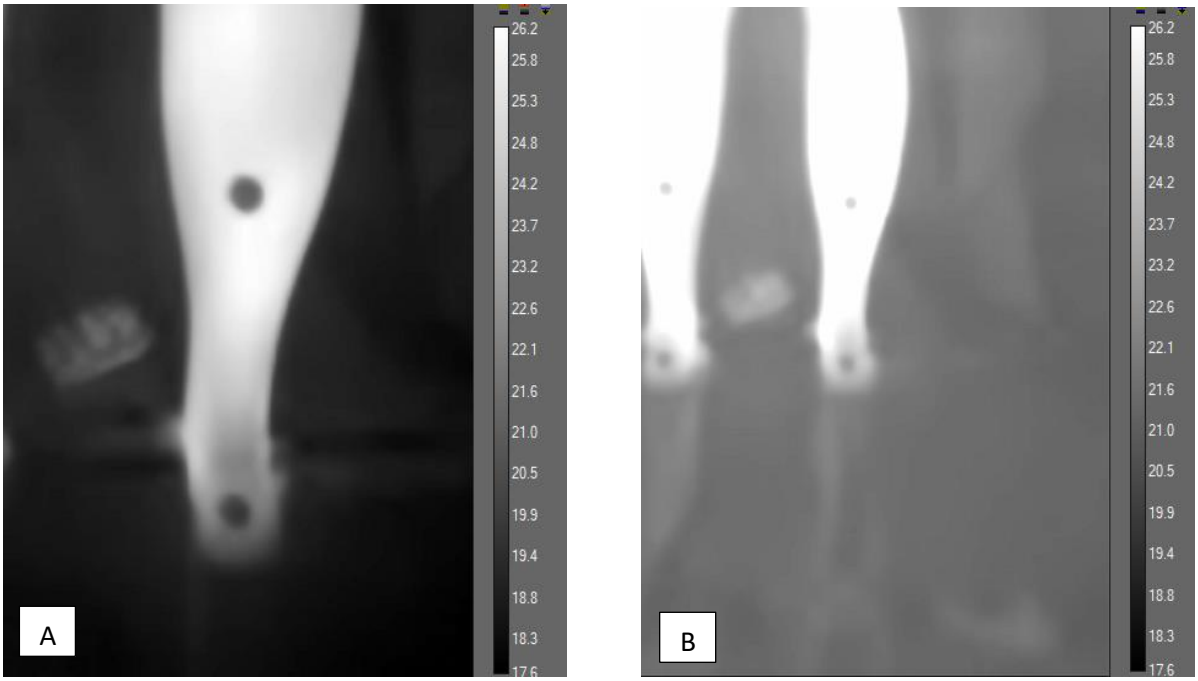



Figure 3.14: An image obtained by the FLIR ONE at 0.5m (A) and an image of the same tendon from a distance of 1m (B)

Tumilty et al. (2019) also assessed AT TSK using IRCs during a 9-week collegiate cross-country season. Acceptable ICC's were found, however, the methodology employed may not be appropriate for measuring ΔTSK in response to exercise. They used the box analysis method on the FLIR Tools (FLIR Systems Inc, Oregon, US) software programme. The box placement was standardised retrospectively at the distal border of the AT using the colour change between the calcaneus and the AT, as judged by the rater. The main limitation of this method of box placement is that any deviations in TSK either between session or post-exercise would result in variations in ROI placement, making it difficult to standardise placement using colours alone, highlighting the need for a priori defined anatomical landmarks. Additionally, as not all AT's travel in a linear fashion, it may be that rectangular box placement read TSK from areas medial and lateral to the AT. The Posterior Tibial Artery lies near the AT medially, which could increase TSK dramatically (Chen et al., 2009).

The inter-rater reliability for the method of TSK analysis was excellent for both devices, leading to the acceptance of hypotheses 5 and 7. The SEM and MDC values were better for

the FLIR E8. The inter-rater reliability of the FLIR ONE at a 1m distance from the ROI was good, leading to the rejection of hypothesis 6. Hypothesis 8 was accepted due to the excellent inter-rater reliability results found for the FLIR E8 at a distance of 1m from the ROI.

The SEM and MDC values were slightly higher for the FLIR ONE at a 1m distance, however, what is classed as "high" at this stage is unknown. Pilot testing has revealed substantial TSK change in excess of 1.6°C in response to treadmill activity, meaning that the MDC may still be acceptable. The difference between the cost of each device is substantial, with the FLIR ONE retailing at approximately one-tenth of the price of the FLIR E8. The price difference, combined with the acceptable intra-rater and inter-rater reliability results of the method of TSK analysis using the FLIR ONE pave the way for further work to assess whether it is a viable option for clinical use to assess midportion AT TSK changes.

The second aim of this chapter was to assess whether the inter-device agreement was acceptable. Hypothesis 9 was rejected, as the inter-device agreement was not acceptable. The mean bias and 95% LoA lay outside of the a priori acceptable 2% limits. It is therefore recommended that despite acceptable reliability of the methods of analysis, that measures from two different IRC's are not directly compared for absolute TSK values.

A limitation to the thermal capture procedure was noted. At distances of 0.5m from the ROI, the proximal anatomical marker was barely visible for the tallest participant who measured 184.2cm in height. It is anticipated that taller participants may partake in future study, therefore the camera may have to be moved back from the ROI. Future study will assess the effect of different distances from the ROI to see if this affects TSK readings.

### 3.5.6 Conclusion

Based on the results of this study, it was deemed that the FLIR ONE IRC displayed excellent intra-rater reliability and good to excellent inter-rater reliability. It is recommended that the IRC is placed as close to the ROI as possible to reduce the SEM and MDC values. New SEM and MDC values need to be obtained for set distances between 0.5m and 1m from the ROI if camera placement is to be moved backwards to account for anatomical variation. The effect of distance on values of absolute TSK of the midportion of the AT should be assessed to see if this affects absolute TSK readings. Based on the lack of agreement found in this study, absolute TSK values in human AT's should not be compared between smartphone and handheld IRCs.

## 3.4 The effect of distance and angle of a smartphone-compatible infrared thermal imaging camera on skin temperature at the midportion of the Achilles tendon

### 3.4.1 Aims

1. To determine the effects of distance and angle on absolute TSK values at the midportion of the AT.

### 3.4.2 Hypotheses

1. There would be no significant differences in absolute TSK between 0.5m and 1m distance from the ROI
2. There would be no significant differences in absolute TSK between 0° (perpendicular to the ROI) and 14° (perpendicular to the area of interest) at 0.5m
3. There would be no significant differences in absolute TSK between 0° (perpendicular to the ROI) and 7° (perpendicular to the area of interest) at 1m

### 3.4.3 Method

Some areas of the methods section for this chapter were repeated in line with those stated in section 3.3.3. Specifically, these areas were; ethical approval, participant recruitment, inclusion and exclusion criteria, anthropometric measurements, room temperature measurements, anatomical marker placements and the acclimatisation procedure.

#### 3.4.3.1 Infrared thermal imaging cameras

As stated in section 3.3.3. Only the images taken by the FLIR ONE were used during this section.

#### 3.4.3.2 Thermal data capture

As stated in section 3.3.3. Images taken from all six locations on figure 3.3 were used during this section.

#### 3.4.3.13 Thermal data analysis

Thermal data was analysed in line with the methods outlined in section 3.3.3.10, except for the detail outlined for the FLIR E8 method, as the results from this camera were no longer of interest. The images were analysed once.

#### 3.4.3.4 Statistical Analysis

Statistical analyses were conducted using SPSS for Windows (v24.0 SPSS Inc, Chicago, Illinois, USA). Normality was assessed using the Shapiro-Wilk test. Data are presented as mean ± SD unless stated otherwise.

To assess whether TSK differences existed over the midportion of the AT between 0.5m and 1m distances perpendicular to the ROI, a paired samples t-test was used. This was also the case for differences between 0° and 14° angles (perpendicular to the ROI and perpendicular to the area of interest) at 0.5m and 0° and 7° angles at a 1m distance.

As three separate hypotheses were tested, a Bonferroni correction was applied to account for type I error, so alpha levels were adjusted to 0.017 (0.05/3). Cohen's d was used as a measure of effect size and was calculated using the formula $\frac{(mean\ 1 - mean\ 2)}{SD}$ (Cohen, 1988). Bland Altman plots mean bias and 95% LoA were created to provide a visual representation of the agreement between different distances and angles. The mean bias represented the mean difference between the distances or angles. The 95% LoA represented the range of differences where 95% of the data points would be expected to fall and was calculated as stated in section 3.3.3.11. Regression analysis was conducted to assess whether there was any proportional bias. A priori acceptable mean bias was defined as ±5% to account for measurement error, in line with the manufacturer stated accuracy of the FLIR ONE device (Hanneman, 2008).

### 3.4.4 Results

The mean absolute TSK values captured by the FLIR ONE can be seen in table 3.9. The TSK differences between 0.5m and 1m distances at 0° to the ROI were not statistically significant, $t_{(13)}$= 0.19, p=0.85, d=0.05. The values recorded at 0.5m were a mean of 0.1°C ± 0.9°C (95% CI -0.5, 0.6) higher than the values recorded at 1m. The Bland Altman plot can be seen in figure 3.15.

Table 3.9: Mean TSK values obtained from the FLIR ONE

| Distance (m) | Angle (°) | Mean TSK (°C) | SD (°C) |
|---|---|---|---|
| 0.5 | 0 | 27.5 | 1.5 |
| | 14 | 27.8 | 1.8 |
| 1 | 0 | 27.5 | 1.4 |
| | 7 | 27.7 | 1.2 |

The TSK differences at 0° and 14° from the ROI at a distance of 0.5m were not statistically significant, $t_{(13)}$= 1.556, p=0.14 d=0.42. At 14° from the ROI, the FLIR ONE TSK reading was a mean of 0.3°C ± 0.7°C (95% CI -0.7, 0.1) higher than at 0°. The Bland Altman plot can be seen in figure 3.16, no proportional bias existed.

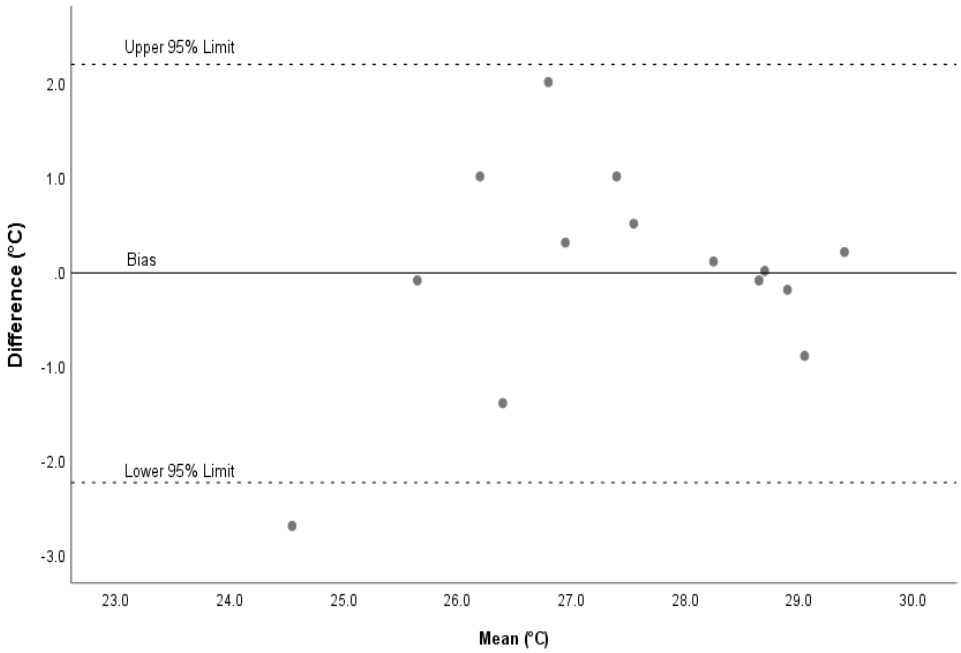



Figure 3.15: Bland Altman plot for 0.5m vs 1m 0° angle

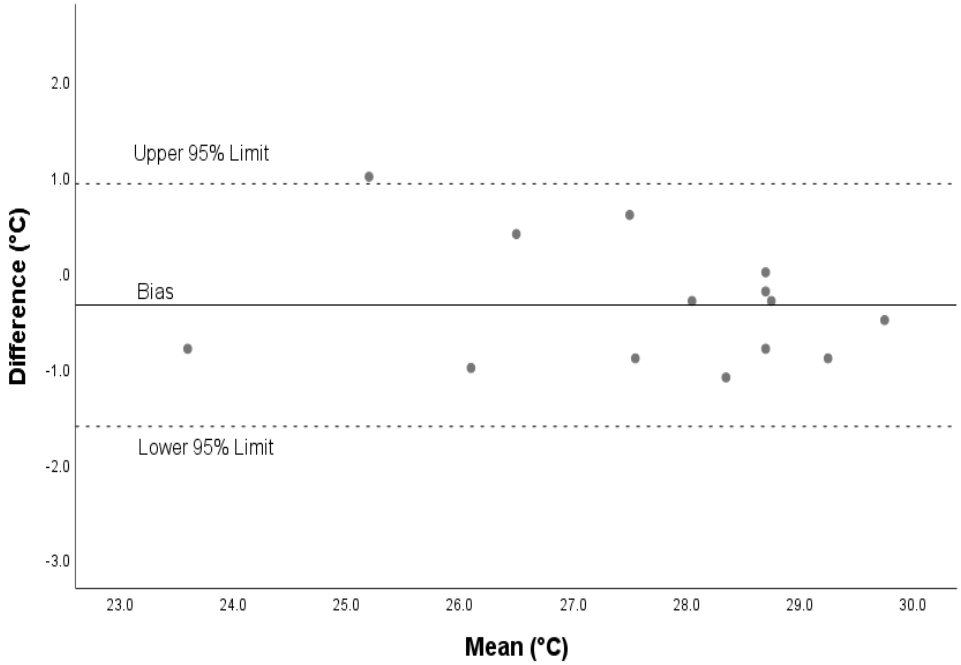



Figure 3.16: Bland Altman plot for 0.5m 0°vs 14°angle

The TSK differences between 0° and 7° at 1m from the ROI were not statistically significant, $t_{(13)}$= 1.28 p=0.22, d=0.34. The TSK recorded by the FLIR ONE at a 7° angle was a mean of 0.2°C ± 0.8°C (95% CI -0.7, 0.2) higher than at 0° perpendicular to the ROI. The Bland Altman plot can be seen in figure 3.17. Linear regression revealed that no proportional bias existed (p=0.474). A Bland Altman plot has also been created to provide visual representation on the agreement between absolute TSK values from camera placements perpendicular to the area of interest (14° vs 7° at 0.5m vs 1m distance), which can be seen in figure 3.18. Linear regression revealed that no proportional bias existed (p=0.055).

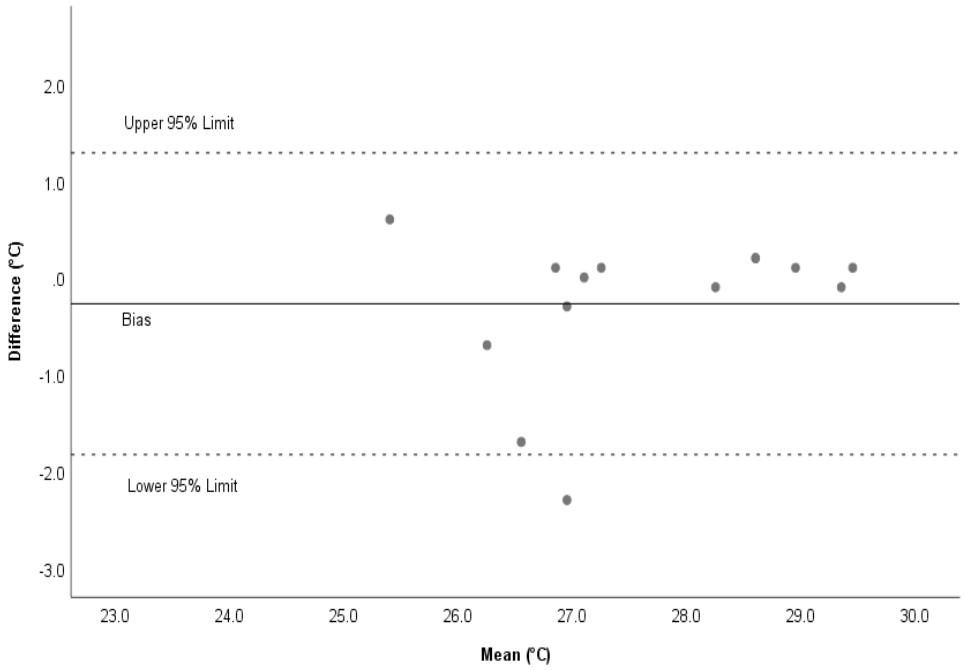



Figure 3.17: Bland Altman plot for 1m 0°vs 7°angle

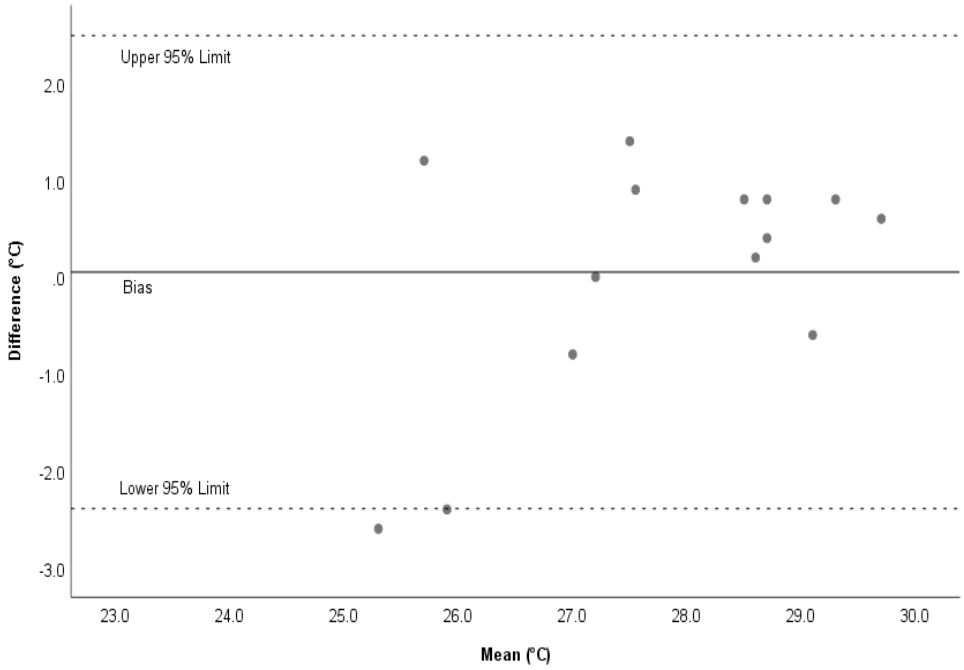



Figure 3.18: Bland Altman plot for 7°vs 14°angle (0.5m vs 1m perpendicular to the area of interest)

### 3.4.5 Discussion

The third aim of this chapter was to assess whether the distance and angle of the FLIR ONE from the ROI on the midportion of the AT affected absolute TSK values. The results of this study led to the acceptance of all three hypotheses for this section, as there were no significant changes ($p>0.017$) in TSK between a 0.5m and 1m distance (hypothesis 1) with a trivial effect size (Cohen, 1988), or a 0° and 14° angle from the ROI (hypothesis 2) and a 0° and 7° angle from the ROI (hypothesis 3). The effect sizes were small for the differences between angles (Cohen, 1988).

When observing the Bland Altman plots for the difference is TSK of the midportion of the AT due to angle change, the mean bias was 0.3°C on both occasions, an acceptable difference that lay within the MDC of the FLIR ONE at 1m. All 14 data points lay within the a priori defined 5% accuracy value at a 0.5m distance (figure 3.16), and 11 data points at the 1m distance (figure 3.17), suggesting that as distance increased there was an impact on the accuracy of the measures obtained by the FLIR ONE. The LoA were wide on each of the Bland Altman plots, slightly beyond the a priori defined acceptable limits. Caution must therefore be drawn when measuring absolute TSK between different angles on multiple testing occasions. Therefore, the recommendation is to keep angles consistent when assessing the TSK of each individual, if agreement of absolute TSK is of importance.

There were no statistically significant ($p>0.017$) differences in TSK between different distances (0.5m and 1m) at a 0° angle to the ROI when using the FLIR ONE. The trivial effect size ($d=0.05$) supports this. The Bland Altman plot (figure 3.15) revealed a mean bias of 0.0°C, with no proportional bias, as assessed using regression analysis. However, the LoA were wide and defied the a priori acceptable limits, suggesting that agreement of TSK between the two distances has the potential to be low. These wide LoA were also found when comparing agreement between the IRC measures perpendicular to the area of interest between 0.5m and 1m distances (figure 3.18). A recommendation based upon this is that distances should not be used interchangeably when measuring the AT TSK if the absolute agreement of TSK values is important.

These results agree with findings by Westermann et al. (2013) who found that an angular change of 20° from the ROI did not significantly change TSK readings in equine

participants. The effect of a 0.5m increase, from 1m to 1.5m from their ROI also had no significant effect on equine TSK readings.

Vardasca et al. (2017) assessed the effect of angle on the temperature of the inner canthus of the eye and found that angle changes of up to 15° had no significant effect. The changes in temperature seen were over those found in the current study, 0.4°C and 0.5°C versus 0.2°C and 0.3°C from 7° and 14° angles respectively. The TSK values from 0.5m to 1m differ in our study compared to the effects of distance in the study by Vardasca et al (2017). They found that beyond a 0.2m distance, there were statistically significant temperature changes, however ascertaining exact values from the graphical presentation is difficult, with approximate changes of 0.15°C over a 0.5m distance from 1m to 1.5m. The TSK change seen in the current study over a 0.5m distance from 0.5m to 1m was 0.1°C which was statistically insignificant with a trivial effect size ($p=0.85$, $d=0.05$) and lay within SEM and MDC values calculated in section 3.3.4.

The main limitation of this study is as described in section 3.3.5, relating to the anthropometrics of the tallest participants. The results of this study suggest that the camera can be moved backwards in relation to the ROI if the angle is kept consistent, without significantly altering TSK values. Caution should be drawn interpreting absolute TSK values between different distances and angles if the absolute agreement is of importance, therefore it is recommended that distance and angle are kept consistent within future studies.

### 3.4.6 Conclusion

The method of analysis has now been found to be reliable and distance and angle from the ROI on the midportion of the AT should be kept consistent. The next step to establishing a robust methodology is to check the repeatability of the FLIR ONE, to check that it can measure a stable TSK over a period of time. As part of this, it is necessary to adjust the distance of the IRC to 0.6m from the ROI and thus calculate new intra-rater reliability, SEM and MDC values.

## 3.5 The reliability and repeatability of the FLIR ONE infrared thermal imaging camera for measuring human AT TSK at a distance of 0.6m from the ROI

### 3.5.1 Aims

1. To determine the intra-rater reliability of the method of analysing human midportion AT TSK at a distance of 0.6m from the ROI
2. To determine SEM and MDC values at a 0.6m from the ROI
3. To determine the repeatability of the FLIR ONE for measuring human midportion AT TSK

### 3.5.2 Hypotheses

1. The method of analysis would show excellent intra-rater reliability
2. SEM and MDC values would be acceptable
3. The FLIR ONE would display acceptable repeatability for AT midportion TSK measurement

### 3.5.3 Methods

Some areas of the methods section for this chapter were repeated in line with those stated in section 3.3.3. Specifically, these areas were; ethical approval, inclusion and exclusion criteria, anthropometric measurements, room temperature measurements, anatomical marker placements and the acclimatisation procedure.

#### 3.5.3.1 Participant recruitment

As stated in section 3.3.3. The difference was that 8 participants were recruited (6 male, 2 female, aged 19.6 ± 0.5 years, height 179.8 ± 5.7cm, mass 73.1 ± 8.5cm).

#### 3.5.3.2 Infrared thermal imaging cameras

The FLIR ONE IRC was used during this study. It was plugged into an electrical supply and switched on 30-minutes before the first participants entering the lab to allow for start-up drift stabilisation to occur (Vardasca et al., 2019). Emissivity was set to 0.98 retrospectively on the FLIR Research IR MAX software (v4.40.9.30, FLIR Systems, Oregon, US).

#### 3.5.3.3 Thermal data capture

A black polycotton sheet was suspended the day prior to testing taking place to provide a smooth and uniform background for the images, allowing a good thermal contrast. A piece of foil was placed into the image to allow the reflective temperature to be measured. A line of gaffer tape was placed parallel to this sheet, 0.4m in front, which served as a line on the floor whereby participants heels could be placed, to standardise their position in from of the IRCs.

The FLIR ONE was placed 0.6m in front of the heel line, centrally in relation to the stance of the participants (perpendicular to the area of interest). It was mounted to a tripod, with the lens 0.21m from the ground.

A total of 7 images were taken per camera, at timepoints baseline (BL), minute-2 (CD2), minute-4 (CD4), minute-5 (CD5), minute-6 (CD6), minute-8 (CD8) and minute-10 (CD10), for each of the 8 participants. In total, 56 images were taken.

#### 3.5.3.4 Thermal data analysis

As outlined in section 3.3.3. Additionally, the spot tool was aligned with the black polycotton sheet and recorded retrospectively to measure cloth temperature. A new macro was created in Microsoft Excel (v16.0, Microsoft corporation, WA, US) using the same approach that was outlined in section 3.3.310, to extract the mean TSK values from the image at a distance of 0.6m from the ROI.

#### 3.5.3.5 Statistical analysis

All testing was conducted using SPSS for Windows v25.0 (SPSS Inc, Chicago, Illinois, USA). Normality assumptions were assessed using the Shapiro-Wilks test and normally distributed unless stated otherwise ($p>0.05$). Data are presented as mean ± SD unless stated otherwise.

An ICC using two-way mixed effects, absolute agreement, single measurement model was used to assess intra-rater reliability. SEM and MDC values were calculated as stated in section 3.3.3.11.

A one-way repeated-measures analysis of variance (ANOVA) was used to determine if there were any statistically significant differences between the mean TSK values in the left leg over the 10-minute timeframe following the acclimatisation period.

The non-parametric equivalent, the Friedman test, was used to assess the non-normally distributed data of the right leg over the 10 minutes.

Bland Altman plots were constructed to assess the agreement between the differences in temperature values between the AT TSK's and the cloth temperature over the 10 minutes. A priori acceptable figures were within the MDC outlined in section 3.3.4.

### 3.5.4 Results

#### 3.5.4.1 Intra-rater reliability

The method of analysis used to assess the TSK of the midportion of the AT demonstrated excellent intra-rater reliability. The results can be seen in table 3.10.

Table 3.10: Intra-rater reliability values for the FLIR ONE at 0.6m from the ROI

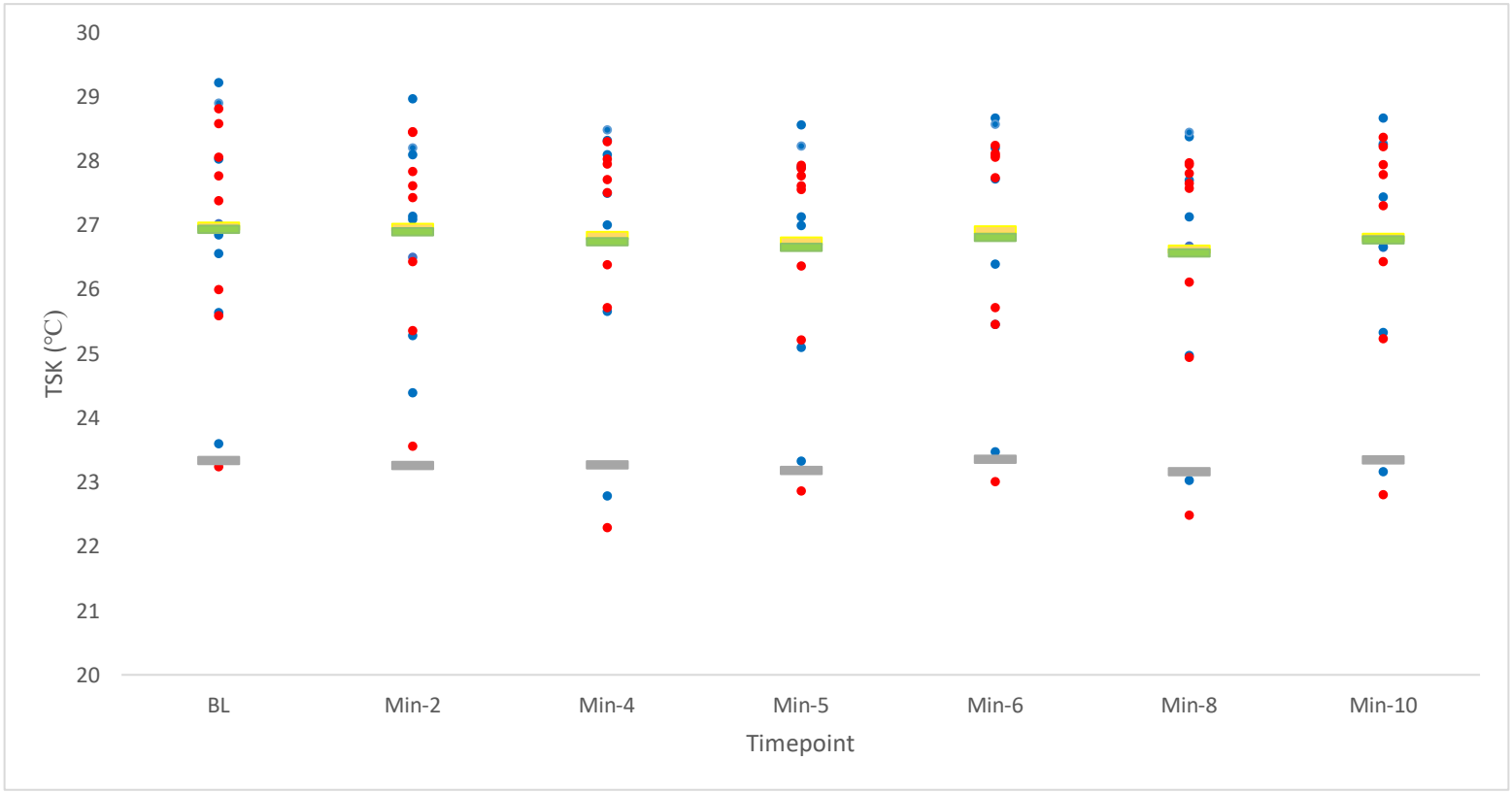
| ICC | 95% CI | | SEM (°C) | MDC (°C) |
|---|---|---|---|---|
| 0.99 | 0.99 | 1.00 | 0.2 | 0.5 |

#### 3.5.4.1.1 Left leg

There were no outliers and the data were normally distributed at each timepoint. The assumption of sphericity was met as assessed by Mauchly's test of sphericity $x^2$ (20) = 30.05, p=0.12. TSK did not change significantly over time, $F_{(6,42)}$ = 1.5, p=0.21, partial $\eta^2$ = 0.18. Mean TSK values over the 10 minutes can be seen in table 3.11 and is graphically represented in figure 3.19. The mean difference values between the left AT TSK and the cloth temperature can be found in table 3.12. The Bland Altman plot assessing the agreement between left AT TSK and cloth temperature over the 10 minutes can be seen in figure 3.20.

Table 3.11: Mean TSK values at 0.6m from the ROI

| Timepoint (mins) | Mean TSK left AT ± SD (°C) | Mean TSK right AT ± SD (°C) | Cloth Temperature ± SD (°C) |
|---|---|---|---|
| 0 (Baseline) | 27.0 ± 1.8 | 26.9 ± 1.9 | 23.3 ± 0.4 |
| 2 | 27.0 ± 1.5 | 26.9 ± 1.7 | 23.3 ± 0.6 |
| 4 | 26.8 ± 1.9 | 26.7 ± 2.0 | 23.3 ± 0.8 |
| 5 | 26.7 ± 1.8 | 26.7 ± 1.8 | 23.2 ± 0.6 |
| 6 | 26.9 ± 1.8 | 26.8 ± 1.9 | 23.4 ± 0.7 |
| 8 | 26.6 ± 1.8 | 26.6 ± 2.0 | 23.2 ± 0.6 |
| 10 | 26.8 ± 1.8 | 26.8 ± 1.9 | 23.3 ± 0.7 |




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 3.19: Mean left and right AT TSK and cloth temperature (± SD) of over time

Table 3.12: Difference values between the left mean AT TSK and the cloth temperature

| Timepoint | Left AT TSK difference ± SD (°C) | Right AT TSK difference ± SD (°C) | Cloth temp difference ± SD (°C) |
|---|---|---|---|
| Min2 to BL | 0.0 ± 0.5 | 0.0 ± 0.4 | -0.1 ± 0.4 |
| Min4 to Min2 | -0.1 ± 0.7 | -0.2 ± 0.6 | 0.0 ± 0.4 |
| Min 5 to Min 4 | -0.1 ± 0.4 | -0.1 ± 0.4 | -0.1 ± 0.3 |
| Min 6 to Min 5 | 0.2 ± 0.3 | 0.2 ± 0.3 | 0.2 ± 0.3 |
| Min 8 to Min 6 | -0.3 ± 0.3 | -0.2 ± 0.3 | -0.2 ± 0.2 |
| Min 10 to Min 8 | 0.2 ± 0.2 | 0.2 ± 0.3 | 0.2 ± 0.2 |

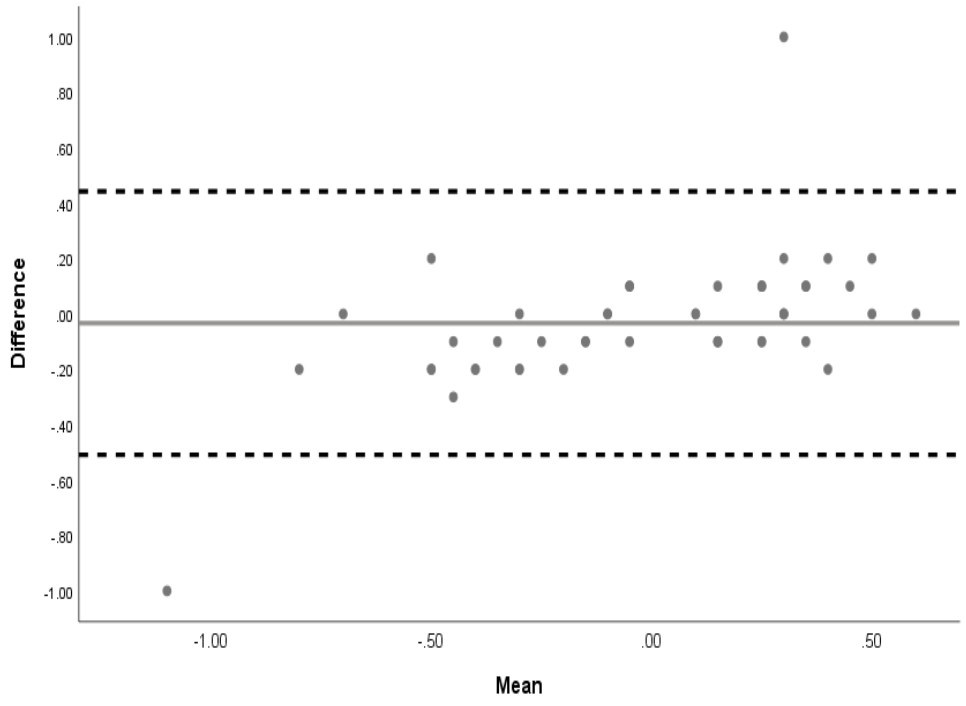



Figure 3.20: Bland Altman Plot for the left AT and cloth temperature

#### 3.5.4.1.2 Right leg

There were no outliers and there was a non-normal distribution of data at minutes 4-6. The Friedman test revealed that there were no statistically significant differences in TSK over the 10 minutes from baseline to minute-10, $x^2$ (6) = 10.16, p=0.12. The mean TSK values can be seen in table 3.11. The mean difference values between the right AT TSK and the cloth temperature can be found in table 3.12. The Bland Altman plot assessing the agreement between right AT TSK and cloth temperature over the 10 minutes can be seen in figure 3.21.

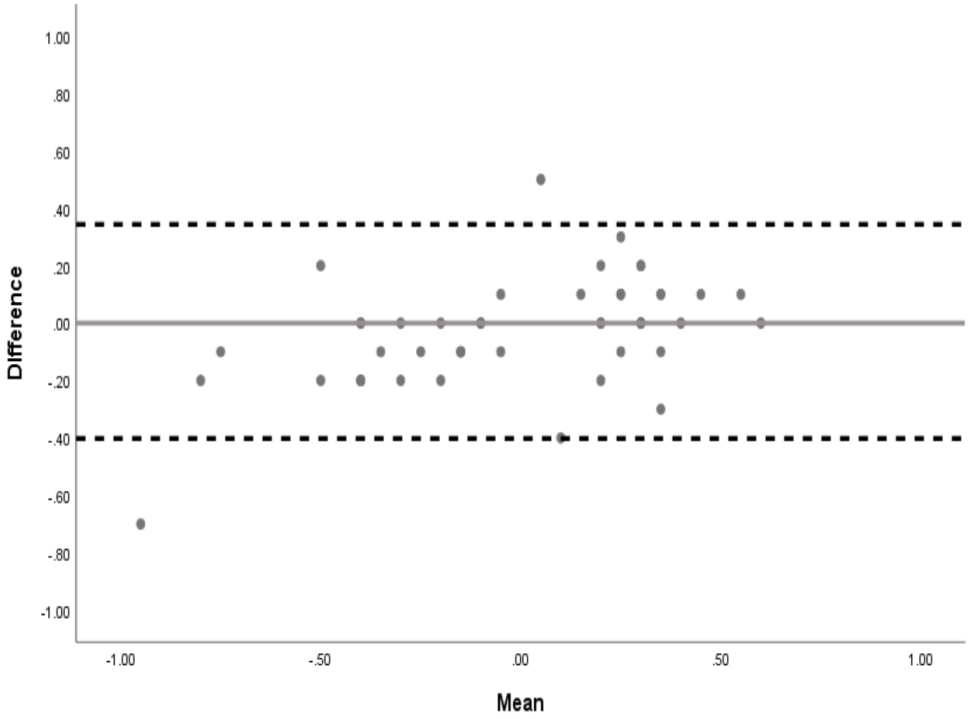



Figure 3.21: Bland Altman Plot for the right AT and cloth temperature

### 3.5.5 Discussion

Hypothesis number 1 was accepted due to the excellent ICC values found. It was necessary to establish SEM and MDC values for the method of analysis at a 0.6m distance from the ROI, due to these values differing at 0.5m and 1m distances from the ROI. The values were comparable with those found at a 0.5m distance leading to the acceptance of hypothesis 2. The results suggested that moving the camera placement backwards in relation to the ROI by 0.1m to account for individual anthropometric variations did not significantly alter the MDC value.

The fourth aim of this chapter was to ascertain whether the FLIR ONE displayed acceptable repeatability when used for measuring the TSK of the midportion of the AT. It was hypothesised that repeatability would be acceptable, and it was deemed true. The results showed that there were no statistically significant differences in TSK change across the 10 minutes following acclimatisation.

The maximum variation in consecutive absolute mean TSK measurements was 0.3°C. This figure was less than the MDC value found therefore for the purposes of TSK assessment at the midportion of the AT, the repeatability was deemed acceptable.

The results of the Bland Altman (figures 3.20 and 3.21) plots revealed that the agreement between the stable cloth temperature and the mean left and right AT TSK's were acceptable with all but two-data points per plot falling within the upper or lower LoA and the a-priori defined values for MDC.

The results of the study agreed with the findings of Vardasca et al. (2019) who suggested that the FLIR ONE output stabilised after 15 minutes. The FLIR ONE mechanical shutter was set to auto-calibrate. At set time intervals, this automated calibration process takes place, in less than one second, as suggested previously. However, a limitation to this is that there is then a lag period where the camera then stabilises to the surrounding scene, which takes another few seconds. If the image is captured within this time, it can lead to variations in TSK measurements. To combat this, the spot tool was kept on during each image and was aligned with the cloth background, which remained at a stable temperature. When the calibration process was complete, the mean temperature of the spot was back to its baseline value. It is important to note this to maintain accurate TSK measurements throughout the data collection process.

#### 3.5.5.1 Limitations

It was assumed that TSK of the AT region would remain constant in line with recommendations by Fernández-Cuevas et al. (2015). If the equipment was available, it would have been ideal to calibrate the device with a blackbody source that would have been contained within the image. This would have allowed better interpretation as to whether small deviations in the results were due to camera error or TSK fluctuation. On two occasions per Bland-Altman plot, the agreement between the AT TSK and the cloth temperature was not acceptable. It is possible that sudden changes in physiological characteristics such as skin surface blood flow could account for this lack of agreement, whereby TSK would change yet cloth temperature would remain the same.

### 3.5.6 Conclusion

The FLIR ONE demonstrated acceptable repeatability for the measurement of AT TSK following on from an acclimatisation phase. The changes in TSK seen were not statistically significant and were within the MDC values calculated in this section. The agreement between AT TSK and cloth temperature was deemed acceptable.

Based on the results of the previous three studies a final methodology can now be established with confidence that the device displays adequate repeatability, the IRC placement is standardised according to the ROI and the method of analysis used to assess TSK displays acceptable reliability. The next section will outline the final methodology used in the subsequent chapters.

## 3.6 The final methodology

### 3.6.1 Section Overview

Contained within this chapter is a final methodological outline derived from the results of the methodological studies, as well as working backwards from the criteria outlined by Moreira et al. (2017) for TISEM reporting standards. This method was employed throughout the studies conducted on the AT unless specified otherwise in each chapter.

### 3.6.2 Methods

#### 3.6.2.1 Ethical approval

Ethical approval was obtained for each study contained within this thesis. All ethical approval was granted by the University of Salford Research, Enterprise and Engagement Ethical Approval Panel. The ethical approval numbers were HSR1718-032 and HSR1718-014 and both approval letters can be seen in appendix 2.

#### 3.6.2.2 Participant recruitment

A retrospective sampling approach was taken, with symptomatic participants selected based on their exposure to chronic midportion Achilles tendinopathy, and asymptomatic participants selected based on not having the condition, as assessed clinically, which is outlined in section 2.6.3. Initial recruitment was conducted mainly through poster advertisement on local running group social media pages and verbally at club headquarters via presentation (appendix 7) in order to target recreational runners who trained a minimum of 5 km twice per week. It was not possible with the available sample sizes to match runners based on weekly running volume or training practices. Runners who attended the Salford University Sports Injury Clinic who had indicated that they were happy to be contacted for research purposes were also sent the advertisement if they presented with symptoms. Those with symptomatic Achilles pain were targeted first, and those who were asymptomatic were recruited second.

Upon expressing their interest in taking part in the study, an information sheet was forwarded to participants (appendix 8). They were initially allowed to respond via email or telephone to discuss any queries that they had regarding the study. Once happy, they were invited to take part in two initial assessment sessions at the University of Salford, and upon

attendance, they were asked to read a copy of the information sheet and sign a consent form (appendix 9) once the procedures had been verbally explained.

#### 3.6.2.3 Inclusion and exclusion criteria

Participants were recreational runners aged 18-60 who undertook 5 km running activity a minimum of twice per week. They had to be suffering from chronic midportion Achilles tendinopathy which involved pain being in the midportion of the tendon, between 2-6cm proximal to the insertion on the Calcaneus. They had to have chronic symptoms which were defined as symptoms lasting greater than 3 months (Beyer et al., 2015). There had to be swelling or thickening of the midportion of the tendon, confirmed via US imaging which would display a fusiform shape, A-P thickening or areas of hypoechogenicity (Sunding et al., 2016). Further information regarding this can be seen in section 3.6.2.11. This was diagnosed through clinical assessment, which is detailed in section 3.6.2.8.

For symptomatic participants to be included, their VISA-A score had to be <90 and asymptomatic participants had to score 100 on the VISA-A questionnaire. Values between 90 and 99 suggested the possibility of having recovered from previous tendon pain according to a published systematic review (Iversen et al., 2012), therefore to ensure that only truly asymptomatic individuals were included, these thresholds were set.

Participants were excluded from the study if they suffered from Insertional Achilles tendinopathy as opposed to midportion tendinopathy, or if they presented with a non-tendinopathy condition (section 2.6.3). Participants were also excluded if they failed to meet the criteria outlined in point 2 of the TISEM checklist (Moreira, Costello, et al., 2017).

#### 3.6.2.4 Anthropometric measures

All participants who attended testing sessions underwent an anthropometric assessment which included standing height and body mass measurements. Standing height was measured using a Leicester SECA 213 height measure (Seca Deutschland, Hamburg, Germany), to the nearest 0.1cm. The participants were instructed to hold their head in the Frankfort plane, to take a deep breath in and hold it whilst the measurement headboard was placed onto the Vertex. Weight was measured using a Seca 769 digital scale (Seca Deutschland, Hamburg, Germany) to the nearest 0.1kg. Both measurements were conducted in line with the International standards for anthropometric assessment guidelines (Marfell-Jones et al., 2011).

#### 3.6.2.5 Room temperature

Ambient temperature and room humidity were recorded for all testing sessions and between participants, using a digital weather station. These values were then applied individually to each thermal image in FLIR Research IR MAX software (v4.40.9.30, FLIR Systems, Oregon, US) so that the resultant temperature values reported were as accurate as possible. The time of day that participants had their data collection recorded was kept as consistent as possible across trials to allow for circadian variation in skin temperature (Marins et al., 2015).

The experiments were conducted away from any external light sources and drafts. The data collection was conducted in either the human performance or physiology laboratories at the University of Salford, where overhead lighting was turned off near the data collection location, meaning that external light sources had no impact on skin temperature readings

#### 3.6.2.6 Anatomical markers

Thermally inert wooden markers, 2 cm in diameter, were placed onto the following anatomical landmarks of each participant before the acclimatisation phase: calcaneus, medial and lateral malleolus, and at the joining point of the medial and lateral heads of the Gastrocnemius. The insertion point on the calcaneus was identified by palpating the calcaneal tuberosity. The joining points of the medial and lateral heads of the Gastrocnemius were palpated in standing, a marker pen dot was placed at the points where the heads met, and subsequently, an anatomical marker was placed over the dot. These markers were placed in these locations based on pilot work so that the ROI's could be identified based on a-priori defined anatomical landmarks. The wooden beads were thermally inert, meaning that the colour displayed on the thermogram contrasted from that of the warm skin, making identification simple for retrospective placement of the line ROI.

#### 3.6.2.7 Acclimatisation procedure

Prior to any thermal data collection, participants underwent a 15-minute acclimatisation period in line with TISEM recommendations (Moreira et al., 2017). In the first session, this coincided with the subjective history phase of the assessment. Participants acclimatised in the standing anatomical position, stood in front of the thermal cameras, to

minimise the transitional movement between that and the baseline thermal images being taken.

#### 3.6.2.8 Clinical assessment

All participants who attended for testing underwent a clinical assessment on day 1 of testing by the same clinician, who at the start of the testing period had 5 years' experience dealing with musculoskeletal injuries in both private clinical and sporting environments.

Initially, a full subjective history was taken for each participant. The standard questions relating specifically to the AT asked can be seen in figure 3.23. During this subjective assessment, it was ascertained that each participant was physically fit and able to partake in the exercise interventions involved in the study before moving onto thermal assessment. Following the subjective assessment, an objective assessment was taken place which is outlined in section 3.6.2.11, before a final diagnosis was reached as outlined in section3.6.2.14.

| | A | B | C |
|---|---|---|---|
| 1 | DX: | | |
| 2 | Subjective TO LAST 15 MINS IN ACCLIMATISATION POSITION | Answer | Notes |
| 3 | How would you describe your pain? | | |
| 4 | Have you noticed crepitus (clicking, cracking or grinding) from the tendon? | | |
| 5 | How long have you had your pain? | | |
| 6 | Was there a mechanism of injury or was it gradual onset? | | |
| 7 | Where is the site of your pain? | | |
| 8 | Does the pain spread anywhere? If so please give details | | |
| 9 | Rate your pain on a scale of 0-10, with 0 being no pain and 10 being the worst that you could possibly imagine | | |
| 10 | When do you get your pain? | | |
| 11 | What aggrevates your pain? | | |
| 12 | What eases your pain? | | |
| 13 | Does the pain get easier once you warm up? | | |
| 14 | How does the pain change throughout your typical day? | | |
| 15 | Online VAS generator score | | |
| 16 | Have you recently increased your training load? | | |
| 17 | Have you had a direct blow to the tendon? | | |
| 18 | Have you had symptoms similar to this in the past, or have you previously been diagnosed with Achille tendon disorders? | | |
| 19 | THREAD? | | |
| 20 | Past medical Hx | | |
| 21 | How many hours of exercise do you complete each week? | | |
| 22 | How quickly do you run 10km on average? | | |
| 23 | | | |

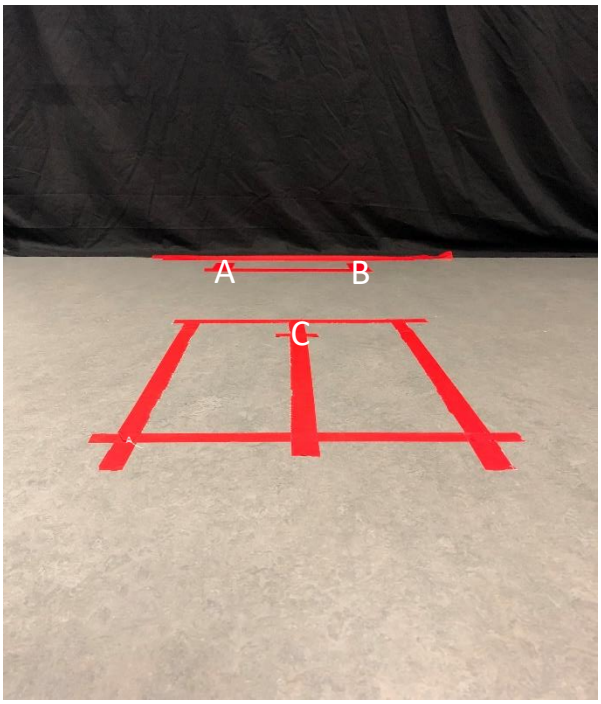
Figure 3.22: Template subjective questions

### 3.6.2.9 Infrared thermal imaging camera

All studies were conducted using the FLIR ONE IRC. The specifications of the device have been outlined in section 3.1. The camera was switched on, attached to an electrical supply and allowed to stabilise for a minimum of 30 minutes before any data collection to allow camera stabilisation and account for start-up drift (Vardasca et al., 2019). The emissivity of the camera was set to 0.98 (Moreira, Costello, et al., 2017).

### 3.6.2.10 Thermal data capture

A black sheet was suspended in front of two markers of tape that were placed on the ground 26cm apart. Participants stood in the anatomical position to acclimatise to room temperature, with their heels on the edge of the tape. A 0.6m line was measured from the centre of the two markers (13cm) to the lens of the camera. The angle was measured with a Goniometer and string from the central point between heel markers to the 0.6m mark to ensure that the FLIR ONE was 0°to the centre of both Achilles' tendons. This can be seen in figure 3.23. The FLIR ONE was mounted to a tripod, with the lens 0.21m from the ground.




A = Participant left heel

B = Participant right heel

C = FLIR ONE IRC

Figure 3.23: Camera set up

#### 3.6.2.11 Objective clinical assessment

Following the thermal images, an objective clinical assessment was conducted. The outline of this objective clinical assessment can be seen in figure 3.24. Patients were first checked whilst lay in prone, with their feet in a neutral position hanging off the end of a therapy plinth, for visible swelling or tendon thickening in the midportion. Following this, they undertook basic range of motion tasks, reporting pain as and when they felt it. Manual muscle testing was conducted to assess whether isometric contraction in inner, mid and outer-range recreated any pain, it has previously been proven valid and reliable as a clinical assessment method (Cuthbert & Goodheart, 2007). The knee to wall test was then conducted in a standing position using a tape measure between the great toe and the wall to assess the range of ankle dorsiflexion bilaterally. This technique has proved to have greater reliability and lower SEM and MDC values that using a goniometer or digital inclinometer (Konor et al., 2012).

Following this, special testing was conducted in line with findings from the literature review in section 2.6.3, to attempt to rule in or rule out both Achilles tendinopathy and other possible conditions. The patients were then classed as load tolerant, partially load tolerant or load intolerant depending on their level of function and irritability to the movement tasks of stretching, calf raising variations and single leg hopping, which then shaped whether they would be allowed to progress to the exercise-based intervention stage of the studies. Patients who were load intolerant were excluded from the study due to ethical considerations around the potential for further injury risk. Those who were partially load tolerant were instructed to stop the testing if their pain became intolerable.

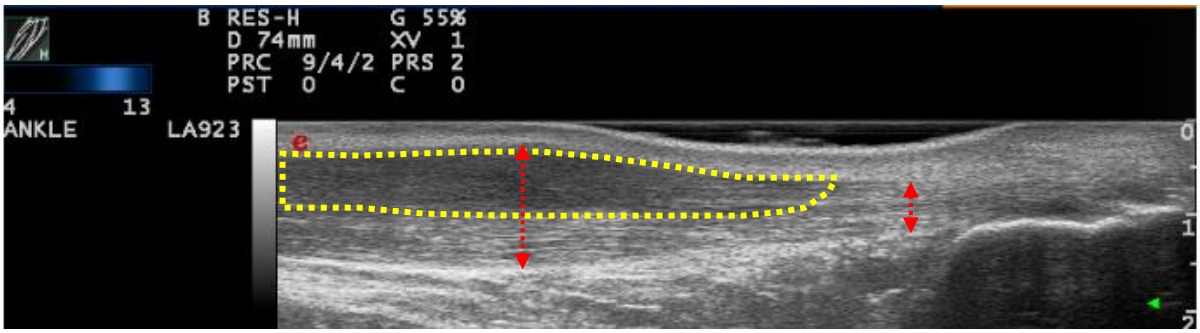
| | | | |
|---|---|---|---|
| 42 | THERMAL IMAGE AFTER 15 MINS | | |
| 43 | **Questions** | **Answers** | **Notes** |
| 44 | Does the patient have visible swelling? | | |
| 45 | Is there visible tendon thickening? | | |
| 46 | AROM | | |
| 47 | PROM | | |
| 48 | MMT | | |
| 49 | KTW | | |
| 50 | **Special testing** | | |
| 51 | Is there palpable pain? | | |
| 52 | Royal London test | | |
| 53 | Painful arc test | | |
| 54 | Does the patient have pain in forced end range plantarflexion? | | |
| 55 | Are there any neural symptoms present (SLR, Sural (DF&INV)) | | |
| 56 | **Objective measure** | | |
| 57 | What is your pain score out of 10 when stretching over a step? | | |
| 58 | How many double leg calf raises can the patient do? | | |
| 59 | How many single leg calf rasies can the patient do? | | |
| 60 | How many single leg hops can the patient do? (2.5hz) | | |
| 61 | How tolerant is the patient to load? | | |
| 62 | **ULTRASOUND** | | |
| 63 | Is there visible fusiform shape on ultrasound imaging? | | |
| 64 | Are there any areas of A-P thickening within the midportion of the AT? | | |
| 65 | Are there any large hypoechoic regions on ultrasound imaging? | | |

Figure 3.24: Objective assessment outline

Following this, the participants then received an US scan, from a non-diagnostic perspective. The purpose of this US scan was to feature map areas of fusiform swelling, A-P thickening and hypoechogenicity which could be used to confirm the presence of pathology within the tendon. Training was received by a qualified Ultrasonographer who worked at the University of Salford. The patients were placed in prone with their feet hanging off the end of the therapy plinth. They were then placed into a neutral ankle position (Baño-aledo et al., 2017; Zhang et al., 2018) as measured with a goniometer, which was then stabilised against the edge of the plinth to ensure that there was no angular change. Aquasonic 100 ultrasound gel (Parker Laboratories INC, Fairfield, NJ, USA) was then applied to the length of the tendon and the US probe. The probe was a 7.5MHz, 100mm linear array, B-mode US probe (MyLab70 XVision, Esaote, Genoa, Italy). Images of the tendon were obtained longitudinally.

#### 3.6.2.12 Ultrasound image analysis

US images were analysed using ImageJ software v1.52a (Wayne Rasband National Institutes of Health, USA). They were classified according to the scale outlined by Sunding et al. (2016) as having homogenous echogenicity or non-homogenous echogenicity (which included discrete, well-defined or extended) for simplicity. They were also classified as having a normal (parallel) or fusiform structure. Examples of a pathological tendon and a non-pathological tendon can be seen in figure 3.26 and 3.27 respectively.




*Dashed yellow line indicates an area of hypoechogenicity and dashed red arrow indicates increased A-P thickness.

Figure 3.25: A pathological Achilles tendon

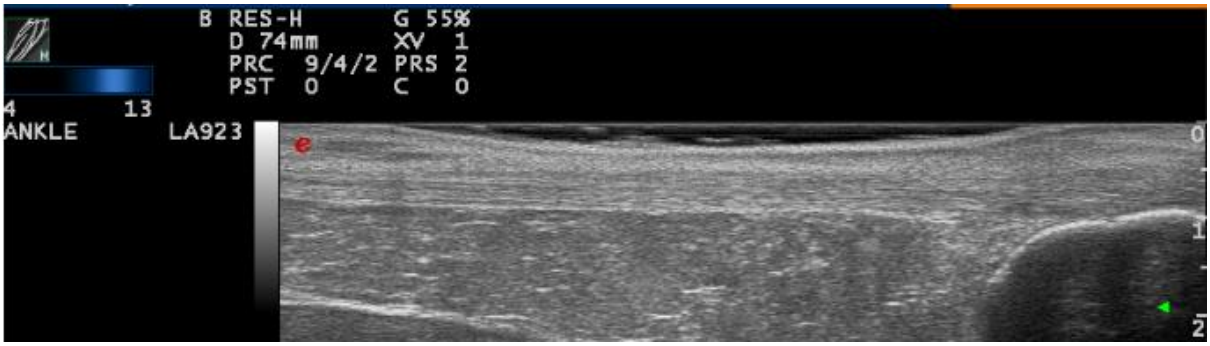



Figure 3.26: A non-pathological tendon

#### 3.6.2.13 Participant diagnosis

Participants were then diagnosed with chronic midportion tendinopathy based up a combination of their subjective and objective assessments. If they met the criteria of having unilateral midportion AT pain, chronic symptoms, palpable pain of the tendon in its midportion, a positive Royal London or painful arc test, with fusiform swelling, A-P thickening or hypoechogenicity as identified on an US scan, then there were included in the study. A lack of pain provocation upon functional testing did not exclude patients from the study as it did not have perfect specificity (Hutchison et al., 2013) and patients often reported easing of symptoms throughout the day, but they had to report these symptoms subjectively.

#### 3.6.2.14 Thermal data analysis

Following the completion of studies, thermal images were then analysed. Captured thermal images were stored locally on the iPhone 6S. They were then transferred to Dropbox, where each file was given a coded name. From Dropbox, these files were downloaded immediately to a laptop for analysis and deleted from the Dropbox file. Images contained no identifying information relating to the participants involved.

Thermal images were analysed retrospectively by drawing a bendable ROI between the centre of the calcaneal marker and the marker at the MTJ through the centre of the AT, using FLIR Research IR Max (v4.40.9.30, FLIR Systems, Oregon, US). An example of this can be seen in figure 3.25.

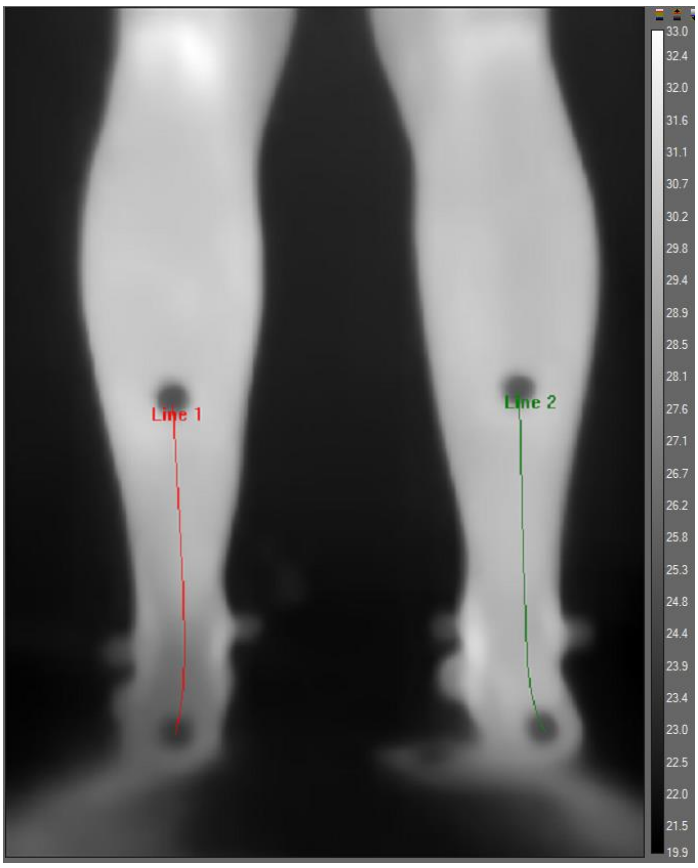



Figure 3.27: An example of the bendable ROI

The line was then exported into Microsoft Excel (v16.0, Microsoft corporation, WA, US) as a CSV file. The mean TSK value was then extracted using the macro, explained in section 3.3.3.10.

### 3.6.3 Conclusion

This chapter has outlined the method of thermal analysis and clinical assessment that was utilised throughout the remainder of this thesis. If any individual variations in this methodology occurred or if there were any additions, it will be stated with each chapter.

# Chapter FOUR

## A comparison of baseline midportion AT TSK between symptomatic and control participants

## 4.1 Introduction

As identified during chapter two some researchers have attempted to identify pathology using infrared thermal imaging. Rodriguez-Sanz et al. (2018) and Rodríguez-Sanz et al. (2017) identified that pathological ankle joints displayed asymmetrically significant TSK changes following an exercise intervention in footballers suffering from ankle equinus, however, no changes existed at baseline. In a case series of lateral ankle sprain, it was noted that there were differences of up to 2.5°C between a pathological and non-pathological limb (Ioannou, 2020).

In non-pathological AT's, it has been shown that no thermal differences existed between limbs (Tumilty, Adhia, Smoliga, & Gisselman, 2019). Tumilty et al. (2019) assessed the AT's of healthy recreational runners over a 9-week collegiate running season and identified a regional hypothermic trend over the duration of the weeks, however, this was bilateral. The findings by Tumilty et al. (2019) may not apply to pathological AT's with some of the pathophysiological characteristics of midportion Achilles tendinopathy suggesting heat change (D'Addona et al., 2017; Knobloch et al., 2006; Wang et al., 2012). Sanz-López, Martínez-Amat, Hita-Contreras, Valero-Campo, & Berzosa (2016) found a similar result at baseline, with no thermal asymmetries existing between asymptomatic AT's.

Some authors have found that values of asymmetry greater than 0.5°C are indicative of pathological change, however, these are not specific to the AT (Hildebrandt, Raschner, & Ammer, 2010; Vardasca, Ring, Plassmann, & Jones, 2012; Zaproudina, Varmavuo, Airaksinen, & Närhi, 2008). It is not possible to use the values contained within these studies to inform us of what constitutes significant thermal asymmetry at the midportion of the AT, due to the regional variability of TSK values as suggested by Tansey & Johnson (2015). However, these studies also suggest that it is possible for bilateral asymmetries to exist.

As indicated in chapter two, infrared thermal imaging may be a useful tool for detecting pathology in those suffering from Achilles tendinopathy. Physiological and biomechanical alterations can occur in a pathological AT, dependent on the category of tendinopathy as outlined by Cook et al. (2016) and described in section 2.6.1. Some of these changes include inflammatory responses in the AT, AT thickening, reductions in intra-tendinous blood flow and heat dissipation through hysteresis. It is possible that by utilising infrared thermal imaging, some of these changes may be visible at the skin surface. No study

has established whether there are baseline TSK differences between symptomatic and asymptomatic AT's.

The use of the FLIR ONE infrared thermal imaging camera in a clinical scenario is both quick, simple and affordable. This novel study could provide proof of concept for TSK asymmetries in symptomatic AT's that may lead to easy identification of the condition alongside clinical assessment. If differences do exist at baseline, it could open the tool in the long term to be used as a screening tool to identify those at risk of Achilles tendinopathy.

Therefore, the aims of this study were:

1. To determine whether there were any significant differences in baseline AT TSK between the limbs of symptomatic and asymptomatic participants

## 4.2 Hypotheses

1. There would be statistically significant differences in BL AT TSK between the SX and ASX limbs of the SX participants
2. There would be statistically significant differences in BL AT TSK between the left and right limbs of the ASX participants
3. There would be statistically significant differences in BL AT TSK between the SX_AT and the left and right limbs of the asymptomatic participants
4. There would be statistically significant differences in BL AT TSK between the ASX_AT and the left and right limbs of the asymptomatic participants

## 4.3 Methods

The methods were conducted in line with the overview outlined in chapter three unless stated otherwise.

### 4.3.1 Sample size calculation

A sample size calculation was conducted using G*Power 3.1.9.7 to detect meaningful change at 80% power and at an alpha level of 0.05. To account for a dropout rate of 10%, recruitment was aimed to be increased by 10% of the required sample size. The sample size calculation was based upon the work of Rodríguez-Sanz et al. (2017). Based on a calculated effect size from this study on non-pathological limbs before exercise, a total of 70 (35 per

group) participants were required to detect a meaningful change in baseline TSK. Therefore, accounting for dropout, the aim was to recruit 39 per group.

### 4.3.2 Participants

39 symptomatic participants volunteered to take part in the study (Mean ± SD age 41.4 ± 9.74 years, mean ± SD height 174.9 ± 9.1 cm, mean ± SD mass 76.3 ± 12.9 kg). 33 asymptomatic participants volunteered (Mean ± SD age 38.6 ± 10.5 years, mean ± SD height 172.6 ± 9.2 cm, mean ± SD mass 72.7 ± 12.4 kg).

### 4.3.3 Room temperature

Measured as stated in section 3.6.2.5. The mean room temperature during BL testing was 21.2 ± 0.9°C and the mean humidity was 42.7 ± 8.6%.

### 4.3.4 Thermal data capture

Thermal data capture was conducted as stated in section 3.6.2.10. A total of 72 images were taken, one image per participant.

### 4.3.5 Statistical analysis

The data were found to be normally distributed as assessed by the Shapiro-Wilk test. A one-way ANOVA was conducted to determine if any differences in Achilles tendon TSK existed between the symptomatic AT (SX_AT) and asymptomatic AT (ASX_AT) of symptomatic participants and the left and right Achilles tendons (CL_AT and CR_AT) of asymptomatic participants. The effect size calculated for the one-way ANOVA was partial eta squared (partial $\eta^2$), which is equal to eta squared ($\eta^2$) in the one way ANOVA and was calculated using the formula $\frac{Sum\ of\ squares\ between}{Sum\ of\ squares\ total + sum\ of\ squares\ error}$ (Lakens, 2013).

## 4.4 Results

The mean TSK values for each of the groups can be seen in table 4.1. The results of the one-way ANOVA revealed that there were no significant differences in BL TSK of the midportion of the AT between the SX_AT, ASX_AT, CR_AT and CL_AT limbs $F_{(3,140)} = 0.71$, $p=0.55$, partial $\eta^2 = 0.02$.

Table 4.1: Mean TSK values and Standard deviations for the symptomatic and asymptomatic participants

| **Group** | **Mean TSK (°C)** | **SD (°C)** |
|---|---|---|
| SX AT | 26.5 | 2.0 |
| ASX AT | 26.2 | 1.9 |
| CL AT | 26.7 | 2.2 |
| CR AT | 26.9 | 2.3 |

## 4.5 Discussion

This study aimed to identify whether statistically significant differences in midportion AT TSK existed between SX and ASX limbs and between the left and right limbs of asymptomatic participants. The null hypotheses 1 and 2 can be accepted as the results of the one-way ANOVA revealed that no significant differences were found between the groups.

Other authors have previously suggested that baseline bilateral asymmetry may be a useful indicator of pathology (Dibai Filho, Packer, Costa, Berni-Schwarzenbeck, & Rodrigues-Bigaton, 2012; Hildebrandt et al., 2010; Soroko et al., 2013; Vardasca et al., 2012; Zaproudina, Varmavuo, Airaksinen, & Närhi, 2008). Vardasca et al. (2012) suggested that bilateral asymmetry of the posterior lower limb of greater than 0.5°C ± 0.3°C indicated abnormal values between limbs and should be used as a clinical benchmark. Zaproudina et al., (2008) suggested that TSK difference of greater than 0.6°C could indicate an autonomic abnormality in the region of the heel. Hildebrandt, Raschner, & Ammer (2010) concluded that values of 0.7°C or greater in the anterior knee between two sides of the body are likely pathological, however in equine participants values of 1.25°C or greater have been suggested (Soroko et al., 2013). It is clear from the available literature that there is no clear consensus as to what constitutes both statistically and clinically significant difference in TSK between limbs and it is likely that comparisons cannot be drawn between different regions of the body.

The results of this study contradicted the results from the aforementioned studies. Despite a clinical diagnosis of AT pathology, the results showed that the mean TSK difference

between the SX and ASX AT's in symptomatic participants was 0.4°C ± 0.1°C. These results are similar to the mean TSK differences found by Tumilty et al. (2019), who found statistically insignificant (p=0.68) bilateral asymmetries between non-pathological AT's, with a mean of 0.5°C ± 0.4°C over a 9-week collegiate cross-country season. The mean differences in TSK were within their published SEM value, so it is possible that the 0.5°C mean change in TSK was down to random measurement error and not bilateral asymmetry. Unfortunately, baseline figures for the first week were not provided, but they appear to be similar to those in the current study, based on visual inspection of the mean Achilles TSK values across the season. Slightly larger mean differences may be explained due to different ROI measurement procedures.

The results of the current study also agreed with findings by Rodriguez-Sanz et al. (2018) and Rodríguez-Sanz et al. (2017), who found no BL differences in AT TSK in those suffering from functional ankle equinus.

There were no significant differences between the CL_AT and CR_AT's, with a mean difference of 0.2°C ± 0.2°C. Again, these results are similar to the results found by both Tumilty et al. (2019) in non-pathological AT's, and Rodríguez-Sanz et al. (2017) in the AT's of control participants in their functional ankle equinus study.

There were also hypotheses indicating that differences would exist between the SX_AT and CL_AT and CR_AT. The null hypotheses 3 and 4 can be accepted based on the results of the one-way ANOVA, as the multiple comparisons revealed no statistically significant differences. This result meant that moving forward throughout the study, the CL and CR AT's could be grouped for assessment.

### 4.5.1 Limitations

A limitation of this study is that it was not possible to completely control participants load exposure before baseline imaging. All participants did not complete exercise on the day of testing in line with the recommendations by Moreira et al. (2017), but because they were recruited from multiple running clubs at various times of the year, their training schedules varied depending on training nights and events that they were preparing for. Ideally, it would have been beneficial to assess baseline TSK values at the beginning of the running season, following a period of rest, but logistically this was not possible. The work by Tumilty et al. (2019) would suggest that Achilles tendon TSK does not significantly differ in healthy

participants throughout the course of a running season, however, this effect within a 24-hour period is unknown.

## 4.6 Conclusion

In conclusion, the results of this chapter showed that baseline AT TSK values did not significantly differ between SX or ASX limbs or between symptomatic and asymptomatic participants. The results of this study suggested that bilateral BL TSK differences of up to 0.7°C did not constitute significant differences, therefore future studies should now explore whether exercise significantly affects the TSK response at the midportion of the AT between symptomatic and asymptomatic AT's and control participants.

# Chapter FIVE

## Midportion Achilles tendon skin temperature and running

## 5.1 The effect of running on midportion Achilles tendon skin temperature in symptomatic and asymptomatic individuals

### 5.1.1 Introduction

Runners are susceptible to developing Achilles tendinopathy, with a lifetime prevalence of up to 57% (Kujala et al., 2005; O'Neill, 2016). Despite the long-standing nature of the symptoms, runners will often continue to run as it is characteristic for the symptoms to cease upon initiation of activity, until the time whereby the symptoms begin to cause intolerable pain with activities of daily living. The condition is often treated in retrospect.

As discussed in the literature review, certain biomechanical and physiological features of the pathology such as the presence of inflammation, changes in intratendinous blood flow, hysteresis and changes in skin blood flow, all point towards the theory of being able to detect changes in TSK (D'Addona et al., 2017; Dakin et al., 2018; Knobloch et al., 2006; Wang et al., 2012a). Chapter four found that these changes did not exist at resting BL, however, the onset of running activity which increases metabolic demand and places different biomechanical demand on the symptomatic AT than at rest could create non-uniform changes in the biomechanical and physiological response of the AT (Karamanidis & Epro, 2020) and thus change TSK disproportionally. If this was the case, it may be possible to screen runners and identify those at risk of chronic midportion Achilles

Rodríguez-Sanz et al. (2017) assessed AT TSK following exercise in footballers suffering from functional ankle equinus and found that significant mean TSK differences existed between symptomatic and asymptomatic individuals in both limbs, with absolute TSK values in the left limb differing by a mean 2.0°C and the right by 1.9°C. This is a condition whereby the ankle joint has limited ranges of dorsiflexion, with suggestions that it could be related to Gastrocnemius-Soleus muscle alterations (Rodriguez-Sanz et al., 2019).

Rodriguez-Sanz et al. (2019) then found that TSK increases in the Gastrocnemius-Soleus musculature were correlated to changes in EMG activity. In a systematic review and meta-analysis, Sancho, Malliaras, Barton, Willy, & Morrissey (2019) identified that limited evidence existed to suggest that those with Achilles tendinopathy displayed variable EMG activity. If variable EMG activity is correlated with thermal change due to pathology such as functional ankle equinus, then it is possible that changes may also be displayed in those with symptomatic AT's.

Based on this, this study aimed to establish the effect of a 15-minute running task on the TSK response of the AT in symptomatic and control participants.

### 5.1.2 Hypotheses

1. There would be a statistically significant increase in absolute TSK of the midportion of the AT from timepoint BL to immediately post running task (POST0) in the SX tendon, the ASX tendon and the control group AT's.
2. There would be a statistically significant decrease in absolute TSK of the midportion of the AT from timepoint POST0 to CD10 in all groups
3. There would be a statistically significant difference in absolute TSK values between the SX_AT and ASX_AT's in response to the running task
4. There would be a statistically significant difference in TSK between the SX_AT and control AT's in response to the running task
5. There would be a statistically significant difference in TSK between the ASX_AT and control AT's in response to the running task

### 5.1.3 Methods

The methods for this section were as outlined in chapter 3 unless otherwise stated.

#### 5.1.3.1 Sample size calculation

A sample size calculation was conducted using G*Power 3.1.9.7 to detect meaningful change at 80% power and at an alpha level of 0.05 based on data from (Rodríguez-Sanz et al., 2017). To account for a dropout rate of 10%, recruitment was aimed to be increased by 10% of the required sample size. A total of 34 participants (17 per group) were needed to detect a meaningful change in midportion AT TSK in response to an exercise task. Therefore, the aim was to recruit a minimum of 19 participants per group.

#### 5.1.3.2 Participants

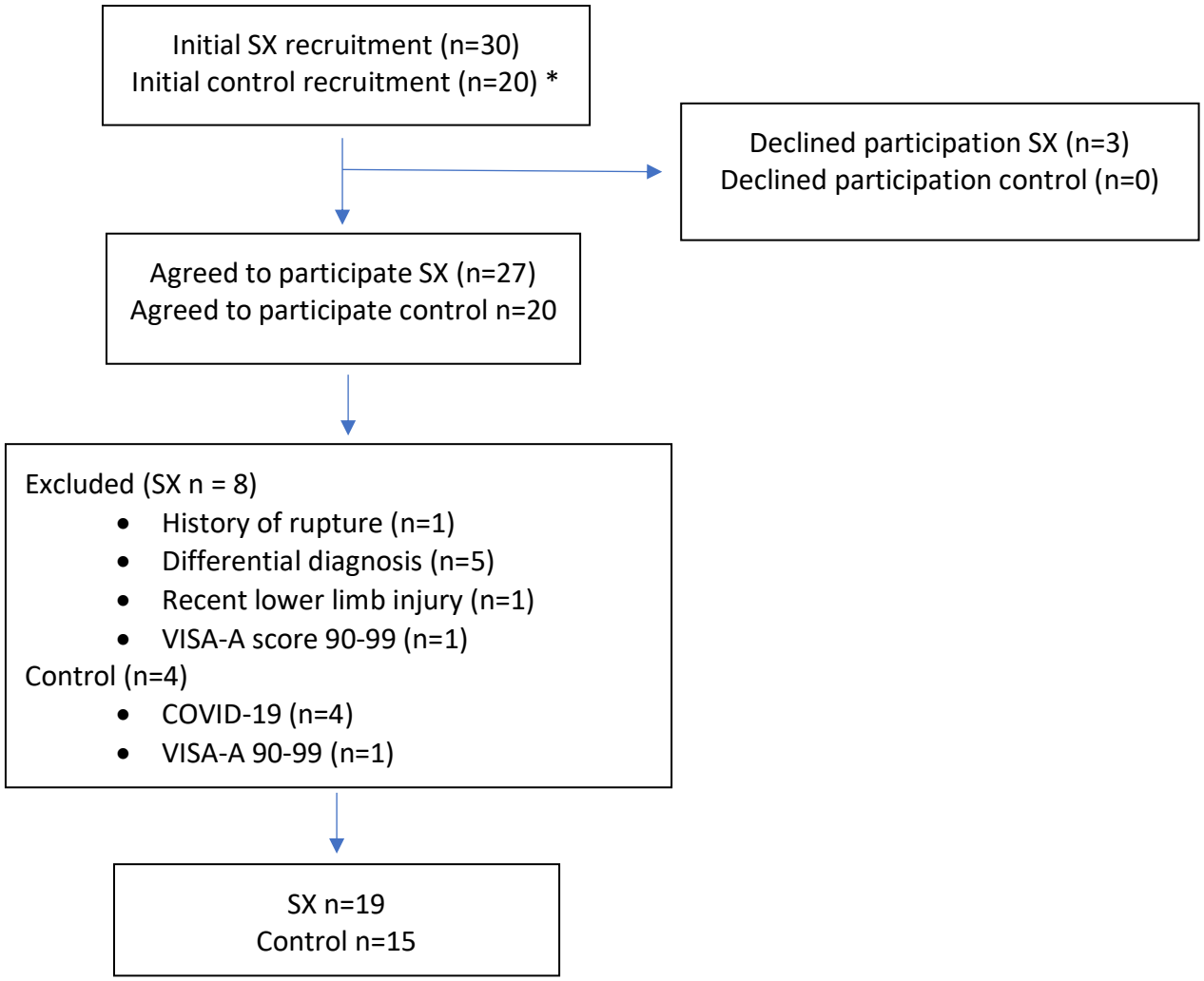
Recruitment was as stated in chapter three section 3.6.2.2. The participants recruited for chapter four were block randomised into a running cohort or a hopping cohort. Therefore, 19 symptomatic and 15 control participants undertook the running task. Participant

anthropometrics can be seen in table 5.1.1. A Consolidated Standards of Reporting Trials (CONSORT) flow diagram can be seen in figure 5.1.1, which outlined participant recruitment.

Table 5.1.1: Participant anthropometrics

| Group | Mean ± SD age (years) | Mean ± SD height (cm) | Mean ± SD mass (kg |
|---|---|---|---|
| SX | 39.6 ± 8.8 | 175.7 ± 11.1 | 75.5 ± 12.9 |
| Control | 38.2 ± 12.2 | 172.1 ± 6.5 | 74.8 ± 13.3 |

Figure 5.1.1: CONSORT flowchart for participant recruitment




***Numbers affected by COVID-19**

#### 5.1.3.3 Room temperature

Measured as stated in chapter three. The mean room temperature during BL testing was 21.1 ± 0.9°C and the mean humidity was 44.4 ± 9.4%.

#### 5.1.3.4 Running Intervention

Participants returned on a second day after their clinical assessment to conduct the running intervention. This was within 7 days of their clinical assessment. The participants followed an acclimatisation period and the BL thermal image was taken. The subjects then undertook a 15-minute treadmill running task. The 15-minute treadmill task was chosen as it was deemed sufficiently long enough to induce AT hysteresis based upon on data obtained by Zelik and Franz (2017). During the subjective part of their assessment in session 1, subjects were asked to provide their average 10 km running time. This was then converted into km/h, by first calculating $\frac{time\ (mins)}{60}$, before using the equation $speed = \frac{distance}{time}$ to determine their running speed for the treadmill. The mean treadmill speed for the SX_AT group was 12.0 ± 2.0km/h and for the control group it was 11.1 ± 1.8 km/h, these were not statistically significantly different, as assessed by the Mann-Whitney U test due to the presence of one outlier within the data (U=25.000, z=-0.738, p=0.505).

The participants were briefed before the run that if during the run their pain became intolerable, they were to notify the researcher and the intervention would be immediately stopped. Participants undertook a 2-minute ramped warm-up, whereby they began walking at a fast pace, and speed was incrementally increased every 30 seconds until they hit their target running speed by the 2-minute mark. This was chosen due to it being progressive in nature, and most runners reported that their pain decreased quickly upon the initiation of movement. Stretching was not included as there is no evidence to suggest that it is beneficial for Achilles tendinopathy, and some runners did not routinely conduct stretch based warm ups, therefore including these may have affected the stiffness properties of the runners AT's (Kubo et al., 2001).

Participants ran at that speed for the 15-minute duration, before the speed was reduced at intervals mirroring the initial increases, over a 2-minute period. In the final minute of the run, participants were asked to rate their maximal midportion AT pain during the run on the NPRS scale.

Following the running task, participants returned to the thermal testing area for post-run thermal imaging. The time between leaving the treadmill and the post-run thermal imaging was no more than 60 seconds. Participants walked from the treadmill to the corner of the lab, a distance of 20m and removed their trainers and socks. This thermal area was chosen because it could be sectioned off and the lighting overhead could be controlled. Participants ran in their trainers and socks to replicate their normal running style and to prevent the risk of any blistering caused by changes to their attire

#### 5.1.3.5 Thermal data capture

Thermal data capture was conducted as stated in chapter three. Thermal images were taken at 8 time points per participant (BL, POST0, Cooldown (CD)2, CD4, CD5, CD6, CD8 and CD10). In total for the running group, this equalled 272 thermal images taken using the FLIR ONE (SX 152, Control 120). During the fifth minute, participants were asked to rate their midportion AT post-run pain on an NPRS scale.

#### 5.1.3.6 Thermal data analysis

Conducted as outlined in chapter three.

#### 5.1.3.7 Statistical analysis

Normality was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise ($p>0.05$). Homogeneity of variances was assessed using Levene's test and the assumption was met unless stated otherwise ($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

Independent samples t-tests were used to assess whether any pre-testing differences were present between the groups for VISA-A, NPRS and rating of perceived exertion (RPE) scores.

A factorial mixed ANOVA (8x3) was used to assess the differences in TSK values following the running intervention, with timepoint (BL, POST0, CD2, CD4, CD5, CD6, CD8, CD10) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subjects independent variable. Mauchly's test of sphericity was violated ($x^2$ (27) = 354.921, $p<0.001$) therefore Greenhouse-Geisser corrected results were reported.

ΔTSK scores were calculated by subtracting the absolute TSK value from the previous (Post0 from BL, CD2 from POST0, CD4 from CD2, CD5 from CD4, CD6 from CD5, CD8 from CD6 and CD10 from CD8). A two-way mixed ANOVA was run on ΔTSK response for each of the 7 pairs of time points, to see if the responses differed between groups.

### 5.1.4 Results

#### 5.1.4.1 VISA-A, NPRS and RPE

The results from the independent samples t-test for VISA-A, NPRS and RPE can be seen in table 5.1.2

Table 5.1.2: Mean and SD data for VISA-A, NPRS and RPE for running participants at week 0.

| Outcome measure | SX mean ± SD | Control mean ± SD | p-value |
|---|---|---|---|
| VISA-A | 77.6 ± 6.9 | 100.0 ± 0.0 | <0.001 |
| NPRS During | 2.1 ± 2.2 | 0.0 ± 0.0 | 0.001 |
| NPRS After | 1.0 ± 1.5 | 0.0 ± 0.0 | 0.009 |
| RPE | 4.9 ± 2.3 | 5.9 ± 1.5 | 0.151 |

There was a statistically significant difference in VISA-A scores between SX and control participants at the week-0 testing session, $t_{(18.000)}$=14.250, p<0.001. The SX participants had a 22.4 point lower mean VISA-A score (95% CI -25.7, -19.1) than the control participants.

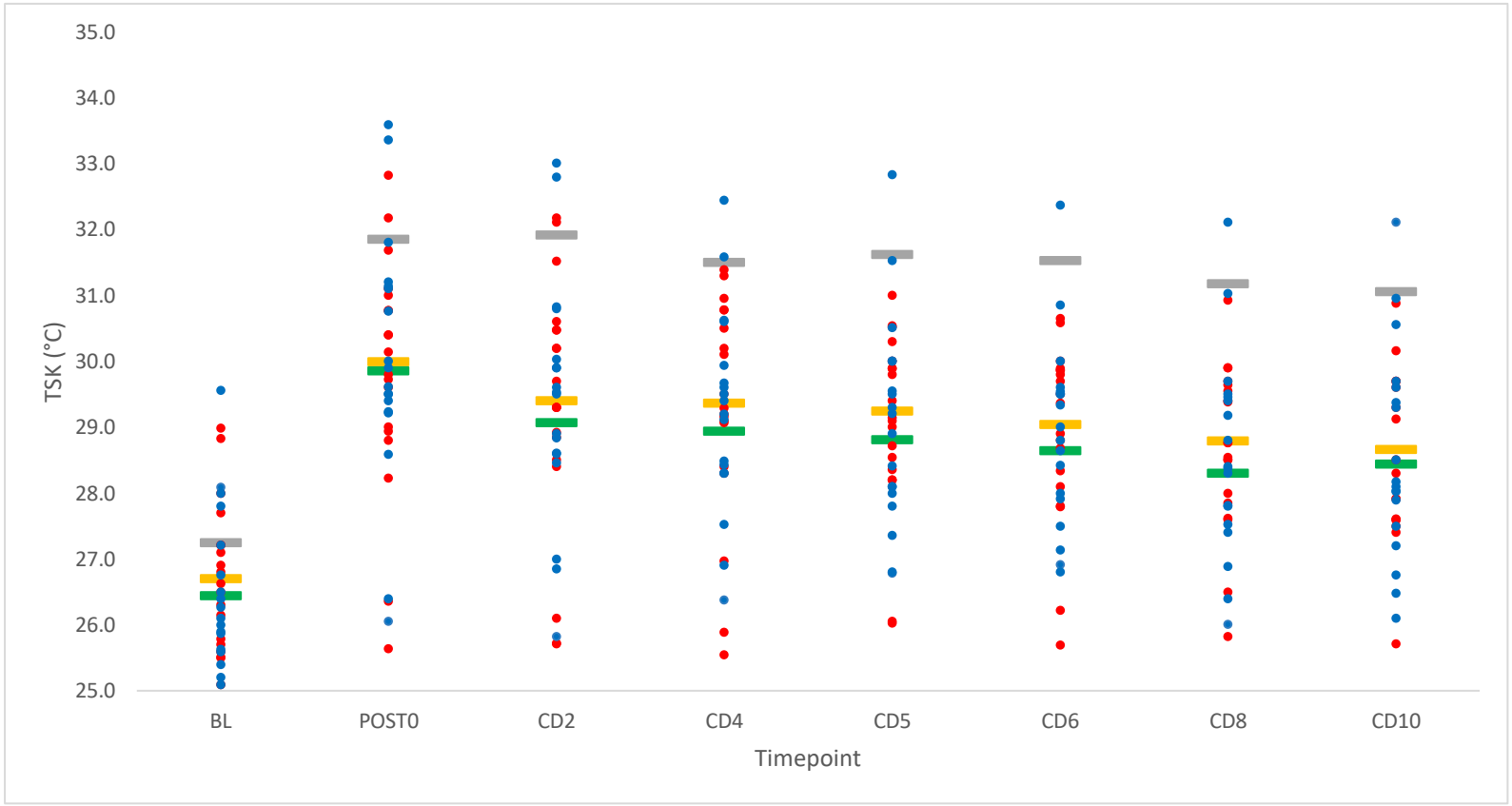
There was a statistically significant difference in NPRS score during the running activity during the week 0 testing session, $t_{(18.000)}$=4.109, p=0.001. NPRS scores during the activity were a mean of 2.1 (95% CI -1.0, 3.2) higher in the SX participants.

There was a statistically significant difference in NPRS scores recorded after activity at the week 0 testing session between the SX and control groups $t_{(18.000)}$=2.924, p=0.009. The NPRS score after activity was a mean of 1.0 (95% CI 0.3, 1.7) higher in the SX participants.

There were no statistically significant differences in mean RPE score between the SX or control participants at the week-0 testing session $t_{(33.000)}$=1.470, p=0.151. The control group mean RPE score was 1.0 (95% CI -0.4, 2.3) higher than the SX participants.

#### 5.1.4.2 Absolute TSK

Mean TSK data for timepoint and group can be seen in table 5.1.3 and graphically in figure 5.1.2.




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 5.1.2: TSK data for runners

Table 5.1.3: Mean WK0 TSK data for running participants

| Time | Group | Mean absolute TSK (°C) | SD (°C) | ΔTSK from BL (°C) | SD (°C) |
|---|---|---|---|---|---|
| BL | SX | 26.7 | 1.3 | - | - |
| | ASX | 26.4 | 1.4 | - | - |
| | Control | 27.2 | 2.2 | - | - |
| | Mean | **26.8** $^{abcdefg}$ | 1.7 | | |
| POST0 | SX | 30.0 | 2.5 | 3.3 | 2.8 |
| | ASX | 29.8 | 2.7 | 3.4 | 2.6 |
| | Control | 31.9 | 2.1 | 4.6 | 2.9 |
| | Mean | **30.6** $^{ahijklm}$ | 2.4 | **4.0** $^{tuvwxy}$ | 2.8 |
| CD2 | SX | 29.4 | 2.6 | 2.7 | 2.8 |
| | ASX | 29.1 | 2.6 | 2.6 | 2.5 |
| | Control | 31.9 | 1.6 | 4.7 | 2.6 |
| | Mean | **30.1** $^{bhn}$ | 2.5 | **3.7** $^{tz}$ | 2.8 |
| CD4 | SX | 29.4 | 2.3 | 2.7 | 2.7 |
| | ASX | 28.9 | 2.4 | 2.5 | 2.3 |
| | Control | 31.5 | 1.5 | 4.3 | 2.6 |
| | Mean | **29.9** $^{cio}$ | 2.3 | **3.5** $^{uaa}$ | 2.6 |
| CD5 | SX | 29.2 | 2.0 | 2.5 | 2.4 |
| | ASX | 28.8 | 2.3 | 2.4 | 2.2 |
| | Control | 31.6 | 1.7 | 4.4 | 2.6 |
| | Mean | **29.9** $^{djp}$ | 2.0 | **3.5** $^{vab}$ | 2.6 |
| CD6 | SX | 29.0 | 2.0 | 2.3 | 2.3 |
| | ASX | 28.6 | 2.1 | 2.2 | 2.1 |
| | Control | 31.5 | 1.8 | 4.3 | 2.7 |
| | Mean | **29.7** $^{ekq}$ | 2.0 | **3.3** $^{w}$ | 2.7 |
| CD8 | SX | 28.8 | 1.8 | 2.1 | 2.1 |
| | ASX | 28.3 | 2.2 | 1.9 | 2.2 |
| | Control | 31.2 | 2.0 | 3.9 | 2.9 |
| | Mean | **29.4** $^{flnopq}$ | 2.0 | **3.0** $^{xzaaab}$ | 2.7 |
| CD10 | SX | 28.7 | 1.5 | 2.0 | 1.3 |
| | ASX | 28.4 | 2.2 | 2.0 | 1.8 |
| | Control | 31.0 | 1.9 | 3.8 | 2.8 |
| | Mean | **29.4** $^{gm}$ | 1.9 | **2.9** $^{y}$ | 2.4 |
| Mean | Sx | 28.9 $^{r}$ | 0.5 | 2.5 | 2.3 |
| | ASX | 28.5 $^{s}$ | 0.4 | 2.4 | 2.2 |
| | Control | 31.0 $^{rs}$ | 0.2 | 4.3 | 2.7 |

**abcd**efghljklmnopq denotes statistical significance for mean absolute TSK (irrespective of group) between timepoints ($p<0.05$)

$^{r\,s}$ denotes statistical significance for mean absolute TSK (irrespective of timepoint) between groups ($p<0.05$)

**t** u v w x y z aa ab denotes statistical significance for mean ΔTSK (irrespective of group) between timepoints ($p<0.05$)

The factorial ANOVA revealed that there was no statistically significant group x time two-way interaction on TSK values of the midportion of the AT ($F_{(4.643, 150.906)}$ = 2.235, p=0.070, partial $\eta^2$ = 0.094).

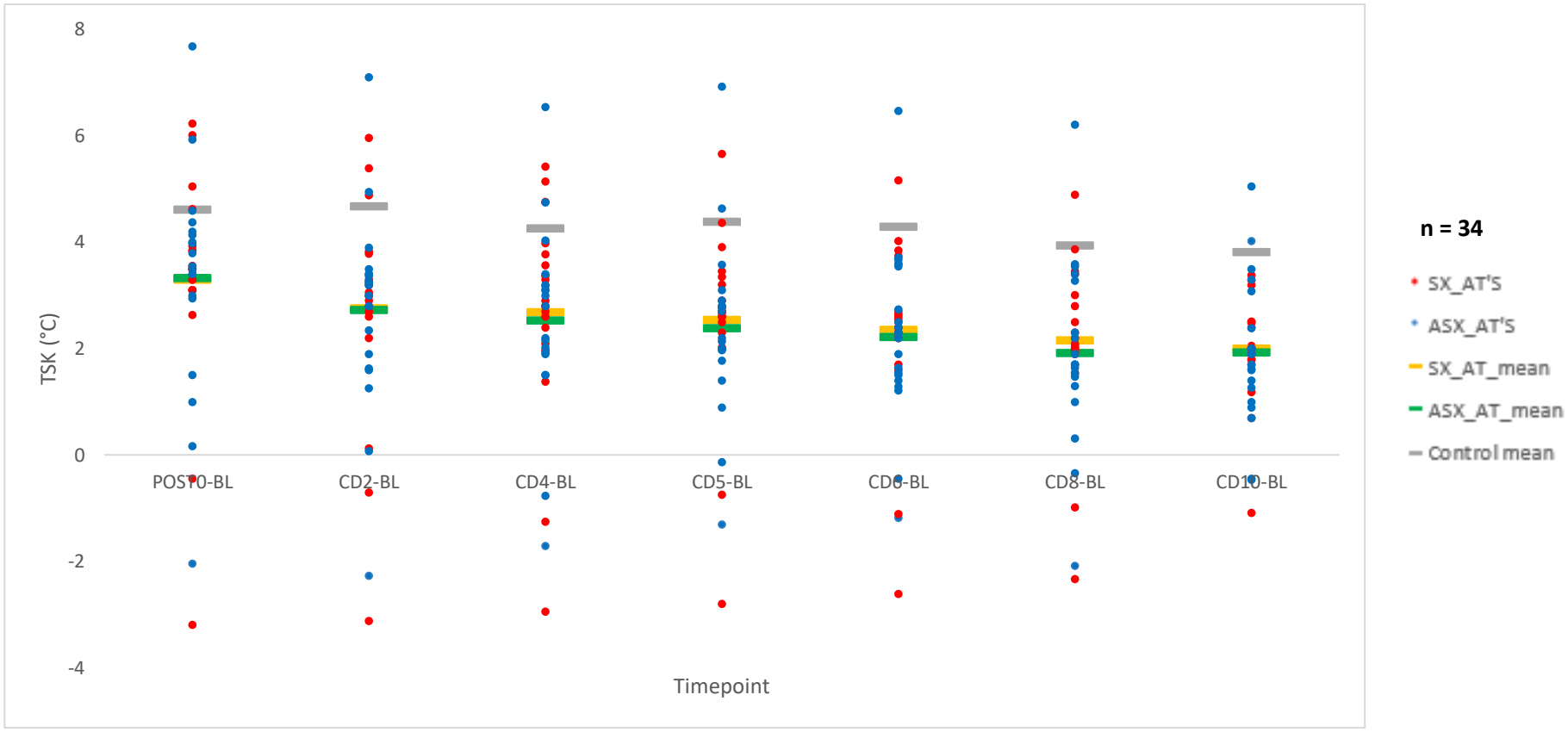
The main effect of time showed a statistically significant difference in TSK of the midportion of the AT ($F_{(2.322,150.906)}$ = 42.966, p<0.001, partial $\eta^2$ = 0.500), irrespective of group. Pairwise comparisons revealed statistically significant absolute TSK differences between timepoints BL and POST0 (p<0.001), with a mean absolute TSK increase of 3.8°C, d=1.8 following the run. All post-run absolute TSK values at each of the time points were significantly greater than baseline, all with large effect sizes (range 1.4-1.8).

POST0 absolute TSK values were statistically significantly (p>0.05) higher than those at CD2 (d=0.2), CD4 (d=0.3), CD5 (d=0.3), CD6 (d=0.4), CD8 (d=0.5) and CD10 (d=0.5). TSK values at timepoint CD8 were statistically significantly (p>0.05) lower than those at CD2 (d=0.3), CD4 (d=0.2), CD5 (d=0.2) and CD6 (d=0.1).

The main effect of group showed that there was a statistically significant difference in mean TSK at the midportion of the Achilles tendon between groups ($F_{(2,65)}$ = 9.967, p<0.001, partial $\eta^2$ = 0.317). Pairwise comparisons revealed statistically significant (p=0.01) TSK differences between SX_AT and control participants tendons, with control participants TSK being hotter by 2.1°C, d=1.0. There was a statistically significant difference (p=0.001) between the ASX_AT's and the control participants tendons, with the control participants TSK being 2.4°C hotter, d=1.1. The difference between SX_AT's and ASX_AT's was not statistically significantly different, with SX_AT's being a mean of 0.3°C hotter, d=0.1.

#### 5.1.4.3 ΔTSK

Mean ΔTSK response can be seen in figure 5.1.3. The results of the ΔTSK factorial mixed ANOVA revealed no significant group x timepoint interaction ($F_{(3.178,103.277)}$ = 0.837, p=0.507, partial $\eta^2$ = 0.037).




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 5.1.3: Week 0 ΔTSK response

The main effect of timepoint was significant, ($F_{(1.589,103.277)}$ = 11.978, p<0.001, partial $\eta^2$ = 0.218). Pairwise comparisons revealed that the mean ΔTSK response between timepoints BL and POST0 was significantly (p=0.025) higher than CD2-BL (d=0.2). POST0-BL ΔTSK response was significantly (p<0.001) different to timepoints CD4-BL (d=0.2), CD5-BL (d=0.3), CD6-BL (d=0.3), CD8-BL (d=0.4) and CD10-BL (p=0.007, d=0.5). The mean ΔTSK cooling response between timepoints CD2-BL and CD8-BL was statistically significantly different (p=0.001, d=0.3). The mean ΔTSK response between timepoints CD4-BL and CD8-BL was statistically significantly different (p=0.011, d=0.2). The mean ΔTSK cooling response between timepoints CD5-BL and CD8-BL was statistically significantly different (p<0.001, d=0.2), as was the mean ΔTSK response between timepoints CD6-BL and CD8-BL (p=0.001, d=0.1).

There was no statistically significant mean ΔTSK responses between the groups ($F_{(2,65)}$ = 3.310, p=0.054, partial $\eta^2$ = 0.127).

### 5.1.5 Discussion

This study aimed to establish the effect of a 15-minute running intervention on the TSK response of the AT in symptomatic and control participants. The main findings of this study were:

1) There were significant elevations in TSK of the midportion of the Achilles tendon in response to a 15-minute running intervention in all the groups.

2) There were significant differences in absolute TSK response between the SX_AT and control group, and the ASX_AT and control group, but not the SX_AT and the ASX_AT's.

3) There were no differences in ΔTSK response between the groups in response to the running intervention.

#### 5.1.5.1 Absolute TSK

The significant main effect of timepoint found in the current study evidenced that there was substantial TSK change in the midportion of the Achilles tendon in response to a 15-minute running intervention, which led to the acceptance of hypothesis 1. BL TSK values were significantly lower than all other time points, with a mean difference across the 10 minutes of 3.1°C (range 2.6°C-3.8°C, mean effect size 1.6), with the greatest ΔTSK being 3.8°C from timepoint POST0, d=1.8. The large effect size emphasised the size of this difference (Cohen, 1988).

These results are aligned to previous works conducted by Sanz-López et al. (2016) who found a mean increase in Achilles tendon TSK of 1.9°C in the right and 1.7°C in the left, immediately after a 1-hour outdoor running intervention. A possible reason for the difference in mean increases found by Sanz-López et al. (2016) and the current study could be the fact that their running intervention was conducted in an outdoor environment, and the thermographic images were taken in an indoor environment. No detail was provided with the length of time it took for the participants to cease running and have the thermogram taken, which may have resulted in substantial TSK cooling.

Post0 TSK values were found to be significantly higher than all the following timepoints by a mean of 0.8°C (range 0.4°C-1.2°C, mean d=0.4) indicating that a TSK cooling response was initiated following cessation of running. This exceeded the 0.5°C MDC value calculated in

chapter three. Hypothesis 2 was accepted based upon these results. The TSK decrease following the cessation of the running exercise was to be expected as this coincides with an increase in sweat production and a reduction in metabolic demand from the musculotendinous unit. Therefore thermal homeostasis will occur to reduce the overall temperature of the body post-exercise (Kenny & McGinn, 2017),

There was a statistically significant decrease in TSK during the cooldown period between timepoints CD6 and CD8 (mean ΔTSK 0.3°C, d=0.1). However, this was within the SEM found in section 3.5, therefore should be disregarded from a clinical perspective as the change could be a result of random error.

Following the initial large increase in TSK in response to running, the temperature remained elevated above the BL value for the resultant cooldown period despite decreasing at a steady rate in all groups. By timepoint CD10, the groups remained a mean of 2.6°C ± 2.0°C higher than resting BL TSK.

AT TSK increases were also found by Sanz-López et al. (2016), who saw a mean TSK increase of 1.8°C in the Achilles tendon of their control group immediately after exercise and then a decrease at the CD10 timepoint, with TSK being a mean of 1.6°C higher than BL. It may be possible that their increase in Achilles tendon TSK is lower than that seen in the current (3.1°C) study as their task was an eccentric Yo-Yo squat, a quadricep dominant exercise. This increased demand on the Achilles tendon with the 15-minute running task that was completed in the current study may also account for why there was a larger TSK reduction post-exercise, as it was returning from a more hyperthermic value, therefore requiring a more rapid cooling response to reach a more optimal resting temperature. Future study may address TSK changes over a longer cooldown period to establish whether SX_AT's and ASX_AT's values return to BL values similarly to control AT's, or whether there are significant differences in recovery time.

There was no statistically significant (p=1.00) difference between SX_AT's and ASX_AT's regardless of timepoint, with SX_AT's being a mean of 0.3°C warmer than the ASX_AT's. This result led to the rejection of hypothesis 3. It was hypothesised that differences would exist due to the features of the pathology in the symptomatic AT that were outlined in chapter 2. However, this was not found to be the case and there was a somewhat symmetrical response of both the SX_AT and the ASX_AT. It is still important to consider the SX_AT and the ASX_AT as two separate groups moving forward throughout the study due to the varied

response to the control group, and it is unknown whether the 12-week rehabilitation intervention will have a symmetrical effect on both AT's.

There was a statistically significant (p=0.005) difference in absolute TSK between the SX_AT group and the control group regardless of timepoint, with the control groups AT TSK being warmer by a mean of 2.1°C, d=1.0. This led to the acceptance of hypothesis 4. The difference between the ASX_AT group and the control group was also statistically significantly (p=0.001) different, with the control groups Achilles tendons being warmer by a mean of 2.4°C (d=1.1). This led to the acceptance of hypothesis 5. The finding that the control participants (asymptomatic individuals) AT's were warmer throughout the timepoints, combined with the initial decrease in TSK post-exercise suggest it is unlikely that inflammation is responsible for skin temperature change in degenerative tendinopathy and support existing literature identifying an atypical inflammatory response (Dakin et al., 2018). Acute inflammatory responses have previously been linked to increases in TSK as detected by infrared thermal imaging (Hildebrandt et al., 2010; Kanazawa et al., 2016; Lasanen et al., 2015).

Another possible reason why differences in TSK may have existed between the groups could be due to changes in blood flow in response to the running intervention. Recent research that was published after data collection had ceased found that 10-minutes of treadmill running led to increased AT blood flow (Pieters et al., 2020). It is also known that there are local changes to microvascular volume in the Achilles tendon in response to activity in both symptomatic and asymptomatic athletes (Boesen et al., 2006; Knobloch et al., 2006; Kubo et al., 2017; Pingel et al., 2013; Praet et al., 2018). Knobloch et al. (2006) found that there were no differences in microvascular volume between the asymptomatic Achilles tendon of the symptomatic participants and both tendons of the asymptomatic participants which could indicate that intratendinous blood flow is unlikely to be responsible for the findings of the current study. It is, however, possible that intratendinous blood flow may not be reflected at the surface of the skin and instead the increased metabolic demand from the Gastrocnemius-Soleus musculature in the symptomatic participants may result in a lesser rate of TSK warming in response to exercise (Katayama & Saito, 2019; Lenasi, 2014; Lichtwark & Wilson, 2007). Future study may seek to investigate this.

#### 5.1.5.2 ΔTSK

The results showed that there was no significant two-way interaction for the ΔTSK response to the 15-minute running intervention. There was no significant difference between the groups (p=0.054, partial $\eta^2$ = 0.127). However, from a clinical perspective, the difference in ΔTSK response between the SX_AT and control group was 1.8°C irrespective of timepoint, and it was 1.9°C for the ASX_AT and control group. The effect sizes for both were d=0.70 and d=0.74, indicating a medium effect. In contrast, the difference in ΔTSK response between the SX_AT and ASX_AT irrespective of timepoint was 0.1°C, d=0.03. It is important to note that the difference in ΔTSK response between the SX_AT and control and ASX_AT and control groups lay outside of the MDC value found in section 3.5, suggesting that detectable differences were present, so, despite statistical insignificance, there may still be clinical relevance to the findings.

These findings are similar to those of Rodríguez-Sanz et al. (2017), who found that the ΔTSK response between the left and right limbs of control participants in response to a running intervention was 2.7°C and 2.9°C respectively (mean absolute values 26.6 ± 1.9°C to 29.3 ± 1.5°C and 26.3 ± 1.7°C to 29.2 ± 1.5°C). The difficulty with comparing their results for symptomatic individuals is that they grouped their participants into symptomatic and non-symptomatic, but by the left and right limbs, so it is unclear in the symptomatic group which limb was affected or if it was a bilateral diagnosis. The ΔTSK response between the left and right limbs was 3.6°C and 3.1°C respectively.

The results of this study would cast doubt on whether infrared thermal imaging can measure hysteresis through surface TSK change. It is known that symptomatic tendons display greater mechanical hysteresis than asymptomatic tendons, with a mean difference of 4.4% (Wang et al., 2012). The lower TSK values seen in the SX_AT and the ASX_AT groups in comparison to the control groups (table 5.1.3), along with the lack of difference in ΔTSK response do not fit with the results found by Wang et al. (2012) and do not evidence greater heat loss at the skin surface in those with degenerative midportion Achilles tendinopathy. It would suggest that the amount of heat dissipated from the symptomatic AT through hysteresis may not be enough to cause surface TSK change.

#### 5.1.5.3 Limitations

The study has limitations. Due to the COVID-19 outbreak, recruitment of control participants was hampered. The aim initially was to recruit a minimum of 34 participants (17 per group). 19 symptomatic participants were recruited for the study, and 15 control participants. Ideally, it would have been beneficial to have an equal sample size in each group. 4 control participants were lost due to not being able to attend for testing due to the COVID-19 outbreak.

A further limitation to testing was that participants were asked to run wearing their normal running attire, which involved wearing socks. It is possible that this affected TSK response around the AT, however, it was necessary for participants to wear them for the duration of a 15-minute treadmill run to maintain comfort and prevent blistering of the foot. Secondly, each participant would normally wear socks to run, meaning that their normal thermal response to running was replicated as closely as possible.

#### 5.1.5.4 Conclusion

To conclude this section, it was found that there was a significant increase in AT absolute TSK in response to a 15-minute treadmill run in SX_AT's, ASX_AT's and control AT's. The increase seen in the control group was significantly higher than the change seen in the SX_AT and the ASX_AT groups. There was a significant decrease in mean AT TSK over a 10-minute cooldown period regardless of group, but TSK values did not return to baseline during this period. Future study should seek to address whether rehabilitation interventions raise the TSK of the SX_AT and the ASX_AT to the values seen in the control group, alongside improvements in symptoms.

## 5.2 A comparison of skin temperature and symptoms response following a treadmill running task between matched controls and Achilles tendinopathy patients exposed to a 12-week HSR training programme.

### 5.2.1 Introduction

HSR training has been shown to produce beneficial effects on the symptoms of mid-portion Achilles tendinopathy, with more favourable patient satisfaction scores when compared solely to eccentric training (Beyer et al., 2015), as discussed in section 2.6.4. One of the hypothesised reasons that tendons have responded well to this intervention is the effect of slow sustained load causing an adaptive response in the tendon (Arampatzis et al., 2007; Docking & Cook, 2019).

In symptomatic participants, Beyer et al. (2015) found a reduction in A-P thickness and neovascularisation in those who completed the 12-week HSR programme and those who completed the eccentric programme, suggesting that load magnitude rather than contraction type created beneficial effects, a theory echoed elsewhere (Arampatzis et al., 2007; Couppé et al., 2015; Docking & Cook, 2019). Docking & Cook (2019) suggested that load magnitude is responsible for adaptational responses in the tendon by shifting the point whereby the tendon undergoes positive or negative adaptational change.

In the Patella tendon, it has been found that a 12-week HSR training programme caused a reduction in stiffness in those suffering from Patella tendinopathy (Kongsgaard et al., 2010). This research suggests a positive adaptational response, as work by Coombes et al. (2018) found that those suffering with patellar tendinopathy had greater stiffness than healthy controls. Interestingly, those suffering from Achilles tendinopathy have demonstrated reduced stiffness properties than healthy controls, with increased AT compliance being linked to a less energy efficient tendon during the SSC (Arya & Kulig, 2010; Chang & Kulig, 2015; Lichtwark & Wilson, 2005a; Wang et al., 2012). It is possible that load placed upon the AT provokes a different morphological response than that of the Patella tendon to optimise the structure to cope with energy storage and return, versus the ability to transfer higher amounts of muscular force that pass through the Patella tendon from the Quadriceps (Wiesinger et al., 2017).

More research is required to understand the physiological effects of HSR on the AT. However, if physiological changes are happening, it may be possible that changes may be

reflected on the surface of the skin, which could be detected using infrared thermography. Docking & Cook (2019) suggested that tendons adapt by changing size, structure, blood flow and mechanical properties, all of which suggested a change in regional metabolic demand. The previous chapter identified a significantly different absolute TSK group response to a 15-minute running intervention, with control participants displaying higher TSK values at the midportion of the AT than symptomatic participants. Therefore, it could be possible that a normalised TSK response could be identified using infrared thermal imaging in response to a loading intervention that alters the physiological characteristics of the AT.

Therefore, this study aimed to establish the TSK response of the midportion of the AT to a 15-minute running intervention following a 12-week HSR programme and to establish the effect of a 12-week HSR programme on the clinical symptoms of chronic midportion Achilles tendinopathy.

### 5.2.2 Hypotheses

1. There would be a statistically significant difference in absolute TSK of the midportion of the AT from timepoint BL to POST0 in each of the groups
2. There would be a statistically significant decrease in absolute TSK of the midportion of the AT from timepoint POST0 to CD10 in all groups
3. There would be a statistically significant difference in absolute TSK values between the SX_AT and ASX_AT's in response to the running intervention
4. There would be a statistically significant difference in TSK between the SX_AT and control AT's in response to the running intervention
5. There would be a statistically significant difference in TSK between the ASX_AT and control AT's in response to the running intervention
6. There would be a statistically significant difference in the absolute TSK cooling response from timepoint POST0 to CD10 between the groups
7. There would be a statistically significant difference in ΔTSK responses between the groups

### 5.2.3 Methods

The methods used in this section follow the methods outlined in chapter three unless otherwise stated.

#### 5.2.3.1 Sample size calculation

A sample size calculation was conducted using G*Power 3.1.9.7 to detect meaningful change at 80% power and at an alpha level of 0.05. Beyer et al., (2015) reported a drop out rate of 22%, therefore, to account for this recruitment was aimed to be increased by 30% of the required sample size. A total of a minimum of 13 participants were needed to detect meaningful TSK changes as a result of the 12-week HSR programme.

#### 5.2.3.2 Participant recruitment

Participants were recruited using the methodology outlined in section 3.6.2.2. At the time participants signed up for testing, they were asked whether they wanted to participate in the 12-week rehabilitation programme. It was made clear that it was entirely voluntary, and that if they declined to participate it would not affect their initial testing. A CONSORT flowchart detailing recruitment can be seen in figure 5.2.1. Participant anthropometrics can be seen in table 5.2.1. Control participants were age and gender-matched to the n=8 participants who completed the HSR programme. Participant mean VISA-A, NPRS scores during and after activity and RPE scores at week 0 can be seen in table 5.2.2. Participant exercise hours can be seen in table 5.2.3.

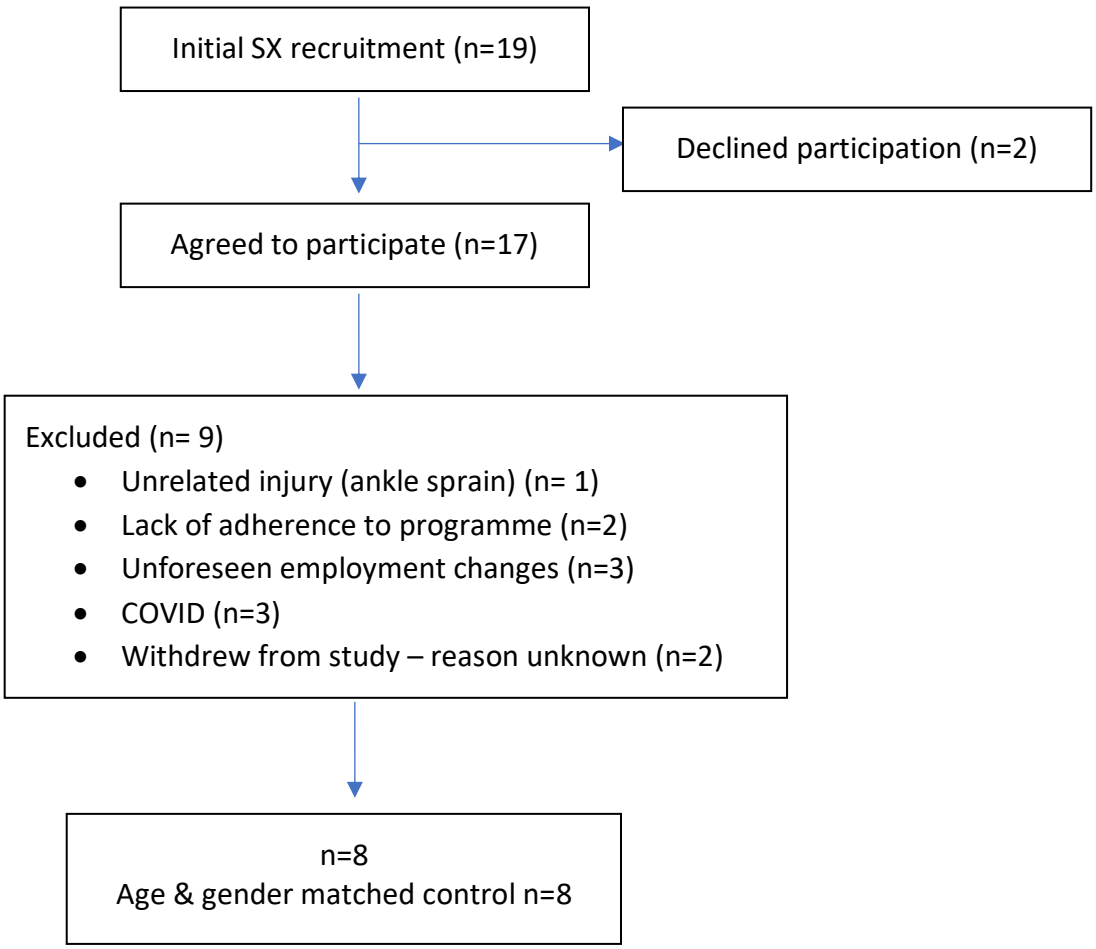



Figure 5.2.1: CONSORT Flowchart for participant recruitment

Table 5.2.1: Participant anthropometrics

| **Group** | **Mean ± SD age (yrs)** | **Mean ± SD height (cm)** | **Mean ± SD mass (kg** |
|---|---|---|---|
| SX | 42.7 ± 9.7 | 181.8 ± 9.7 | 82.3 ± 8.8 |
| Control | 42.8 ± 8.0 | 175.0 ± 6.9 | 81.6 ± 12.4 |

Table 5.2.2: Mean and SD data for VISA-A, NPRS and RPE for hopping participants at Week 0

| Outcome measure | SX mean ± SD | Control mean± SD |
|---|---|---|
| VISA-A | 73.4 ± 4.4 | 100.0 ± 0.0 |
| NPRS During | 3.1 ± 2.1 | 0.0 ± 0.0 |
| NPRS After | 1.1 ± 1.5 | 0.0 ± 0.0 |
| RPE | 5.3 ± 2.4 | 3.6 ± 0.9 |

Table 5.2.3: Participant exercise hours

| **Hours** | **SX** | **Control** |
|---|---|---|
| 3-6 | 3 | 6 |
| 6-9 | 4 | 2 |
| 10+ | 1 | 0 |
| **Total Number** | **8** | **8** |

#### 5.2.3.3 HSR programme

Participants followed a guide for the 12-week HSR programme that was outlined by Beyer et al. (2015). This consisted of 3 exercises (standing smith machine calf raise, seated smith machine calf raise, and leg press calf raise) that followed a progressive plan over the 12 weeks which can be seen outlined in table 5.2.4. The full guide can be seen in appendix 10.

Table 5.2.4: 12-week HSR programme

| Week | Sets | Reps | Rest |
|---|---|---|---|
| 1 | 3 | 15RM | 2 min |
| 2 & 3 | 3 | 12 RM | 2 min |
| 4 & 5 | 4 | 10RM | 3 min |
| 6, 7 & 8 | 4 | 8RM | 3 min |
| 9, 10, 11 & 12 | 4 | 6RM | 3 min |

Participants were requested to download the metronome app from their relevant app store (depending on their mobile device) and set it to 60 beats per minute (bpm) to time the 3-seconds concentric and 3-seconds eccentric contractions for each repetition.

Each participant was taken into the strength and conditioning suite at the University of Salford following their second week 0 session and coached on how to perform each exercise. Each exercise was technique focused and demonstrated with no weight. Participants were not told how much weight to use and were reminded that it was a repetition maximum programme. They were given the criteria of a minimum of 9/10 difficulty by the end of the sets on an RPE scale and pain created by each exercise must have been tolerable. Participants were then told to conduct a familiarisation session in their own gym to establish their baseline weight for each exercise before starting the programme.

Participants were requested to fill out a log of exercise, detailing each rehabilitation session, RPE and NPRS scores for each exercise. As they were not requested to stop their normal running activity, they were asked to outline any running activity that they completed each week.

#### 5.2.3.4 Clinical assessment

Participants underwent a repeat clinical assessment during week 4, week 8 and week 12. The assessment was a repeat of the subjective and objective clinical examination that was outlined in section 3.6.

#### 5.2.3.5 Room temperature

Ambient temperature data was collected as stated in section x. The mean room temperature during week 12 testing was 20.8 ± 1.0°C and the mean humidity was 45.5 ± 8.0%.

#### 5.2.3.6 Running intervention

The procedure for the running intervention was a replica of that outlined in section 3.6.2.5. The speed that the participants ran at during week 0 was replicated. The mean treadmill speed for the was 12.0 ± 2.0 km/h for the SX_AT group and 11.1 ± 1.8 km/h for the control group.

#### 5.2.3.7 Thermal data capture

Thermal data capture was conducted as stated in section 3.6.2.10. In total for the running group, this equalled 64 thermal images taken using the FLIR ONE.

#### 5.2.3.8 Thermal data analysis

Conducted as outlined in chapter three.

#### 5.2.3.9 Statistical analysis

Normality was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise($p>0.05$). Homogeneity of variances was assessed using Levene's test and the assumption was met unless stated otherwise ($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

Independent samples t-tests were used to assess whether any pre-testing differences were present between the groups for VISA-A, NPRS and RPE scores.

A factorial mixed ANOVA (8x3) was used to assess the differences in TSK values following the running intervention, with timepoint (BL, POST0, CD2, CD4, CD5, CD6, CD8, CD10) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subjects independent variable. Mauchly's test of sphericity was violated ($x^2$ (27) = 354.921, $p<0.001$) therefore Greenhouse-Geisser corrected results were reported.

ΔTSK scores were calculated by subtracting the absolute TSK value from the previous (Post0 from BL, CD2 from POST0, CD4 from CD2, CD5 from CD4, CD6 from CD5, CD8 from CD6

and CD10 from CD8). A two-way mixed ANOVA was run on ΔTSK response for each of the 7 pairs of time points, to see if the responses differed between groups.

### 5.2.4 Results

#### 5.2.4.1 HSR Adherence

There was a 62.5% (5/8) success rate for participants returning their HSR exercise log at the end of the 12 weeks. 3 out of 8 participants did not return their log of exercise following the programme. At each of the 4-weekly clinical follow-up sessions, the adherence to the programme was checked and these participants were following the programme as outlined. Participants were allowed to miss a maximum of one session per 4-week block before they were excluded from the study. Participants were allowed to modify sessions provided that they used external resistance and remained to the metronome throughout the duration of the exercises.

Out of the 5 returned exercise log forms, there was a total of 140 out of 180 completed rehab sessions as outlined in the programme. There were a total of 28 modified sessions and 12 non-completed sessions. All the sessions that were modified were due to access to equipment, with one participant changing gym facilities and there being no leg press available, and two participants travelling due to work commitments.

Mean RPE and NPRS data for each block of the HSR programme can be seen in table 5.2.5.

Table 5.2.5: Mean RPE and NPRS data for the 12-week HSR programme

| **Block** | **Mean RPE ± SD** | **Mean NPRS ± SD** |
|---|---|---|
| 1 (Week 1) | 6.5 ± 0.3 | 4.0 ± 0.2 |
| 2 (Weeks 2 & 3) | 7.1 ± 0.9 | 3.9 ± 0.3 |
| 3 (Weeks 4 & 5) | 7.8 ± 0.7 | 3.5 ± 0.4 |
| 4 (Weeks 6, 7 & 8) | 6.4 ± 0.4 | 2.6 ± 0.6 |
| 5 (Weeks 9, 10, 11 & 12) | 5.6 ± 0.5 | 3.1 ± 0.5 |

#### 5.2.4.2 VISA-A, NPRS and RPE

The results from the Mann Whitney U-test for VISA-A, NPRS and RPE can be seen in table 5.2.6.

Table 5.2.6: Mean and SD data for VISA-A, NPRS and RPE for running participants at week 12

| Outcome measure | SX mean ± SD | Control mean± SD | SX median | Control median | p-value |
|---|---|---|---|---|---|
| VISA-A | 93.8 ± 10.0 | 100.0 ± 0.0 | 99.0 | 100.0 | **0.038*** |
| NPRS During | 1.0 ± 1.4 | 0.0 ± 0.0 | 0.5 | 0.0 | 0.279 |
| NPRS After | 0.5 ± 0.5 | 0.0 ± 0.0 | 0.5 | 0.0 | 0.105 |
| RPE | 5.0 ± 2.4 | 6.1 ± 1.2 | 5.0 | 7.0 | 0.105 |

*** Denotes statistical significance**

There was a statistically significant difference in VISA-A scores between SX and control participants at the week 12 testing session, U=52.000, z=2.557, p=0.038. The SX participants had a lower VISA-A score by a median of 1.0 and a mean of 6.2 (95% CI -14.6, -2.1) lower than the control participants.

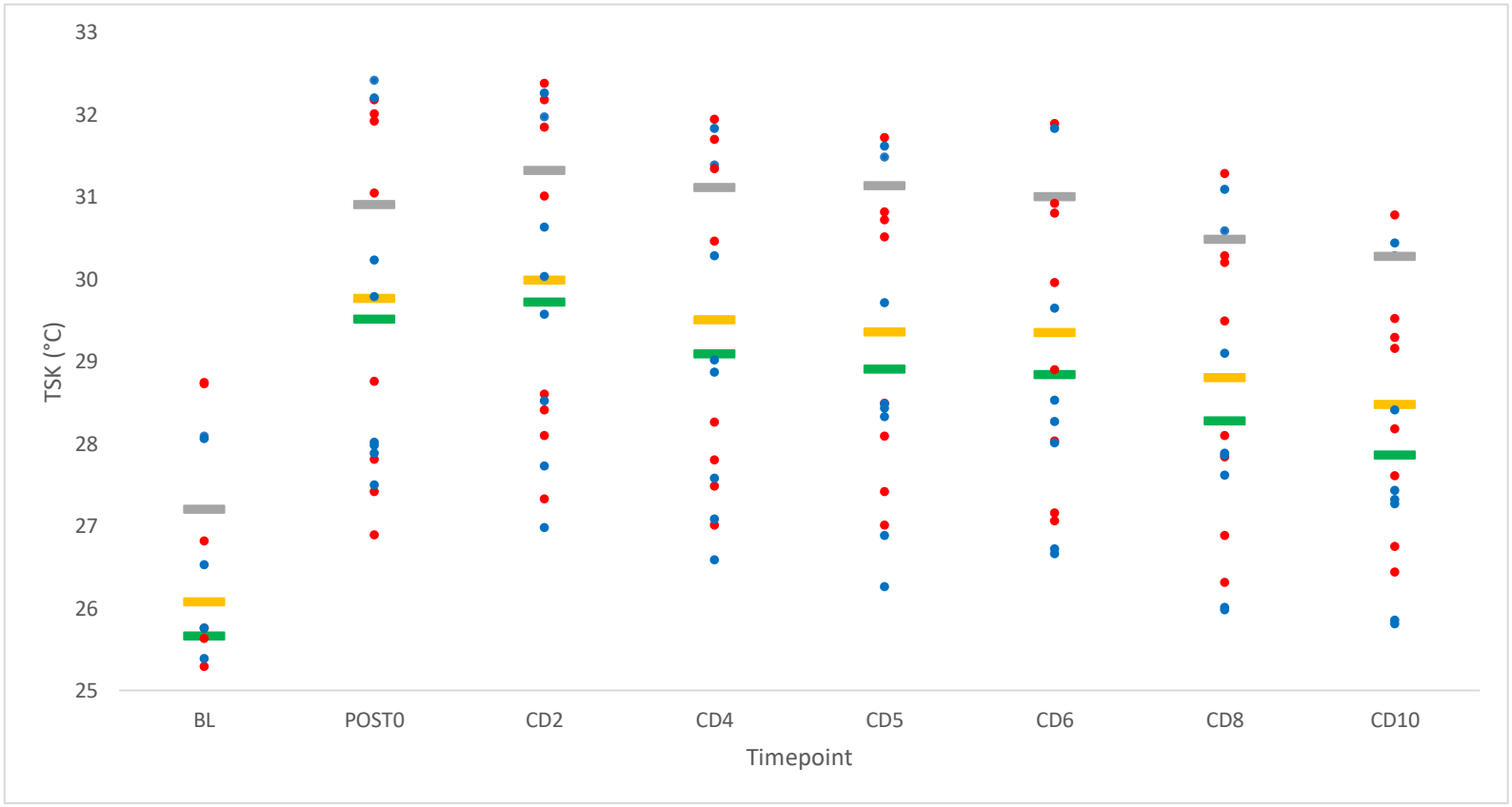
There were no statistically significant differences in mean RPE score between the SX or control participants at the week-12 testing session U=43.000, z=1.197, p=0.279. The control group mean RPE score was a median of 2.0 and a mean of 1.1 (95% CI -3.7, 1.5) higher than the SX participants.

There were no statistically significant differences in NPRS score during the running activity during the week 12 testing session, U=16.000, z=-2.210, p=0.105. NPRS scores during the activity were a median of 0.5 points and a mean of 1.0 points (95% CI -0.2, 2.2) higher in the SX participants.

There were no statistically significant differences in NPRS scores recorded after activity at the week 12 testing session between the SX and control groups U=16.000, z= 2.236, p=0.105. The NPRS score after activity was a median of 0.5 and a mean of 0.5 points (95% CI 0.1, 0.9) higher in the SX participants.

#### 5.2.4.3 Absolute TSK

Table 5.2.7 shows the mean TSK results from the week 12 testing session. Figure 5.2.2 shows a graphical representation of the mean TSK response of each group.




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 5.2.2: TSK data for age and gender-matched control runners at week 12

Table 5.2.7: Mean TSK data for running participants at week 12

| Time | Group | Mean TSK (°C) | SD (°C) | ΔTSK from BL (°C) | SD (°C) |
|---|---|---|---|---|---|
| Baseline (BL) | SX | 26.1 | 2.0 | - | - |
| | ASX | 25.7 | 2.0 | - | - |
| | Control | 27.2 | 1.6 | - | - |
| | Mean | 26.3 [a b c d e f g] | 1.9 | | |
| Immediately post-activity (POST0) | SX | 29.8 | 2.3 | 3.7 | 2.1 |
| | ASX | 29.5 | 2.0 | 3.8 | 1.9 |
| | Control | 30.9 | 2.9 | 3.7 | 3.5 |
| | Mean | 30.1 [a h] | 2.4 | 3.7 [u] | 2.5 |
| Cooldown minute-2 (CD2) | SX | 30.0 | 2.1 | 3.9 | 2.2 |
| | ASX | 29.7 | 1.9 | 4.1 | 1.9 |
| | Control | 31.3 | 1.9 | 4.1 | 2.6 |
| | Mean | 30.3 [b i j k l] | 2.0 | 4.1 [v w x] | 2.2 |
| Cooldown minute-4 (CD4) | SX | 29.5 | 2.1 | 3.4 | 2.2 |
| | ASX | 29.1 | 2.0 | 3.4 | 2.0 |
| | Control | 31.1 | 1.5 | 3.9 | 2.3 |
| | Mean | 29.9 [c i m n] | 1.9 | 3.6 [y z] | 2.2 |
| Cooldown minute-5 (CD5) | SX | 29.3 | 1.8 | 3.3 | 2.0 |
| | ASX | 28.9 | 1.9 | 3.2 | 1.9 |
| | Control | 31.1 | 1.6 | 3.9 | 2.3 |
| | Mean | 29.8 [d o p] | 1.8 | 3.5 [aa av] | 2.1 |
| Cooldown minute-6 (CD6) | SX | 29.3 | 1.8 | 3.3 | 2.0 |
| | ASX | 28.8 | 1.9 | 3.2 | 1.8 |
| | Control | 31.0 | 1.6 | 3.8 | 2.4 |
| | Mean | 29.7 [e j q r] | 1.8 | 3.4 [v ac ad] | 2.1 |
| Cooldown minute-8 (CD8) | ASX | 28.8 | 1.8 | 2.7 | 2.0 |
| | ASX | 28.3 | 1.9 | 2.6 | 1.8 |
| | Control | 30.5 | 1.7 | 3.3 | 2.4 |
| | Mean | 29.2 [f k m o q s] | 1.8 | 2.9 [w y aa ac ae] | 2.1 |
| Cooldown minute-10 (CD10) | SX | 28.5 | 1.5 | 2.4 | 1.7 |
| | ASX | 27.9 | 1.8 | 2.2 | 1.7 |
| | Control | 30.3 | 1.7 | 3.1 | 2.5 |
| | Mean | 28.9 [g h l n p r s] | 1.7 | 2.6 [u x z ab ad ae] | 2.0 |
| Mean | Sx | 28.9 | 0.5 | 2.5 | 2.3 |
| | ASX | 28.5 [t] | 0.4 | 2.4 | 2.2 |
| | Control | 30.4 [t] | 0.2 | 4.3 | 2.7 |

[a b c d e f g h l j k l m n o p q r s] denotes statistical significance for mean absolute TSK (irrespective of group) between timepoints ($p<0.05$)

[t] denotes statistical significance for mean absolute TSK (irrespective of timepoint) between groups ($p<0.05$)

[u v w x y z aa ab ac ad ae] denotes statistical significance for mean ΔTSK (irrespective of group) between timepoints ($p<0.05$)

The two-way mixed ANOVA revealed that there was no statistically significant group x time two-way interaction on TSK values of the midportion of the Achilles tendon ($F_{(3.903, 56.592)}$ = 0.451, p=0.766, partial $\eta^2$ = 0.030). The main effect of time showed a statistically significant difference in TSK of the midportion of the Achilles tendon ($F_{(1.951,56.592)}$ = 47.607, p<0.001, partial $\eta^2$ = 0.621). Pairwise comparisons revealed statistically significant TSK differences between timepoints BL and all other time points (p<0.001), all with large effect sizes ranging from d=1.5 at time point CD10 to d=2.1 at timepoint CD2.

Post0 TSK values were statistically significantly higher than those at CD10 (p=0.005). TSK values at timepoint CD2 were statistically significantly higher than those at CD4 (P=0.011), CD6 (P=0.038), CD8 (p<0.001) and CD10 (p<0.001). TSK values at timepoint CD4 were significantly higher than those at CD8 (p<0.001) and CD10 (p<0.001). TSK values at CD5 were significantly (p<0.001) higher than those at CD8 and CD10. TSK values at CD6 were significantly (p<0.001) higher than those at CD8 and CD10. TSK values at timepoint CD8 were significantly (p=0.001) higher than those at CD10.

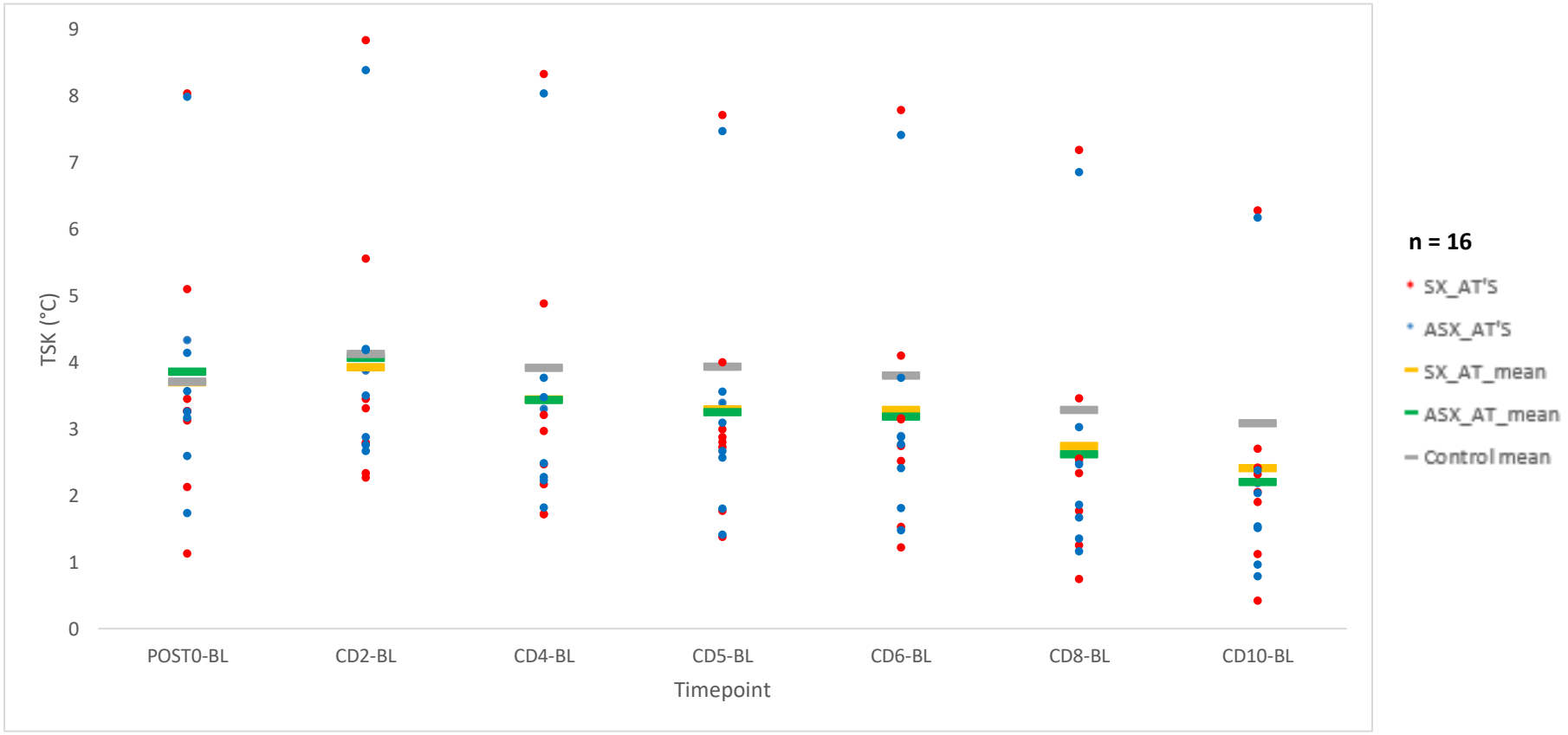
The main effect of group showed that there was a statistically significant difference in mean TSK at the midportion of the Achilles tendon between groups ($F_{(2,29)}$ = 4.617, p=0.018, partial $\eta^2$ = 0.242). Pairwise comparisons revealed statistically significant (p=0.031) difference in mean TSK between the ASX_AT and the control group, with the control participants being hotter by a mean of 1.9°C, d=1.0. There was not a statistically significant (p=0.123) difference between the SX_AT and control group, with the control group being hotter by a mean of 1.5°C, d=0.8. The difference between the SX_AT and ASX_AT limbs was not statistically significantly (p=1.00) different, with the SX_AT being warmer by a mean of 0.4°C, d=0.2.

#### 5.2.4.4 ΔTSK

Mean ΔTSK response can be seen in figure 5.2.3. The results of the two-way mixed ANOVA for ΔTSK response revealed no significant two-way group x timepoint interaction ($F_{(3.828,55.513)}$ = 0.930, p=0.450, partial $\eta^2$ = 0.368). The main effect of timepoint was statistically significant ($F_{(1.914,55.513)}$ = 16.903, p<0.001, partial $\eta^2$ = 0.368). Pairwise comparisons revealed statistically significant differences in ΔTSK responses between timepoints POST0-BL and CD10-BL. The mean ΔTSK response between timepoints CD2-BL to CD6-BL (p=0.029), CD8-BL (p<0.001) and CD10-BL (p<0.001) were statistically significant. The mean ΔTSK response between timepoints CD4-BL to CD8-BL (p<0.001) and CD10-BL (p<0.001) were statistically

significant. The mean ΔTSK response between timepoints CD5-BL to CD8-BL ($p<0.001$) and CD10-BL ($p<0.001$) were statistically significant. The mean ΔTSK response between timepoints CD6-BL to CD8-BL ($p<0.001$) and CD10-BL ($p<0.001$) were statistically significant. The mean ΔTSK response between timepoints CD8-BL to CD10-BL ($p=0.001$) was statistically significant.

The main effect of group was not statistically significant, $F_{(2,29)} = 0.163$, $p=0.851$, partial $\eta^2 = 0.011$.




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 5.2.3: ΔTSK response at Week 12

### 5.2.5 Discussion

This study aimed to establish the effect of a 15-minute running intervention on the TSK response over the midportion of the Achilles tendon, in participants who had undertaken a 12-week HSR programme. The main findings of this study were:

1) There were significant elevations in TSK of the midportion of the Achilles tendon in response to a 15-minute running intervention in all of the groups.

2) There were no significant differences in absolute TSK response between the SX_AT and control group, appearing to show a normalised TSK response to running of the SX_AT group in response to the 12-week HSR programme.

3) There were significant differences in absolute TSK response between the ASX_AT and control group.

4) There were no differences in ΔTSK response between the groups in response to the running intervention.

5) There were statistically significant differences in median VISA-A scores between symptomatic and control participants however these were not clinically significant

#### 5.2.5.1 VISA-A, NPRS and RPE

VISA-A, NPRS and RPE scores were collected to gauge the severity of symptoms that were experienced by the participants during the testing session. Nonparametric Mann Whitney U-testing revealed that there were statistically significant differences between the symptomatic and control participants VISA-A scores during the week 12 testing session, but not NPRS scores during and after activity or RPE scores. Crucially, despite statistical significance, VISA-A scores differed by a mean of 6.2 points and a median of 1.0 points, both of which are not clinically significant. Further, according to Iversen et al. (2012), a VISA-A score of greater than 90 on the VISA-A indicated recovery from Achilles tendinopathy. Of the 8 symptomatic participants, 6 had achieved scores greater than 90 on the VISA-A, a 75% success rate. The other two participants had improved their scores by 4 and 14 points respectively, the latter being a clinically significant improvement (Beyer et al., 2015; Murphy et al., 2018). As expected, there were no statistically significant differences in RPE scores during or after activity between the groups indicating that the treadmill running task was standardised in

terms of exertion. There were no statistically significant differences in reported NPRS scores during or after activity between the groups.

#### 5.2.5.2 Absolute TSK

The results revealed that immediately post-exercise, there was a significant mean increase in TSK regardless of group (3.7°C 95% CI 1.9°C, 5.6°C, $p<0.001$, $d=1.8$) leading to the acceptance of hypothesis 1. This response was very similar to that found during the baseline testing week, week 0 (chapter 4). Baseline values were found to be significantly lower than all other time points (range -4.0°C, -2.6°C, mean 3.4°C, $d=1.8$) indicating that post-running intervention, absolute TSK values did not return to their resting BL levels. During the week 0 testing session, it was apparent that in the SX_AT and ASX_AT groups, TSK began to decrease immediately post-exercise, whereas the control group TSK continued to rise, albeit statistically insignificantly. During the testing at week 12, the results evidenced that the SX_AT and ASX_AT groups adopted this trend of rising until the CD2 timepoint before declining steadily until timepoint CD10. POST0 TSK values were only statistically significantly higher than those at timepoint CD10 ($p=0.005$), leading to the acceptance of hypothesis 2, and evidencing that there was significant cooling across the10-minute cool down period. This response differed to that of the week 0 cooling response, as POST0 values at week 0 were significantly ($p<0.001$) higher than timepoints CD4 to CD10. This suggested that there was a slower TSK cooling response irrespective of the group. The mean cooling response from POST0 to CD10 at week 0 was 1.0°C, compared to 0.8°C in week 12, albeit this difference is 0.2°C and is within the SEM.

Once the TSK had reached its peak increase at timepoint CD2 it began to fall. There was a statistically significant ($p=0.011$) cooling response from timepoint CD2 to CD4 of 0.4°C. TSK at CD2 was also statistically significantly ($p<0.001$) higher than those at timepoints CD6-CD10, again evidencing the consistent cooling of TSK following the 15-minute running intervention, with an insignificant TSK decrease at timepoint CD5. Timepoints CD4, CD5 and CD6 were all statistically significantly ($p<0.001$) higher than timepoints CD8 and CD10. There was also a statistically significant ($p=0.001$) TSK decrease between timepoints CD8 and CD10 of 0.3°C.

The results revealed that there was a statistically significant main effect of group on absolute TSK response. There was a statistically significant ($p=0.031$) difference in absolute

TSK between the ASX and control AT's of 1.9°C (d=1.0), but not between the SX_AT and control group despite there being a mean 1.5°C difference. There was a large effect size (d=0.8). This led to the rejection of hypothesis 4 and the acceptance of hypothesis 5. There were no significant differences between the SX_AT and ASX_AT groups as expected, leading to the rejection of hypothesis 3.

The normalisation of SX_AT TSK was a novel and potentially important finding. Whilst the underpinning physiological or biomechanical reasons for this normalisation are unknown, it may highlight that there are changes within the region of the midportion of the AT in response to 12-weeks of HSR training. In conjunction with symptom improvement, it is worthy of further investigation moving forward.

#### 5.2.5.3 ΔTSK

The results for ΔTSK showed no statistically significant two-way interactions between the group or the time point, and there were no statistically significant differences in ΔTSK response between the groups, which led to the rejection of hypothesis 7. However, there were significant main effects for timepoint for the ΔTSK response. The ΔTSK response, irrespective of the group did not differ between consecutive timepoints until CD6-BL to CD8-BL, where there was a 0.5°C change (d = 0.3). This indicated that at timepoint CD6-BL, across the groups, there was a consistent drop in ΔTSK over 2 minutes. The same decrease in ΔTSK was found between timepoints CD8-BL and CD10-BL, however, the rate of ΔTSK decreased to 0.3°C (d = 0.1). The small effect size, and the fact that 0.3°C is within the MDC of the camera as identified in section 3.5, means that this change in ΔTSK could be attributed to random error.

#### 5.2.5.4 limitations

One of the limitations of the 12-week HSR programme that was identified in the study by (Beyer et al., 2015) was that it required the use of specialist gym equipment. On occasion, this was reflected in the adherence rates in the current study. Only 5 out of 8 symptomatic participants returned their completed exercise logs, which is a limitation in itself, but out of these, there were a total of 28 modified rehab sessions. Participants self-adapted their programmes based on equipment available at the time that they were in the gym, or dependent on the equipment that they had available for use. Two of the participants in the programme unexpectedly travelled abroad with work, therefore had sporadic access to unfamiliar gyms and equipment. Patients were instructed that if they had to modify their

exercises, they should still adhere strictly to the metronome controlled 6-second repetitions to place slow, sustained load through the AT in line with the suggestions made by Arampatzis et al. (2007) and Docking & Cook (2019) around tendon adaption. Despite this, there were only 12 out of 180 non-completed gym sessions, equating to a 93.3% adherence rate (from the 5 returned logs).

### 5.2.6 Conclusion

The results of this study revealed that the TSK response of the symptomatic participants was similar to the response observed during the week 0 testing sessions, where there was a significant rise in TSK in response to the 15-minute running intervention in the SX_AT's and the ASX_AT's. The TSK response to the 15-minute running intervention had appeared to have normalised in the SX_AT as there were no longer statistically significant differences between those and the control AT's, yet there were still differences between the ASX_AT and control AT's. There was still a statistically significant decrease in TSK during the cooldown period, and values did not return to baseline during this period. It is now necessary to explore these differences from week 0 to week 12.

## 5.3 Skin temperature and symptom response to a treadmill running task in Achilles tendinopathy patients prior to and following a 12-week HSR intervention

### 5.3.1 Introduction

The individual responses to the 15-minute running interventions have now been established, and it appeared that there was a similar absolute TSK response in each of the groups. Following the 12-week HSR intervention, it appeared that the TSK response of the SX_AT group had normalised as there were no statistically significant differences between those and the control AT's.

Therefore, this section aims to establish whether there were any changes in the absolute and ΔTSK response by comparing week 0 and week 12 TSK data. The second aim of this study was to establish whether the 12-week HSR programme resulted in clinically significant improvement in those suffering from chronic midportion Achilles tendinopathy.

### 5.3.2 Hypotheses

1. There would be a statistically significantly different VISA-A score between week 0 and week 12
2. There would be a statistically significantly different NPRS_DURING score between week 0 and week 12
3. There would be a statistically significantly different NPRS_AFTER score between week 0 and week 12
4. There would be a statistically significantly different RPE score between week 0 and week 12
5. There would be a statistically significantly different absolute TSK response between week 0 and week 12 in the SX_AT group
6. There would be a statistically significantly different absolute TSK response between week 0 and week 12 in the ASX_AT group
7. There would be a statistically significantly different ΔTSK response between week 0 and week 12 in the SX_AT group
8. There would be a statistically significantly different ΔTSK response between week 0 and week 12 in the ASX_AT group

### 5.3.3 Methods

The data used in this section were obtained using the methods outlined in section 5.1 and section 5.2. It is a combination of the TSK data from week 0 and the TSK data obtained at week 12, following the 12-week HSR intervention for the running cohort.

#### 5.3.3.1 Statistical Analysis

Normality of the data was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

VISA-A, NPRS and RPE scores between week 0 and week 12 were assessed using individual paired samples t-tests.

Separate two-way repeated measures ANOVA's with Bonferroni correction were used for the SX_AT and ASX_AT groups, with week number and timepoint as the within-subject variables. Normality of the data was assessed using the Shapiro-Wilks test and data were normally distributed ($p>0.05$). The assumption of sphericity was violated in both groups as assessed by Mauchly's test ($p<0.05$), there the Greenhouse-Geisser statistics were interpreted.

Separate two-way repeated measures ANOVA's were also used to assess ΔTSK response for week 0 to week 12 for each of the groups.

### 5.3.4 Results

#### 5.3.4.1 VISA-A, NPRS and RPE

The paired samples t-test for VISA-A revealed that there was a statistically significant improvement in scores between week 0 and week 12 $t_{(7)} = 6.917$, $p<0.001$, $d=2.4$. The mean difference in VISA-A scores between the weeks was 20.4 ± 8.3 (95% CI 13.4, 27.3) and can be seen in table 5.3.1. There were no detrimental changes in VISA-A scores in any of the participants.

The results for NPRS scores during the 15-minute treadmill run revealed no statistically significant changes between week 0 and week 12 $t_{(7)} = -2.125$, $p=0.061$, $d=0.2$. The mean improvement in scores between the weeks was 2.1 ± 2.7 (95% CI -0.1, 4.4) and can be seen in

table 5.3.1. 6 out of the 8 participant scores improved, however, there were worsened NPRS scores in 2 of the participants.

There were no significant changes in score for NPRS scores experienced once the 15-minute treadmill running intervention had ceased $t_{(7)}$ = -1.357, p=0.217, d=0.6. The mean improvement in score was 0.6 ± 1.3 (95% CI -0.5, 1.7) and can be seen in table 5.3.1. The scores of 4 of the 8 participants remained the same, 3 scores improved and 1 slightly declined.

There were no significant changes in RPE scores between the weeks $t_{(7)}$ = -0.6, p=0.598, d=1.6. The mean improvement in RPE score was 0.3 ± 1.3 (95% CI -0.8, 1.3) and can be seen in table 5.3.1. The scores of 2 of the 8 participants remained the same, 3 scores improved and 3 slightly declined.

Table 5.3.1: Mean VISA-A, NPRS and RPE results week 0 vs week 12

| Outcome measure | WK0 mean ± SD | WK12 mean± SD | p-value |
|---|---|---|---|
| VISA-A | 73.4 ± 4.4 | 93.8 ± 10.0 | **<0.001*** |
| NPRS During | 3.1 ± 2.1 | 1.0 ± 1.4 | 0.061 |
| NPRS After | 1.1 ± 1.5 | 0.5 ± 0.5 | 0.217 |
| RPE | 5.3 ± 2.4 | 5.0 ± 2.4 | 0.598 |

***denotes statistical significance**

#### 5.3.4.2 Absolute TSK

The results of the two-way repeated measures ANOVA revealed that there was no statistically significant two-way week number by timepoint interaction in the SX_AT group ($F_{(2.176, 15.233)}$ = 1.353, p=0.283, partial $\eta^2$ = 0.162), and the mean values can be seen in table 5.3.2 and graphically in figure 5.3.1. There was no main effect of week number ($F_{(1,7)}$ = 0.444, p=0.527, partial $\eta^2$ = 0.060).

There was a statistically significant main effect of timepoint ($F_{(1.438,10.067)}$ = 12.996, p=0.003, partial $\eta^2$ = 0.650). Pairwise comparisons revealed a statistically significant increase in TSK between timepoints BL and CD10 (p=0.019) and a statistically significant decrease between timepoints POST0 and CD8 (p=0.044).

The results of the second two-way repeated measures ANOVA revealed that there was no statistically significant two-way week number by timepoint interaction in the ASX_AT group ($F_{(2.078, 14.547)}$ = 1.949, p=0.177, partial $\eta^2$ = 0.218). The mean TSK values can be seen in table 5.3.2 and graphically in figure 5.3.1. There was no main effect of week number ($F_{(1,7)}$ = 0.174, p=0.689, partial $\eta^2$ = 0.024).

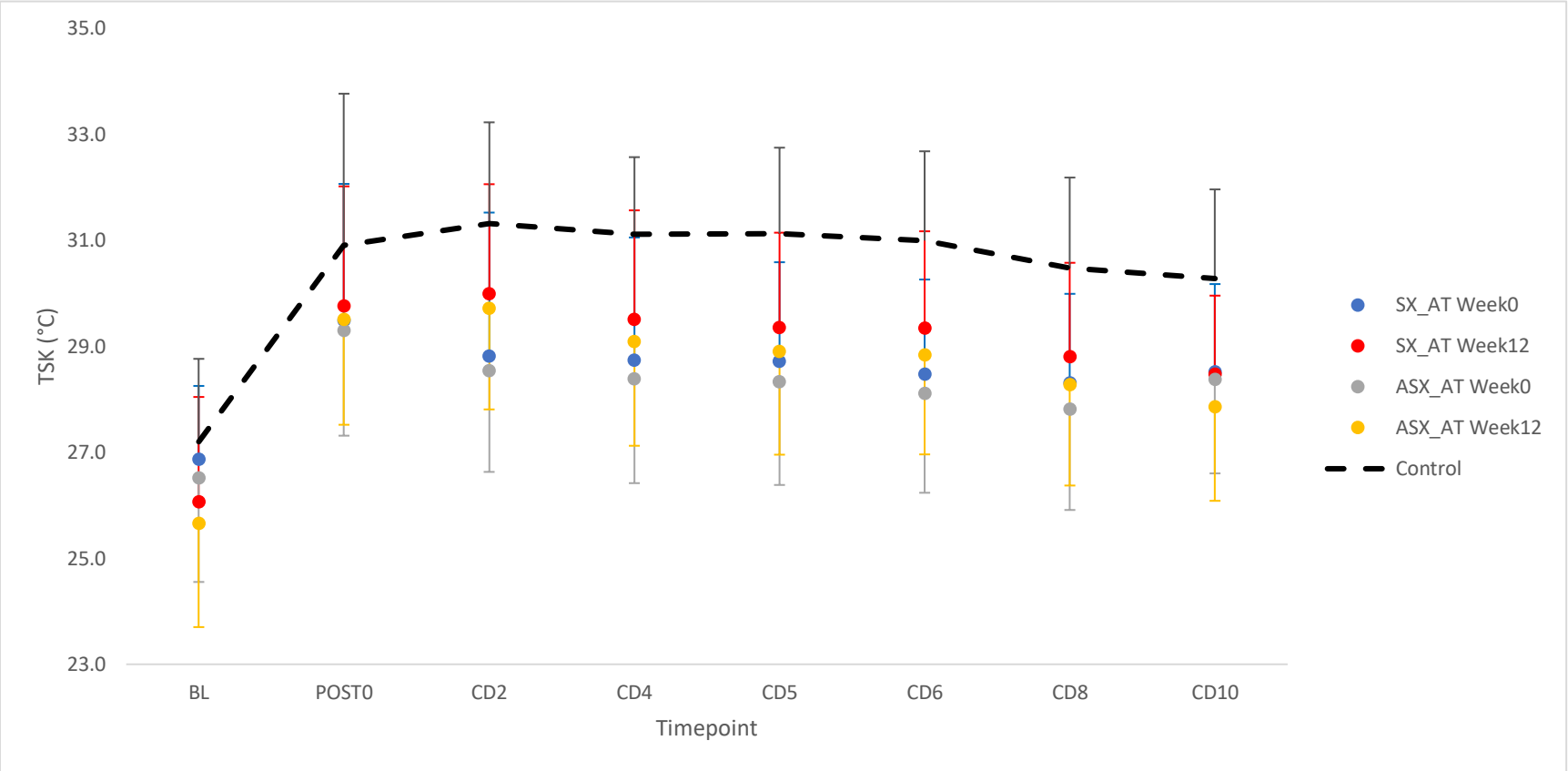
There was a statistically significant main effect of timepoint ($F_{(1.742,12.191)}$ = 18.479, p=0.001, partial $\eta^2$ = 0.725). Pairwise comparisons revealed a statistically significant increase in TSK between timepoints BL and POST0 (p=0.015). There were statistically significant increases in TSK between timepoints BL and CD2 (p=0.031), CD4 (p=0.043), CD5 (p=0.026) CD6 (p=0.028) and CD10 (p=0.035). Pairwise comparisons revealed a statistically significant decrease in TSK between timepoints POST0 and CD4 (p=0.039), CD6 (p=0.046) and CD8 (p=0.001). Pairwise comparisons revealed a statistically significant TSK decrease between timepoints CD2 and CD8 (p=0.001). There was a statistically significant (p=0.006) decrease between timepoints CD4 and CD8.

Table 5.3.2: Mean absolute TSK ± SD (°C) week 0 vs week 12

| | **Week 0** | | **Week 12** | |
|---|---|---|---|---|
| **Timepoint** | **SX_AT** | **ASX_AT** | **SX_AT** | **ASX_AT** |
| BL [a c d e f g h] | 26.9 ± 1.4 | 26.5 ± 1.6 | 26.1 ± 2.0 | 25.7 ± 2.0 |
| POST0 [b c l j k] | 29.5 ± 2.6 | 29.3 ± 2.8 | 29.8 ± 2.3 | 29.5 ± 2.0 |
| CD2 [d l] | 28.8 ±2.7 | 28.5 ± 2.6 | 30.0 ± 2.1 | 29.7 ± 1.9 |
| CD4 [e l m] | 28.7 ± 2.3 | 28.4 ± 2.4 | 29.5 ± 2.1 | 29.1 ± 2.0 |
| CD5 [f] | 28.7 ± 1.9 | 28.3 ± 2.2 | 29.3 ± 1.8 | 28.9 ± 1.9 |
| CD6 [g j] | 28.5 ±1.8 | 28.1 ± 2.0 | 29.3 ± 1.8 | 28.8 ± 1.9 |
| CD8 [b k l m] | 28.3 ±1.7 | 27.8 ± 2.0 | 28.8 ± 1.8 | 28.3 ± 1.9 |
| CD10 [a h] | 28.5 ±1.7 | 28.4 ± 2.4 | 28.5 ± 1.5 | 27.9 ± 1.8 |

[a b] denotes a statistically significant timepoint interaction in the SX_AT group (irrespective of week number)

[c d e f g h l j k l m] denotes a statistically significant timepoint interaction in the ASX_AT group (irrespective of week number)




**n=16**

**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 5.3.1: Mean TSK of the SX  AT and ASX  AT age and gender-matched groups at week 0 and week 12

#### 5.3.4.3 ΔTSK

The mean ΔTSK data can be seen in table 5.3.3 and graphically in figure 5.3.2. The results of the two-way repeated measures ANOVA for ΔTSK response in the SX_AT group between week 0 and week 12 revealed no statistically significant two-way week number by timepoint interaction ($F_{(1.615,11.304)}$ = 0.812, p=0.444, partial $\eta^2$ = 0.104). There was no significant main effect of week number ($F_{(1,7)}$ = 2.194, p=0.182, partial $\eta^2$ = 0.239).

There was a statistically significant main effect of timepoint ($F_{(1.883,13.184)}$ = 4.831, p=0.028, partial $\eta^2$ = 0.408). Pairwise comparisons revealed statistically significant (p=0.033) differences between timepoint POST0-BL to CD8-BL.

The results of the two-way repeated measures ANOVA for ΔTSK response in the ASX_AT group between week 0 and week 12 revealed no statistically significant two-way week number by timepoint interaction ($F_{(1.499,10.493)}$ = 1.716, p=0.225, partial $\eta^2$ = 0.255). There was no significant main effect of week number ($F_{(1,7)}$ = 2.286, p=0.174, partial $\eta^2$ = 0.246).

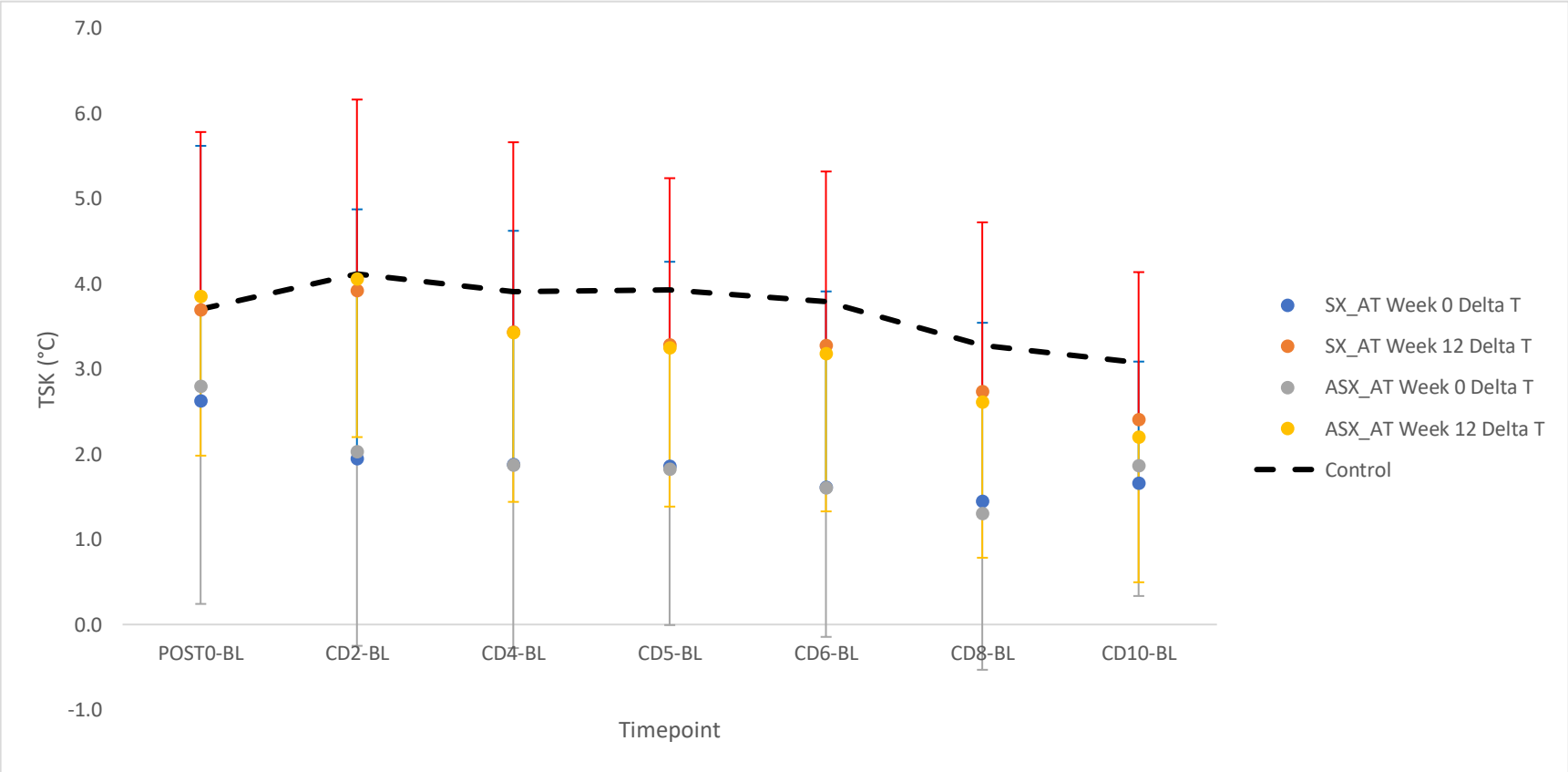
There was a statistically significant main effect of timepoint ($F_{(1.447,10.128)}$ = 7.220, p=0.016, partial $\eta^2$ = 0.508). Pairwise comparisons revealed statistically significant differences (p=0.001) between timepoint POST0-BL to CD4-BL, CD5-BL (p=0.006), CD6-BL (p=0.002), CD8-BL (p<0.001) and CD10-BL (p=0.035). Pairwise comparisons revealed statistically significant (p=0.003) differences between timepoint CD2-BL to CD4-BL, CD5-BL (p=0.015), CD6-BL (p=0.006) and CD8-BL (p<0.001). Pairwise comparisons revealed statistically significant differences between timepoints CD4-BL and CD8-BL (p<0.001), CD5-BL and CD8=BL (p=0.002) and CD6-BL and CD8-BL (p=0.003).

Table 5.3.3: Mean ΔTSK ± SD (°C) week 0 vs week 12

| | Week 0 | | Week 12 | |
|---|---|---|---|---|
| **Timepoint** | **SX_AT** | **ASX_AT** | **SX_AT** | **ASX_AT** |
| POST0-BL [a b c d e f] | 2.6 ± 3.0 | 2.3 ± 2.5 | 3.7 ± 2.1 | 3.8 ± 1.9 |
| CD2-BL [g h l j] | 1.9 ± 2.9 | 2.0 ± 2.3 | 3.9 ± 2.2 | 4.1 ± 1.9 |
| CD4-BL [b g k] | 1.9 ± 2.7 | 1.9 ± 2.1 | 3.4 ± 2.2 | 3.4 ± 2.0 |
| CD5-BL [c h l] | 1.9 ± 2.4 | 1.8 ± 1.8 | 3.3 ± 2.0 | 3.2 ± 1.9 |
| CD6-BL [d l m] | 1.6 ± 2.3 | 1.6 ± 1.7 | 3.3 ± 2.0 | 3.2 ± 1.8 |
| CD8-BL [a e j k l m] | 1.4 ± 2.1 | 1.3 ± 1.8 | 2.7 ± 2.0 | 2.6 ± 1.8 |
| CD10-BL [f] | 1.7 ± 1.4 | 1.9 ± 1.5 | 2.4 ± 1.7 | 2.2 ± 1.7 |

[a] denotes a statistically significant timepoint interaction in the SX_AT group (irrespective of week number)

[b c d e f g h l j k l m] denotes a statistically significant timepoint interaction in the ASX_AT group (irrespective of week number)




**n=16**

Figure 5.3.2: Mean ΔTSK of the SX_AT and ASX_AT age and gender-matched groups at week 0 and week 12

### 5.3.5 Discussion

This is the first study of its kind to assess the effects of a 12-week HSR programme on the TSK response of the midportion of the AT. This study aimed to establish whether there were any statistically significant changes in absolute and ΔTSK response, as well as investigating whether the 12-week HSR programme had resulted in clinically significant improvement of symptoms in those suffering from chronic midportion Achilles tendinopathy. The main findings of the section were:

1. There were no statistically significant changes in absolute TSK following the 12-week HSR programme in either of the SX_AT or ASX_AT groups
2. There were no statistically significant changes in ΔTSK following the 12-week HSR programme in either the SX_AT or ASX_AT groups.
3. There was a clinically significant improvement in VISA-A scores following the 12-week HSR programme.

#### 5.3.5.1 Absolute TSK

The results of this section revealed that there were no statistically significant TSK responses for either the SX_AT or the ASX_AT between week 0 and week 12, leading to the rejection of hypothesis 1 and 2.

Based on the results of the previous section, it was expected that the week 12 TSK response of the SX_AT would not differ from week 0, as there were no significant differences found between these or the control AT's in either of the weeks. However, as there were significant absolute TSK differences found during week 12 between the ASX_AT and the control group, it was thought that there would be significant differences between week 0 and week 12 absolute TSK values. This was not found to be the case.

Large SD's were found in the absolute TSK data, which reflected the variance in the individuals' TSK responses across the weeks. This likely contributed to the lack of statistical significance found between week 0 and week 12 responses. The effect sizes (partial $\eta^2$) for both the SX_AT and the ASX_AT groups when comparing the week 0 to week 12 data were large (Richardson, 2011), but caution should be drawn when interpreting this due to the small sample size.

As a result, post-hoc power calculations were conducted in G*Power (Specs) and revealed that the study was underpowered with a value of 52% for SX_AT's and 71% for ASX_AT's. Part of the reason for this may be because the desired sample size required to achieve appropriate power as calculated in 5.3.2.1 was not reached due to factors beyond control. A total of 17 running participants agreed to participate in the 12-week intervention, but unfortunately, 9 of these were excluded, as seen in figure 5.2.1, due to injuries sustained whilst running during the 12-week programme, unforeseen locational changes, lack of adherence to the HSR programme and COVID-19. Two participants withdrew from the study without reason.

Interestingly, the profile of the mean TSK results from both SX_AT's and ASX_AT's comparing the week 0 to week 12 lines as seen in figure 5.3.2, appears to adopt a more normalised pattern when visually compared to the control group. It must be noted that there are no statistically significant changes between the weeks, however visualising the trend and considering that the study was underpowered, it may be beneficial for future research to repeat the study with a larger sample to see whether this influences findings in either direction.

#### 5.3.5.2 ΔTSK

This was also found to be the case with the ΔTSK response, with no statistically significant differences and large SD's being found between week 0 and week 12 in both groups. Again, this could be explained by the variance in the individuals' data. The effect size for the SX_AT group was medium (partial $\eta^2$ =0.10) and large for the ASX_AT group (partial $\eta^2$= 0.26), but again caution should be drawn when interpreting this due to the small sample size.

Post-hoc power calculations revealed that the SX_AT group was underpowered at only 30%, but the ASX_AT group was adequately powered at 82%, however, due to the sample size not being the required number, there may be type 2 error involved in the study (Banerjee et al., 2009).

#### 5.3.5.3 VISA-A, NPRS and RPE

There were statistically and clinically significant improvements in VISA-A scores following the 12-week HSR programme. These findings were consistent with those found by Beyer et al. (2015), who found a 22.0 ± 2.7 point improvement at the 12-week follow up in their study of recreational athletes. The results found in the present study, a mean

improvement of 20.4 ± 8.3 (95% CI 13.4, 27.3), have greater variance, reflected by the larger SD. One of the possible reasons for this is the population chosen. Beyer et al. (2015) use recreational athletes, however, no insight into the type or level of activity is provided, whereas the present study used recreational runners. Recreational runners are known to cover moderately large distances, in some instances over 30 km per week (Rasmussen et al., 2013). It could be possible that greater variance seen in the current study was down to the individuals still participating in their normal running activity throughout the programme and thus experiencing greater total load on the AT, whereas they were not allowed to do this in the study by Beyer et al. (2015). Despite the greater variance, it was encouraging that there was clinically significant improvement following the 12-week HSR programme and provides evidence that Achilles tendinopathy can be managed alongside a normal running regime.

There were no statistically significant improvements in NPRS during running activity from week 0 to week 12. The mean improvement in score was 2.1 ± 2.7 (95% CI -0.1, 4.4). The mean improvement exceeded the minimal clinically important difference (MCID) of the scale that had previously been established (Farrar et al., 2001) however, it is possible that the study was underpowered, making this statistically insignificant. Three of the participants were completely asymptomatic throughout the run. Two of the participants scores slightly worsened following the programme but fell within the MCID scores reported by Farrar et al., (2001). It is also of note that the mean NPRS scores during the activity were only classed as mild (Boonstra et al., 2016) and the participants were able to complete their normal running activity with tolerable pain.

There were no statistically significant improvements in NPRS scores following running activity from week 0 to week 12. The mean improvement in score was 0.6 ± 1.3 (95% CI -0.5, 1.7). The improvement in scores did not exceed the MCID (Farrar et al., 2001), however, the pain scores were mild (Boonstra et al., 2016).

There were no significant changes in RPE scores from week 0 to week 12, with the mean improvement being 0.3 ± 1.3 (95% CI -0.8-1.3). Participants rated the 15-minute activity between hard and somewhat hard on the RPE scale (Steele et al., 2017). The results of the RPE assessment evidenced that the task difficulty was consistent across the weeks.

#### 5.3.5.4 Limitations

A limitation to the programme was that participants attended their own gym facilities to conduct the rehabilitation programme following their initial induction to the exercises. Some participants encountered problems with equipment and had to modify their exercises, which is outlined in section 5.2.4.1. This could also explain why there was greater variance in the VISA-A results than seen in the study by Beyer et al. (2015), however, it was impractical to ask participants to attend the university gym three times per week around work.

In summary, the results suggested that infrared thermal imaging is not a suitable tool to identify changes in absolute TSK or ΔTSK of the midportion of the AT in symptomatic individuals in response to a 12-week HSR rehabilitation programme. Studies with greater power may be able to further investigate this, however, it is made difficult due to the individual variations in TSK response to exercise. It was encouraging that the 12-week HSR programme resulted in clinically significant improvement in VISA-A scores for the recreational runners and enabled them to continue running with improved symptoms, however, these symptom changes were not statistically significant in the present study.

# Chapter SIX

## Midportion Achilles tendon skin temperature and vertical single leg hopping

## 6.1 The effect of single-leg vertical hopping on midportion Achilles tendon skin temperature in symptomatic and asymptomatic individuals

### 6.1.1 Introduction

Single leg vertical hopping (SLH) is often used as a functional assessment technique to assess the severity of clinical symptoms for Achilles tendinopathy due to the demands that it places on the AT (O'Neill, 2016). It is an action that requires the participant to repeatedly take off and land, usually weight-bearing on the forefoot. It utilises the SSC by placing demands on both the active (muscle) and passive (tendon) components of the Gastrocnemius-Soleus muscle-tendon unit, particularly when completed at frequencies greater than or equal to 2.0Hz (McMahon, 2015). It is considered one of the most provocative functional clinical tests (Hutchison et al., 2013; Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006), which tends to worsen with continued repetition, the opposite reaction to what is reported clinically with the onset of running, where a decrease in symptoms of Achilles tendinopathy is often described. With that in mind, different biomechanical and physiological responses may occur during the two activities.

SLH differs from running in that it requires the participant to land and take off usually on the forefoot using predominantly the ankle joint, with kinetic data showing a contact point and a take-off point (McMahon, 2015). In comparison, running is a more complex multi-joint activity with synchronous input from the rest of the kinetic chain (Dugan & Bhat, 2005). Kinetic data during running shows a substantially different loading pattern when compared to SLH with runners usually adopting a rear to midfoot landing strategy and only a minority adopting a forefoot landing strategy (Moore, 2016). Kinetic data typically shows an initial loading phase, a midstance phase and toe-off (Dugan & Bhat, 2005). As SLH and running display different biomechanical characteristics, which will load the AT in different ways, it is reasonable to assume that the TSK response to the loading will differ between the two activities.

Gutmann & Bertram (2017) suggest that running and hopping at controlled frequencies resulted in similar metabolic demand, however outside of the controlled frequencies, metabolic demand changed between the activities due to variables such as time of leg swing during running or muscle impulse at the knee during SLH. As hopping frequency increases beyond 2.0Hz, it requires an overall greater leg and ankle joint stiffness, thus reducing the demand placed on the active and passive structures of the knee and hip joints,

making it a primarily ankle dominant exercise (McMahon, 2015). The Gastrocnemius is thought to activate up to 100ms before making contact with the ground, where it is thought to pre-stiffen the ankle joint ready for ground contact (Funase et al., 2001). Interestingly, this pre-activation has not been seen in the Soleus, leading to the conclusion that it is predominantly a force-generating component of the AT complex as activity onset is seen before take-off and not landing which could reflect the monoarticular anatomical arrangement when compared to Gastrocnemius that may also serve to create knee flexion on landing (Funase et al., 2001).

As SLH at a frequency of 2.5Hz is primarily an ankle dominant exercise as there is limited time for changes in other joint angles (McMahon, 2015), the emphasis is placed upon the AT as a spring-like structure to store and release elastic energy to reduce the metabolic demand on the Gastrocnemius and Soleus musculature (Lamontagne & Kennedy, 2013). AT stiffness is thought to play an important role in the efficiency of the AT in being able to effectively utilise the SSC, however, what constitutes optimal is variable amongst different tasks that require different force/velocity characteristics (Abdelsattar et al., 2018; Lamontagne & Kennedy, 2013). As discussed during chapter 2, the SSC is composed of positive and negative tendon work (Zelik & Franz, 2017). Elastic energy is stored during the negative work phase of the movement before being released in conjunction with the initiation of positive (concentric) work, and any delay in this transition results in some of the stored energy being dissipated as heat (Lamontagne & Kennedy, 2013). When suffering from Achilles tendinopathy, it is known that the stiffness properties of the AT are reduced, resulting in a more compliant AT which is less efficient during the SSC, creating the possibility of reduced running economy and performance (Arampatzis et al., 2006; Fletcher, Esau & MacIntosh, 2010). As a result, it would be expected that more energy would be dissipated as heat which may be reflected at the surface of the skin.

One previous study has assessed the thermal response of the AT in response to SLH (Jang et al., 2019). Jang et al., (2019) found that there were statistically different responses in the left and right AT's of 10 healthy males following 1000 SLH's on the right leg. There were statistically significant increases in midportion AT TSK in the right leg, however, there was a non-statistically significant decrease in TSK in the left AT which had remained off the ground. The rationale for the increase in TSK in the right AT was due to hysteresis increasing the skin surface and tendon core temperatures, as it was estimated that 18000 joules of energy were

released. Further explanation for the differences in TSK between the midportion of the AT was suggested to be due to redistribution of blood flow away from the skin to supply the metabolic demand of the Gastrocnemius. As hysteresis is known to be greater in an AT suffering from tendinopathy (Wang et al., 2012), it would be interesting to investigate whether the thermal response over the AT is the same in control versus symptomatic tendons, which to date has not been investigated (Arya & Kulig, 2010; Chang & Kulig, 2015; Wang et al., 2012).

In those with Achilles tendinopathy, it would be unrealistic and unethical to investigate the thermal response of the midportion with 1000 hops due to the provocative nature of the test (Hutchison et al., 2013; Silbernagel et al., 2006). However, Chang & Kulig (2015) utilised a series of 20 hops in those with Achilles tendinopathy to assess neuromechanical factors associated with the condition, where they found statistically significant differences in stiffness, electromechanical delay, pre-activation, spinal and supraspinal responses and co-contraction ratio.

To date, no study has assessed kinetic or kinematic variables in a SLH in those suffering from Achilles tendinopathy. Considering that SLH is a clinical test used to assess the function of the AT, it is vital to understand whether kinetic or kinematic differences exist in those with and without Achilles tendinopathy. Alterations in stiffness properties of the AT, as seen in those that are symptomatic (Arya & Kulig, 2010; Chang & Kulig, 2015; Wang et al., 2012), can affect both GCT, flight time, hop height and peak vertical GRF's. As a result, reactive strength index (RSI) will also be affected. RSI describes the duration of force production to achieve a hop height in an SSC cycle and is calculated by dividing the hop height by the GCT and is a useful indicator of SSC function (Ebben & Petushek, 2010; McMahon, Suchomel, Lake, & Comfort, 2018).

Ground contact times (GCT) during hopping at 2.5Hz have previously been shown to be a mean of 265 ± 15ms which is considered a slow SSC action (Flanagan & Comyns, 2008; McMahon, 2015; Turner & Jeffreys, 2010). Similar GCT's have been reported at running speeds of 10 kilometres per hour (km/h). Speeds of 12 km/h are deemed to border fast and slow SSC actions, where speeds over 14 km/h are classified as fast (Lussiana et al., 2019).

With that in mind, this study aimed to assess the absolute and ΔTSK response of the midportion of the AT in response to a SLH intervention. A second aim was to assesses whether

any differences existed between kinetic and kinematic variables in the SX_AT, ASX_AT and control AT's.

### 6.1.2 Hypotheses

1. There would be a statistically significant increase in absolute TSK of the midportion of the AT from timepoint BL to immediately post SLH intervention (POST0) in the SX tendon, the ASX tendon and the control group AT's.
2. There would be a statistically significant decrease in absolute TSK of the midportion of the AT from timepoint POST0 to CD10 in all groups
3. There would be a statistically significant difference in absolute TSK values between the SX_AT and ASX_AT's in response to the SLH intervention
4. There would be a statistically significant difference in TSK between the SX_AT and control AT's in response to the SLH intervention
5. There would be a statistically significant difference in TSK between the ASX_AT and control AT's in response to the SLH intervention
6. There would be a statistically significant difference in ΔTSK response between the SX_AT and control AT's in response to the SLH intervention
7. There would be a statistically significant difference in ΔTSK response between the ASX_AT and control AT's in response to the SLH intervention
8. There would be a statistically significant difference in ΔTSK response between the SX_AT and ASX_AT's in response to the SLH intervention
9. There would be a statistically significant difference in SLH frequency between the SX and control participants in response to the SLH intervention
10. There would be a statistically significant difference in SLH GCT between the SX and control participants in response to the SLH intervention
11. There would be a statistically significant difference in SLH flight time between the SX and control participants in response to the SLH intervention
12. There would be a statistically significant difference in SLH height between the SX and control participants in response to the SLH intervention
13. There would be a statistically significant difference in SLH RSI between the SX and control participants in response to the SLH intervention
14. There would be a statistically significant difference in SLH GRF between the SX and control participants in response to the SLH intervention

### 6.1.3 Methods

The methods for this section were as outlined in section 3 unless otherwise stated.

#### 6.1.3.1 Sample size calculation

A sample size calculation was conducted using G*Power 3.1.9.7 to detect meaningful change at 80% power and at an alpha level of 0.05. To account for a dropout rate of 10%, recruitment was aimed to be increased by 10% of the required sample size. A total of 38 participants (19 per group) were needed to detect a meaningful change in midportion AT TSK in response to a SLH intervention.

#### 6.1.3.2 Participant recruitment

Recruitment was conducted as stated in section 3.6.2.2 with the aim of recruiting 38 participants. As mentioned previously the block randomisation process that occurred during section 5.1.3.2 meant that 21 symptomatic and 17 control participants undertook the SLH intervention. Participant anthropometrics can be seen in table 6.1.1. There were no statistically significant differences in mean age ($t_{(36)}$ = 1.391, p=0.173), mean height ($t_{(36)}$ = 0.395, p=0.096) or mean mass ($t_{(36)}$ = 1.181, p=0.246) between the SX or control group as assessed by independent samples t-tests. A CONSORT flow diagram can be seen in figure 6.1.1, which outlined participant recruitment.

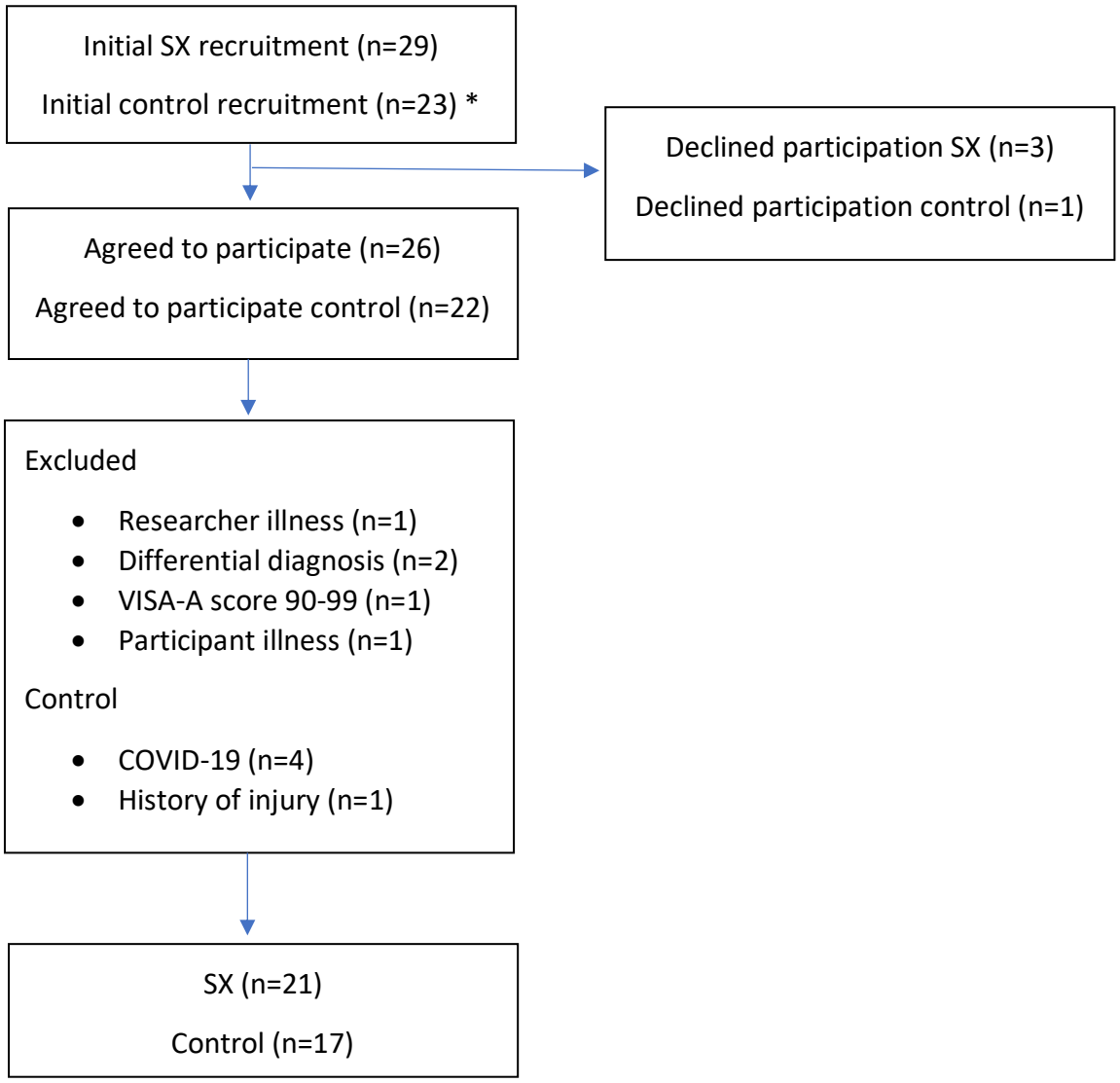



Figure 6.1.1: CONSORT flowchart for SLH participant recruitment

#### 6.1.3.3 Room temperature

Measured as stated in section 3.6.2.5. The mean room temperature during BL testing was 21.1 ± 0.8°C and the mean humidity was 43.1 ± 8.4%.

#### 6.1.3.4 SLH task

Participants returned on a second day (within 7 days) of testing following their clinical assessment to conduct the SLH task. They underwent an acclimatisation period, as outlined in section 3.6.2.7, before conducting 3 sets of 20 barefoot hops at a frequency of 2.5Hz on a Kistler type 9286AA force platform (Kistler Instruments Inc., Amherst, New York, USA), which sampled at a frequency of 1000Hz. BioWare software (version5.3.0.7, Kistler Instruments Inc., Amherst, New York, USA) was used to acquire the vertical GRF data. 3 sets of 20 hops were

chosen to repeat the methodology employed by Lichtwark & Wilson (2005a) so that the total load on the symptomatic participants AT's was not overly provocative, as it is known to be painful and places the AT under high load per repetition (Baxter et al., 2020; Hutchison et al., 2013). A frequency of 2.5Hz was chosen so that there was greater overall leg stiffness, thus reducing the input of the knee joint to the movement, and it is also a frequency whereby there is a more efficient SSC action due to the isometric Gastrocnemius muscle behaviour (Lichtwark & Wilson, 2005b; McMahon, 2015). The frequency also led to a similar GCT to the running tasks in previous studies (Starbuck et al., 2020). The overall rest period in between sets was 30 seconds, which was enough time to zero the force plate and complete a set of hops on the other limb.

Table 6.1.1: SLH participant anthropometrics

| Group | Mean ± SD age (yrs) | Mean ± SD height (cm) | Mean ± SD mass (kg) |
|---|---|---|---|
| SX | 43.5 ± 10.1 | 174.3 ± 7.7 | 76.3 ± 13.8 |
| Control | 39.1 ± 9.0 | 173.0 ± 11.1 | 71.0 ± 11.9 |

The participants were briefed before their hopping trial that if their pain became intolerable, they should stop and notify the researcher immediately. Participants undertook a warmup which consisted of 1x20 double leg pogo hops at a 2.5Hz frequency and 1x10 SLH at the same frequency.

Before each set of hops, the participants were asked to stand on the wooden frame that surrounded the force plate. This acted as a safety device to prevent them from falling off the force plate mid-trial. Once zeroed, participants were then asked to stand on the plate, and the trial was commenced. A metronome was activated using the metronome application for iPhone, set at 150bpm to replicate a 2.5Hz frequency. A minimum of 15 from the 20 hops within a 5% margin of 2.5Hz frequency were required to be counted as a successful hopping trial (McMahon, 2015). Participants were encouraged to keep the knee straight and hop on the ball of the foot if possible.

Following the hopping intervention, participants returned to the thermal area for post-hop thermal images, a distance of 3 metres. Anatomical markers were reapplied, and the lights were switched off before images were taken. This process took no more than 60 seconds.

#### 6.1.3.5 Thermal data capture

Thermal data capture was conducted as stated in section 3.6.2.10. Thermal images were taken at 8 time points per participant (BL, POST0, CD2, CD4, CD5, CD6, CD8 and CD10). In total, 168 infrared thermal images were taken for the SX hoppers, and 136 images were captured for the control participants.

#### 6.1.3.6 Thermal data analysis

Conducted as outlined in section 3.6.2.12.

#### 6.1.3.7 Vertical SLH data analysis

Hopping data was collected using BioWare software (version5.3.0.7, Kistler Instruments Inc., Amherst, New York, USA). Data for each SLH trial were saved on the laboratory laptop in a coded fashion as a data file and then they were converted to a text file so that they were readable in Microsoft Excel (v16.0, Microsoft corporation, WA, US). They were then immediately transferred upon cessation of the session via memory stick to the researcher's laptop.

The text files were then opened with Microsoft Excel (v16.0, Microsoft corporation, WA, US) and data were copied into a template spreadsheet which was designed to identify each frame of movement and extract force data. The threshold for take-off and touchdown used was 20.0N (McMahon, 2015). From this force data, hop frequency, GCT, flight time, hop height and RSI were automatically calculated for 15 successful hopping trials per set. The formulae used for these can be seen in table 6.1.2 (Flanagan & Comyns, 2008; Lloyd et al., 2009). A macro was then developed which extracted peak ground reaction force (GRF) for each hop, so that mean peak GRF could be calculated.

Table 6.1.2: SLH kinetic and kinematic formulae

| Variable | Formula |
|---|---|
| SLH frequency | (1 ÷ (GCT + Flight time)) |
| GCT | (Repetition take off – Repetition touch down) |
| Flight time | (Repetition touch down – previous repetition take off) |
| Hop height | ((Flight time2) x 9.81) ÷ 8 |
| RSI | (Hop height ÷ GCT) |

#### 6.1.3.8 Statistical analysis

Normality was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise($p>0.05$). Homogeneity of variances was assessed using Levene's test and the assumption was met unless stated otherwise ($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

Cohen's d was used to measure effect size, and these values represented the size of the differences in the two groups means (Lakens, 2013). Effect sizes were classed as trivial ($d<0.2$), small ($d=0.2$-$0.49$), medium ($d=0.50$-$0.79$) and large ($d<0.80$) in accordance with existing literature (Cohen, 1988; Lakens, 2013) as the data was novel and could not be compared to any existing findings in the literature (Lakens, 2013).

VISA-A, NPRS and RPE data were not normally distributed ($p<0.05$). Separate non-parametric Mann-Whitney U tests were run for each variable to assess if there were differences in scores between SX and control participants.

A factorial mixed ANOVA (8x3) was used to assess the differences in TSK values following the hopping intervention, with timepoint (BL, POST0, CD2, CD4, CD5, CD6, CD8, CD10) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subjects independent variable. Mauchly's test of sphericity was violated ($x^2$ (27) = 433.306, p<0.001) therefore Greenhouse-Geisser corrected results were reported.

ΔTSK scores were calculated by subtracting the absolute TSK value from BL. A factorial mixed ANOVA (7x3) was run on ΔTSK response for each of the 7 pairs of time points, to see if the responses differed between groups, with timepoint (POST0-BL, CD2-BL, CD4-BL, CD5-BL, CD6-BL, CD8-BL, CD10-BL) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subject independent variable. Mauchly's test of sphericity was violated ($x^2$ (20) = 415.643, p<0.001) therefore Greenhouse-Geisser corrected results were reported.

The ICC (3,1), SEM and MDC values for kinetic and kinematic data were calculated from the control participant data using the equations outlined in section 3.3.3.11.

A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping frequency, with set number (Set 1, Set 2, Set3) as the within-subjects factor and group (SX_AT, ASX_AT, Control) as the between-subjects factor. Mauchly's test of sphericity was violated ($x^2$ (2) = 7.960, p=0.019) therefore Greenhouse-Geisser corrected results were reported.

A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping GCT, with set number (Set 1, Set 2, Set3) as the within-subjects factor and group (SX_AT, ASX_AT, Control) as the between-subjects factor.

A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping flight time, with set number (Set 1, Set 2, Set3) as the within-subjects factor and group (SX_AT, ASX_AT, Control) as the between-subjects factor.

A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping height, with set number (Set 1, Set 2, Set3) as the within-subjects factor and group (SX_AT, ASX_AT, Control) as the between-subjects factor.

A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping RSI, with set number (Set 1, Set 2, Set3) as the within-subjects factor and

group (SX_AT, ASX_AT, Control) as the between-subjects factor. Variances were homogenous for set 1 (p>0.05) but heterogeneous for set 2 (p=0.032) and set 3 (p=0.041), as assessed by Levene's test. Mauchly's test of sphericity was met ($x^2$ (2) = 0.026, p=0.987), therefore sphericity was assumed.

Mean peak GRF during hopping was expressed in multiples of body weight, using the equation $Mean\ peak\ GRF\ (N) \div body\ weight\ (N)$. A factorial mixed ANOVA (3x3) was used to assess whether there were any differences in mean hopping peak GRF, with set number (Set 1, Set 2, Set3) as the within-subjects factor and group (SX_AT, ASX_AT, Control) as the between-subjects factor.

### 6.1.4 Results

#### 6.1.4.1 VISA-A, NPRS and RPE

The mean scores for VISA-A, NPRS during activity, NPRS after activity and RPE can be seen in table 6.1.3.

Table 6.1.3: Mean and SD data for VISA-A, NPRS and RPE for SLH participants at week 0

| Outcome measure | SX mean | SX SD | SX median | Control mean | Control SD | Control median |
|---|---|---|---|---|---|---|
| VISA-A | 77.3 | 10.2 | 79.0 | 100.0 | 0.0 | 100.0 |
| NPRS During | 4.1 | 2.9 | 4.0 | 0.0 | 0.0 | 0.0 |
| NPRS After | 1.3 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| RPE | 3.4 | 2.0 | 4.0 | 3.6 | 0.9 | 4.0 |

There was a statistically significant difference between VISA-A scores in the SX and control groups, with the SX participants having a lower VISA-A score by 22.7 points, U=357.000, z=5.493, p<0.001.

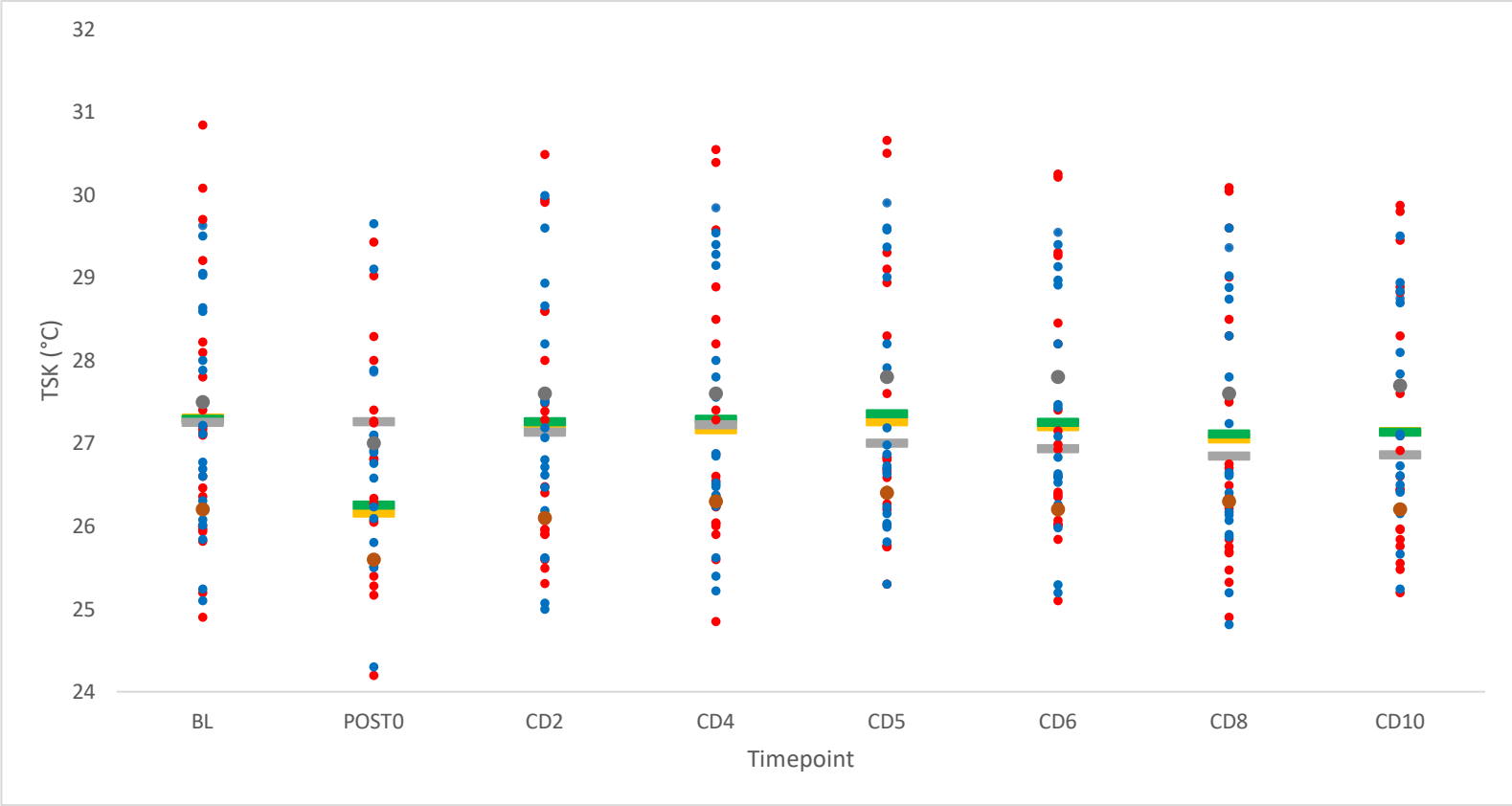
There was a statistically significantly different NPRS response during the activity, with the SX participants reporting NPRS scores a mean of 4.4 points higher than the control group, U=34.000, z=-4.659, p<0.001.

There was a statistically significant difference in NPRS scores reported following hopping between the groups, with the SX participants reporting pain scores a mean of 1.3 points higher, U=110.500, z=-2.802, p=0.045.

The difference in RPE scores between the groups was not statistically significant, with a mean difference of 0.2 points, U=190.500, z=0.378, p=0.72

#### 6.1.4.2 TSK

Mean TSK data for timepoint and group can be seen in table 6.1.4 and graphically in figure 6.1.2.




**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 6.1.2: WK0 TSK data for SLH participants

Table 6.1.4: Mean TSK data for SLH participants

| Time | Group | Mean TSK (°C) | SD (°C) | ΔTSK from BL (°C) | SD (°C) |
|---|---|---|---|---|---|
| BL | SX | 27.3 | 1.7 | - | - |
| | ASX | 27.3 | 1.4 | - | - |
| | Control | 27.2 | 2.1 | - | - |
| | Mean | 27.3 | 1.8 | - | - |
| POST0 | SX | 26.1 | 2.4 | -1.1 | 2.5 |
| | ASX | 26.2 | 2.3 | -1.0 | 2.5 |
| | Control | **27.3** [e f] | 2.0 | **0.0** [n o] | 0.7 |
| | Mean | 26.7 | 2.2 | -0.6 | 1.9 |
| CD2 | SX | 27.2 | 1.7 | -0.1 | 1.0 |
| | ASX | 27.3 | 1.5 | -0.1 | 0.9 |
| | Control | 27.1 | 2.0 | -0.1 | 0.5 |
| | Mean | **27.2** [a] | 1.8 | **-0.1** [j] | 0.8 |
| CD4 | SX | 27.2 | 1.8 | -0.1 | 1.0 |
| | ASX | 27.3 | 1.5 | 0.0 | 1.0 |
| | Control | **27.2** [g h i] | 1.9 | **0.0** [p q r] | 0.8 |
| | Mean | **27.2** [b] | 1.7 | **-0.1** [k] | 0.9 |
| CD5 | SX | 27.3 | 1.7 | -0.0 | 0.7 |
| | ASX | 27.4 | 1.4 | 0.1 | 0.7 |
| | Control | **27.0** [e] | 2.0 | **-0.3** [n] | 0.7 |
| | Mean | **27.2** [c] | 1.7 | **-0.1** [l] | 0.7 |
| CD6 | SX | 27.2 | 1.6 | -0.1 | 0.8 |
| | ASX | 27.3 | 1.3 | -0.0 | 0.7 |
| | Control | **26.9** [g] | 1.9 | **-0.3** [p] | 0.8 |
| | Mean | **27.1** [d] | 1.6 | **-0.2** [m] | 0.8 |
| CD8 | SX | 27.0 | 1.7 | -0.3 | 0.9 |
| | ASX | 27.1 | 1.4 | -0.2 | 0.9 |
| | Control | **26.8** [f h] | 1.9 | **-0.4** [o q] | 0.8 |
| | Mean | **26.9** [a b c d] | 1.7 | **-0.4** [j k l m] | 0.8 |
| CD10 | SX | 27.1 | 1.5 | -0.2 | 0.9 |
| | ASX | 27.1 | 1.2 | -0.2 | 0.7 |
| | Control | **26.9** [i] | 1.9 | **-0.4** [r] | 0.9 |
| | Mean | 27.0 | 1.6 | -0.3 | 0.8 |

[a b c d] denotes statistical significance for mean absolute TSK (irrespective of group) between timepoints ($p<0.05$)

[e f g h l] denotes statistical significance for mean absolute TSK in the control group between time points ($p<0.05$)

[j k l m] denotes statistical significance for mean ΔTSK (irrespective of group) between timepoints ($p<0.05$)

[n o p q r] denotes statistical significance for mean ΔTSK in the control group between time points ($p<0.05$)

There was a statistically significant group x time two-way interaction on TSK values of the midportion of the AT in response to a hopping intervention ($F_{(2.402, 165.704)}$ = 2.768, p=0.036, partial $\eta^2$ = 0.93). Pairwise comparisons revealed statistically significant (p=0.04) differences in TSK between timepoints CD2 and CD8, CD4 and CD8 (p<0.001), CD5 and CD8 (p=0.01) and CD6 and CD8 (p<0.001). The pairwise comparisons for group revealed no statistically significant differences between any of the groups.

There was a statistically significant simple main effect of time on TSK at the midportion of the Achilles tendon for the control group. Pairwise comparisons for the simple main effect of time revealed statistically significant differences in TSK between timepoints POST0 and CD5 (p=0.04) and between POST0 and CD8 (p=0.019). Statistically significant differences were also present between timepoints CD4 and CD6 (p<0.001), CD4 and CD8 (p<0.001) and CD4 and CD10 (p=0.011). There were no simple main effects of time in either the SX_AT or ASX_AT groups.

There were no statistically significant (p>0.05) simple main effects of group at any of the time points.

#### 6.1.4.3 ΔTSK response

Mean ΔTSK responses are presented in table 6.1.4 and figure 6.1.3. There was a statistically significant group x time two-way interaction on ΔTSK values of the midportion of the AT in response to a hopping intervention ($F_{(2.948, 134.115)}$ = 3.125, p=0.031, partial $\eta^2$ = 0.104). Pairwise comparisons revealed statistically significant (p=0.033) differences between timepoints CD2-BL and CD8-BL, CD4-BL and CD8-BL (p<0.001), CD5-BL and CD8-BL (p=0.005) and CD6-BL and CD8-BL (p=0.002). Group pairwise comparisons revealed no statistically significant differences.

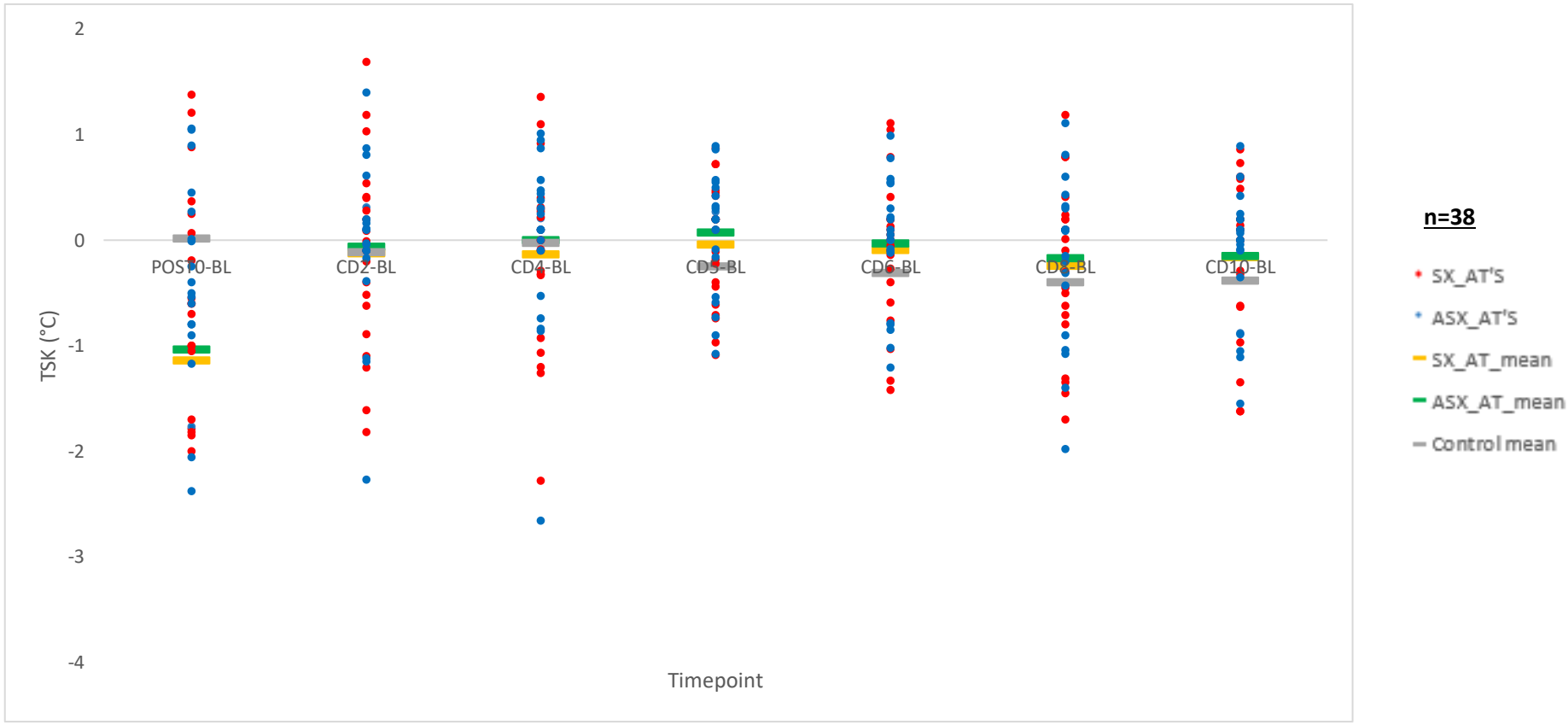



Figure 6.1.3: WK0 ΔTSK response of the SLH participants

There was a statistically significant simple main effect of timepoint for the control group ($F_{(3.272, 94.891)}$ = 6.734, p<0.001, partial $\eta^2$ = 0.206). Pairwise comparisons revealed statistically significant differences in TSK between timepoints POST0-BL and CD5-BL (p=0.030) and POST0-BL and CD8-BL (p=0.014). There were also statistically significant differences in the control group between timepoints CD4-BL and CD6-BL (p<0.001), CD4-BL and CD8-BL (p<0.001) and CD4-BL and CD10-BL (p=0.008). There were no statistically significant simple main effects for the SX_AT ($F_{(1.332,26.640)}$ = 2.451, p=0.128, partial $\eta^2$ = 0.149). or ASX_AT groups ($F_{(1.326, 26.512)}$ = 2.525, p=0.124, partial $\eta^2$ = 0.153).

There were no statistically significant simple main effects of group at any of the time points (p>0.05).

#### 6.1.4.4 Kinetic and kinematic within-session reliability

The within-session reliability and associated SEM and MDC values can be seen presented in table 6.1.5.

Table 6.1.5: Within-session reliability of SLH kinetic and kinematic variables

| Parameter | ICC | Lower 95% CI | Upper 95% CI | SEM | MDC |
|---|---|---|---|---|---|
| Hop Frequency | 0.621 | 0.246 | 0.824 | 0.07Hz | 0.18Hz |
| Hop GCT | 0.929 | 0.860 | 0.967 | 0.004s | 0.010s |
| Hop Flight Time | 0.927 | 0.854 | 0.966 | 0.003s | 0.010s |
| Hop Height | 0.901 | 0.805 | 0.954 | 0.004m | 0.010m |
| Hop RSI | 0.923 | 0.847 | 0.964 | 0.001 | 0.002 |
| Hop Peak GRF | 0.928 | 0.855 | 0.966 | 0.09xBW | 0.25xBW |

Hz = Hertz

s = Seconds

m = Metres

xBW = times body weight

#### 6.1.4.5 SLH frequency

Mean hopping frequencies can be seen in table 6.1.6. There was no statistically significant two way set x group interaction for hopping frequency ($F_{(3.487,88.914)}$ = 1.579, p=0.194, partial $\eta^2$ = 0.058). There were no statistically significant simple main effects for

group ($F_{(2,51)}$ = 1.210, p=0.307, partial $\eta^2$ = 0.045) or set number ($F_{(1.743,88.914)}$ = 1.539, p=0.222, partial $\eta^2$ = 0.029).

#### 6.1.4.6 SLH GCT

Mean hopping GCT's can also be seen in table 6.1.6. There was no statistically significant two way interaction between set number and group for hopping GCT ($F_{(3.252,84.564)}$ = 1.018, p=0.194, partial $\eta^2$ = 0.038).

There was a statistically significant main effect for group on GCT during the hopping trials ($F_{(2,52)}$ = 5.515, p=0.007, partial $\eta^2$ = 0.175). Pairwise comparisons revealed a statistically significant (p=0.014) mean difference in GCT between the SX_AT and the control groups, with the control groups GCT being quicker by 0.02s, d=0.8. There was a statistically significant (p=0.040) mean difference in GCT between the ASX_AT and the control group, with the control group being quicker by 0.02s, d=0.5. There was no statistically significant (p=1.00) mean difference between the SX_AT and ASX_AT, with a mean difference of 0.00s, d= 0.4.

There were no statistically significant main effect for set number ($F_{(1.626,84.564)}$ = 0.164, p=0.805, partial $\eta^2$ = 0.003).

Table 6.1.6: Mean kinetic and kinematic SLH data

| Set Number | Group | Mean Freq. (Hz) | SD Freq. (Hz) | Mean GCT (s) | SD GCT (s) | Mean Flight Time (s) | SD Flight Time (s) | Mean Hop Height (m) | SD Hop Height (m) | Mean RSI | SD RSI | Mean peak GRF (BW) | SD Peak GRF (BW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SX_AT | 2.49 | 0.10 | 0.30 | 0.03 | **0.11**$^{g}$ | 0.01 | **0.02**$^{mn}$ | 0.00 | **0.06**$^{s}$ | 0.01 | 2.33 | 0.15 |
| | ASX_AT | 2.48 | 0.10 | 0.29 | 0.02 | 0.11 | 0.01 | 0.02 | 0.00 | 0.06 | 0.02 | 2.36 | 0.13 |
| | Control | 2.51 | 0.07 | 0.28 | 0.02 | **0.12**$^{h}$ | 0.02 | 0.02 | 0.01 | 0.07 | 0.02 | 2.47 | 0.16 |
| | Mean | 2.50 | 0.09 | 0.29 | 0.02 | 0.12 | 0.01 | 0.02 | 0.00 | 0.06 | 0.02 | 2.40 | 0.16 |
| 2 | SX_AT | 2.51 | 0.07 | 0.30 | 0.02 | **0.11**$^{c}$ | 0.01 | **0.01**$^{im}$ | 0.00 | **0.05**$^{o}$ | 0.01 | 2.32 | 0.16 |
| | ASX_AT | 2.47 | 0.06 | 0.30 | 0.02 | **0.11**$^{d}$ | 0.01 | **0.02**$^{j}$ | 0.00 | **0.06**$^{p}$ | 0.06 | 2.39 | 0.15 |
| | Control | 2.51 | 0.06 | 0.29 | 0.02 | **0.12**$^{cdh}$ | 0.02 | **0.02**$^{ij}$ | 0.01 | **0.07**$^{op}$ | 0.03 | 2.52 | 0.18 |
| | Mean | 2.50 | 0.07 | 0.29 | 0.02 | 0.12 | 0.02 | 0.02 | 0.01 | 0.06 | 0.02 | 2.43 | 0.18 |
| 3 | SX_AT | 2.52 | 0.06 | 0.30 | 0.02 | **0.10**$^{eg}$ | 0.01 | **0.01**$^{kn}$ | 0.00 | **0.05** $^{qs}$ | 0.01 | 2.31 | 0.17 |
| | ASX_AT | 2.51 | 0.06 | 0.29 | 0.03 | **0.11**$^{f}$ | 0.01 | **0.02**$^{l}$ | 0.00 | **0.06** $^{r}$ | 0.02 | 2.40 | 0.15 |
| | Control | 2.51 | 0.06 | 0.28 | 0.02 | **0.12**$^{ef}$ | 0.02 | **0.02**$^{kl}$ | 0.01 | **0.07** $^{qr}$ | 0.03 | 2.53 | 0.20 |
| | Mean | 2.51 | 0.06 | 0.29 | 0.02 | 0.12 | 0.02 | 0.02 | 0.01 | 0.06 | 0.02 | 2.43 | 0.20 |
| Mean | SX_AT | 2.51 | 0.08 | 0.30$^{a}$ | 0.02 | 0.11 | 0.001 | 0.01 | 0.00 | 0.05 | 0.01 | **2.32**$^{t}$ | 0.16 |
| | ASX_AT | 2.49 | 0.07 | 0.29$^{b}$ | 0.02 | 0.11 | 0.001 | 0.02 | 0.00 | 0.06 | 0.03 | **2.38**$^{u}$ | 0.14 |
| | Control | 2.50 | 0.06 | 0.29$^{ab}$ | 0.02 | 0.10 | 0.002 | 0.02 | 0.01 | 0.0 | 0.03 | **2.51**$^{tu}$ | 0.18 |

$^{a\,b\,t\,u}$ denotes statistically significant main effect for group ($p<0.05$)

$^{c\,d\,e\,f\,l\,j\,k\,l\,o\,p\,q\,r}$ denotes statistically significant simple main effect for group ($p<0.05$)

$^{g\,h\,m\,n\,s}$ denotes statistically significant simple main effect for set number ($p<0.05$)

#### 6.1.4.7 SLH flight time

Mean hopping flight time can be seen in table 6.1.6. There was a statistically significant set x group two-way interaction on mean flight time ($F_{(4,102)}$ = 4.796, p=0.001, partial $\eta^2$ = 0.158). There was a statistically significant simple main effect for group during set 2 ($F_{(2,55)}$ = 8.067, p=0.001, partial $\eta^2$ = 0.227). Multiple comparisons showed a statistically significant (p=0.001) difference between the SX_AT and control group, with the control group displaying a longer flight time by 0.02s, d=1.2. There was also a statistically significant difference between the ASX_AT and control group with the control group displaying a longer flight time by 0.01s, d=1.0. There was also a statistically significant simple main effect for group during set 3 ($F_{(2,54)}$ = 8.397, p=0.001, partial $\eta^2$ = 0.237). Multiple comparisons showed a statistically significant (p=0.001) difference between the SX_AT and control group, with the control group displaying a longer flight time by 0.02s, d=1.2. There was also a statistically significant difference between the ASX_AT and control group with the control group displaying a longer flight time by 0.01s, d=1.0. The simple main effect for group during set 1 was not statistically significant ($F_{(2,52)}$ = 1.366, p=0.264, partial $\eta^2$ = 0.050).

There was a statistically significant simple main effect of set on hop flight time for the SX_AT group ($F_{(2,28)}$ = 6.828, p=0.04, partial $\eta^2$ = 0.328). Pairwise comparisons revealed a statistically significant (p=0.013) difference between set 1 and 3, with flight time being shorter by a mean of 0.01s in set 3, d=0.06. There was a statistically significant simple main effect of set on hop flight time for the control group ($F_{(2,46)}$ = 4.470, p=0.017, partial $\eta^2$ = 0.163). Pairwise comparisons revealed a statistically significant (p=0.04) difference between set 1 and 2, with flight time being longer by a mean of 0.01s in set 2, d=0.31. There was no simple main effect of set on hop flight time for the ASX_AT group ($F_{(2,28)}$ = 0.290, p=0.751, partial $\eta^2$ = 0.020).

#### 6.1.4.8 SLH height

Mean hop height data can be seen in table 6.1.6. There was a statistically significant two-way interaction between set number and group for hop height ($F_{(4,102)}$ = 3.160, p=0.017, partial $\eta^2$ = 0.110). There was a statistically significant simple main effect of group during set 2 ($F_{(2,55)}$ = 7.249, p=0.002, partial $\eta^2$ = 0.209). Multiple comparisons showed a statistically significant (p=0.002) difference between the SX_AT and control group during set 2, with the control group hopping a mean of 0.006m higher, d=1.5. There was a statistically significant (p=0.049) difference between the ASX_AT and control group during set 2, with the control

group hopping a mean of 0.004m higher, d=0.8. There was a statistically significant simple main effect of group during set 3 ($F_{(2,54)}$ = 7.732, p=0.001, partial $\eta^2$ = 0.223). There was a statistically significant (p=0.001) difference between the SX_AT and control group during set 3, with the control group hopping higher by a mean of 0.006m, d=1.2. There was a statistically significant (p=0.046) difference between the ASX_AT and control group during set 3, with the control group hopping a mean of 0.004m higher, d=0.7. The simple main effect for group during set 1 was not statistically significant ($F_{(2,52)}$ = 1.137, p=0.329, partial $\eta^2$ = 0.042).

There was a statistically significant simple main effect of set on hop height for the SX_AT group ($F_{(2,28)}$ = 7.057, p=0.003, partial $\eta^2$ = 0.335). Pairwise comparisons revealed a statistically significant (p=0.029) difference between set 1 and 2, with hop height in set 1 being a mean of 0.001m higher, d=0.4. There was also a statistically significant (p=0.018) difference between set 1 and 3, with hop height being a mean of 0.002m higher in set 1, d=0.6. There were no statistically significant simple main effects for the ASX_AT ($F_{(2,28)}$ = 0.525, p=0.597, partial $\eta^2$ = 0.036) or the control group ($F_{(2,46)}$ = 2.845, p=0.068, partial $\eta^2$ = 0.110).

#### 6.1.4.9 SLH RSI

Mean hopping RSI can be seen in table 6.1.6. There was a statistically significant two-way set x group interaction ($F_{(4,102)}$ = 3.205, p=0.016, partial $\eta^2$ = 0.112). There was a statistically significant simple main effect for group during set 2 ($F_{(2,55)}$ = 8.187, p=0.00, partial $\eta^2$ = 0.229). Multiple comparisons revealed statistically significant (p<0.001) differences between the RSI of the SX_AT and control group, with RSI in the control group being larger by a mean of 0.03, d=1.2. There was also a statistically significant (p=0.019) difference between the ASX_AT and control group during set 2, with RSI being a mean 0.02 higher in the control group, d=0.7. There was a statistically significant simple main effect for group during set 3 ($F_{(2,54)}$ = 7.353, p=0.001, partial $\eta^2$ = 0.214). Multiple comparisons revealed a statistically significant (p=0.002) difference between the RSI of the SX_AT group and the control group, with the RSI being a mean of 0.03 higher in the control group, d=1.2. There was also a statistically significant (p=0.046) difference between the RSI of the ASX_AT and control groups during set 3, with control group RSI being a mean of 0.02 higher, d=0.6.

There was a statistically significant simple main effect of set on RSI for the SX_AT group ($F_{(2,28)}$ = 7.002, p=0.003, partial $\eta^2$ = 0.333). Pairwise comparisons revealed a statistically significant (p=0.012) difference between set 1 and set 3, with the RSI during set 1 being a

mean of 0.008 higher, d=0.6. There were no statistically significant simple main effects for set on the RSI of the ASX_AT group ($F_{(2,28)}$ = 0.157, p=0.855, partial $\eta^2$ = 0.011), or the control group ($F_{(2,46)}$ = 3.144, p=0.053, partial $\eta^2$ = 0.120).

#### 6.1.4.10 SLH mean peak GRF

Mean hopping peak GRF can be seen in table 6.1.6. There was no statistically significant set x group two-way interaction ($F_{(4,106)}$ = 2.024, p=0.096, partial $\eta^2$ = 0.071). The main effect of set showed no statistically significant differences in mean peak GRF across the 3 sets ($F_{(2,106)}$ = 1.901, p=0.155, partial $\eta^2$ = 0.035).

The main effect of group showed that there was a statistically significant difference in mean peak GRF between the groups ($F_{(2,53)}$ = 7.960, p=0.001, partial $\eta^2$ = 0.231). Pairwise comparisons revealed a statistically significant (p=0.001) difference between the SX_AT and control group, with the control group displaying mean peak GRF's 0.19 times bodyweight higher, d= 1.1. There was also a statistically significant (p=0.041) difference between the ASX_AT and control group, with the control group displaying mean peak GRF's 0.13 times bodyweight higher, d= 0.8. There we no statistically significant (p=0.855) differences between the SX_AT and ASX_AT groups, d=0.4.

### 6.1.5 Discussion

The main purpose of this study was to establish the effect of a SLH intervention on the TSK response of the midportion of the AT. This is the first study of its kind to assess the TSK response to SLH. The second aim of this study was to assess whether any differences existed in kinetic or kinematic variables associated with single leg hopping between the SX_AT, ASX_AT or control groups. The main findings of this study were:

1. There was an initial but statistically insignificant decrease in TSK of the midportion of the AT following the SLH intervention in SX_AT's and ASX_AT's.
2. There were no between-group differences in absolute TSK response of the midportion of the AT following the SLH intervention.
3. There were no between-group differences in ΔTSK response of the midportion of the AT following the SLH intervention.
4. There were significant differences in mean GCT between the SX_AT and control groups and the ASX_AT and control groups.
5. There were significant differences between groups and across sets for SLH flight time in the SX_AT and control group.
6. There were significant differences between groups and across sets for mean hop height, but these did not exceed the calculated MDC value.
7. There were significant differences between groups and across sets for SLH RSI.
8. There were significant differences between groups for mean SLH peak GRF, but these did not exceed the calculated MDC value.

#### 6.1.5.1 TSK

There was a statistically significant two-way group x timepoint interaction following the SLH intervention, with various statistically significant differences existing between timepoints CD2-6 with CD8. The reason for these statistically significant differences appeared to be due to a reduction in TSK at the CD8 timepoint across all groups. It is not known why there was a sudden statistically significant decrease at this time point, however, the ΔTSK values between timepoints CD2-6 and CD8 did not exceed the MDC value of 0.5°C calculated in section 3.5.4.1, therefore it cannot be concluded that this represented true TSK change.

The results revealed that there was an initial but statistically insignificant decrease in TSK between timepoints BL and POST0, which led to the rejection of hypothesis 1. Hypothesis

2 was also rejected as there was not a statistically significant decrease in TSK across the cooldown period. There were statistically significant simple main effects of time point, meaning that irrespective of the group there were statistically significant increases in TSK from timepoint POST0 to CD5 (0.5°C, d=0.2) and CD8 (0.2°C, d=0.1), however, the effect sizes were small and trivial respectively (Cohen, 1988; Lakens, 2013) and the latter absolute TSK value fell within the MDC of the IRC as found in chapter 3, therefore it cannot be said with certainty that the differences fell outside of the within-subject variability or random error. Statistically significant simple main effects of timepoint were also present between timepoints CD4 and CD6-CD10, with decreases in TSK of 0.1°C (d=0.1), 0.3°C (d=0.2) and 0.2°C (d=0.2) respectively, again with trivial to small effect sizes, with these values falling within the MDC of the camera. There were no statistically significant simple main effects for group irrespective of timepoint, which led to the rejection of hypotheses 3, 4 and 5.

The response demonstrated following the SLH activity was unexpected, and it differed from that of the response to the 15-minute running intervention (section 5.1). Following the running intervention, there was an immediate significant increase in TSK in all groups. Based on the increases seen following running, it was expected that the ankle dominant SLH would have resulted in increases in TSK. Several possible reasons may explain the different response seen following SLH.

Firstly, the level of the exercise may not have been high enough to induce fatigue. The mean RPE scores for both groups fell between easy and somewhat hard on the RPE scale (Steele et al., 2017). It may have been possible that the duration of the exercise, 3 x 20 repetitions, was not enough to elicit a significant change in TSK, however the mean NPRS scores during the activity were on the upper threshold of tolerable, so there had to be a balance between causing intolerable discomfort and maximum effort. Recent research by Pieters, Wezenbeek, Ridder, Witvrouw, and Willems (2020) published after data collection had ceased highlighted that blood flow in the AT increased significantly after 10-minutes of running, however, stretching and eccentric exercises of the same duration did not significantly change it. This could support the notion that the exercise load played a part in elevating the local AT TSK through local blood flow changes in the running cohort, and when combined with total load may explain why TSK did not increase in the SLH cohort.

The slight, but statistically insignificant decrease in TSK was unexpected. SLH at a frequency of 2.5Hz is an ankle plantar flexor dominant exercise (Farris & Sawicki, 2012), that

utilises the SSC. As previously described, during the SSC energy may be lost via heat dissipation, termed hysteresis. It could have been possible that the immediate, but non-significant decreases in TSK in the SX_AT and ASX_AT groups reflected a dissipation of heat from the AT region altogether. However, from a physiological perspective, it would make more sense that if the heat was dissipated from the AT during the SSC activity, that it would have increased the TSK in the more superficial tissues as the heat was radiated. This could explain the rapid but non-significant rise in TSK at the CD2 timepoint and reflected a delay in convective or conductive heat transfer from deep to superficial tissues (Luchakov & Nozdrachev, 2009), however, this theory is speculative.

It is possible that the immediate reduction in TSK was due to changes in blood flow, due to the energy demands of the ankle plantar flexor muscles during the hopping motion. Results from work conducted by Kubo et al. (2017) could support this. They found significant reductions in skin blood flow over the Achilles region in response to isometric contraction of the ankle plantar flexors. Baker et al. (2017) found that Gastrocnemius muscle blood flow increased by 108% ± 79% in response to treadmill walking, and Henry et al. (2015) found an increase of 116% ± 96% in response to plantarflexion contractions on a dynamometer. AT's that display tendinopathic changes are known to be more compliant and therefore less efficient during the SSC (Wang et al., 2012), therefore it is plausible that the metabolic demand from the Gastrocnemius-Soleus musculature may increase. It could be possible that blood flow distribution changed in response to the SLH activity to supply the metabolic needs of the Gastrocnemius-Soleus musculature, thus redirecting it away from the region of the AT. Future work should look to quantify both skin and muscle blood flow over the Gastrocnemius-Soleus musculature along with TSK and blood flow of the Achilles tendon.

Finally, Li & Hua (2016) posed an interesting theory, that the tensile forces that are generated through exercise cause a temporary block to blood flow through neovessels, which could provide the rationale as to why there was a small decrease in TSK as a result of the SLH task. Tensile forces during SLH are known to be large (Lichtwark & Wilson, 2005c). Coupled with the fact that midportion tendinopathy often occurs in a hypoxic environment, which does not allow for organised collagen deposition, it could create an ischemic environment within the tendon during exercise (Järvinen, 2020), which may explain why there was a TSK return to BL levels by timepoint CD2. However, neovessels are not present in all pathological tendons (De Marchi et al., 2018; Hucthison et al., 2020). Future work could look to explore the link

between neovascularisation and infrared thermal imaging to assess whether decreased in TSK reflect the presence of underlying neovessels within the midportion of the Achilles tendon.

#### 6.1.5.2 ΔTSK

There was a statistically significant group x time two-way interaction on ΔTSK values of the midportion of the Achilles tendon in response to a SLH intervention. The ΔTSK response was steady throughout the cooldown period, with the only consecutive statistically significant changes occurring between timepoints CD6-BL and CD8-BL with a mean ΔTSK of 0.2°C, however, the effect size was small (d=0.2) and the value did not exceed the MDC that was calculated in chapter 3 (Cohen, 1988; Lakens, 2013). Statistically significant simple main effects for timepoint existed within the control group with significant decreases in ΔTSK response from POST0-BL to CD5-Bl and CD8-BL, which indicated a delayed cooling response in the control participants compared with the symptomatic ones, however, neither of these exceeded the 0.5°C MDC value. There were also significant differences between timepoint CD4-BL to CD6-BL, CD8-BL and CD10-BL, due to a slight increase in mean ΔTSK. These changes were not seen in the SX_AT or ASX_AT groups. There were no statistically significant simple main effects of group at any of the time points which led to the rejection of hypotheses 6, 7 and 8.

#### 6.1.5.3 SLH frequency

There were no statistically significant differences in hopping frequency between the groups or across the sets which led to the rejection of hypothesis 9. This demonstrated that despite participants suffering from chronic midportion Achilles tendinopathy, they were able to maintain a SLH frequency of 2.5Hz. It was expected that symptomatic participants would have demonstrated a reduced SLH frequency as the sets progressed due to a decreased efficiency of the AT, however, this was found not to be the case. It is possible that symptomatic participants adapted their SLH strategy through stiffening the lower limb and hopping with greater ankle dorsiflexion to distribute force away from the AT and meet the 2.5Hz, however, there is only limited evidence for this theory and it would require further kinematic and kinetic investigation (Debenham et al., 2016; Sancho et al., 2019).

#### 6.1.5.4 SLH GCT

It was found that GCT was significantly shorter in the control group than the SX_AT and ASX_AT groups, with a mean difference of 0.02s to both. The effect sizes were large, d=0.8

and d=0.5 respectively. The mean differences of 0.02s exceeded the MDC value of 0.01s, therefore the difference is likely to represent true change and thus hypothesis 10 was accepted. No differences existed between the SX_AT's and ASX_AT's (d=0.4). Shorter GCT's have previously been associated with greater overall limb stiffness (Arampatzis, Brüggemann, & Klapsing, 2001) and increased AT stiffness (Abdelsattar et al., 2018). These results could support the finding that increased GCT's were found in the SX_AT's due to an increased AT compliance (Wang et al., 2012). It could also be possible that negative neuromuscular adaptations in response to Achilles tendinopathy could be present in the contralateral limb (ASX_AT) in line with suggestions by Rio et al. (2016), however further work is needed to investigate this suggestion. Rio et al. (2016) suggested that pathology could alter motor control of the asymptomatic limbs to maintain homeostasis in line with the symptomatic limb as a protective mechanism. This could explain the lack of difference in the symptomatic participants between limbs, but the statistically significant difference between those and the control group.

#### 6.1.5.5 SLH Flight time

Statistically significant differences in flight time existed between the SX_AT and control group during set 2 and set 3 which led to the acceptance of hypothesis 11. The control group displayed longer flight times by a mean of 0.02s on both occasions, exceeding the MDC value of 0.01s, with large effect sizes (d=1.2). The main effect of set also showed statistically significant differences as set 1 flight time was 0.01s shorter than set 3, although the effect size was trivial (d=0.06). The time difference of 0.01s seemed small, but when it is considered as a percentage of overall flight time, it equates to a 10% discrepancy. In contrast, the flight time in set 2 in the control group increased by 0.01s, evidenced with a small effect size (d=0.3). These results, combined with the results of the SLH height data, suggested that the efficiency of the control group tendons was higher than that of the SX_AT group.

#### 6.1.5.6 Hop height

Statistically significant differences existed between the groups during set 2 and set 3. During both sets, the control group hop height was a mean of 0.006m higher than the SX_AT group both with large effect sizes (d=1.5 and d=1.2 respectively). However, caution should be drawn interpreting these results as they did not exceed the calculated MDC value of 0.01m, therefore they could be attributed to random error, thus hypothesis 12 could not be accepted.

Differences were also seen between the ASX_AT and control group of 0.004m in both sets, with large and medium effect sizes (d=0.8 and d=0.7 respectively), however, these did not exceed the MDC value of 0.010m. During set 1, there were no statistically significant between-group differences.

There were statistically significant simple main effects for set in the SX_AT group but not the ASX_AT or control group. Mean hop height was 0.001m and 0.002m lower in set 2 and 3 respectively, with small and medium effect sizes (d=0.4, d=0.6), although these did not exceed the MDC value. Again, these hop height differences may seem small, but they were limited due to the requirement of the participants meeting the 2.5Hz SLH frequency and were similar to those found by McMahon (2015). Considering that the mean hop height of the control group was 0.02m across all 3 of the sets, these differences equated to discrepancies of 5-20% of total hop height. These results suggested that the SX_AT lost efficiency through the sets as there was a reduction in the height that the participant achieved across the sets.

#### 6.1.5.7 SLH RSI

The RSI in the control group was significantly larger than in both the SX_AT and ASX_AT groups, irrespective of set number, with the differences exceeding the MDC value of 0.002 therefore hypothesis 13 was accepted. When combined with the findings of hop height and GCT, this was to be expected, with hop height being greater in the control group during sets 2 and 3 compared to both the SX_AT and ASX_AT groups and GCT being quicker in the control group when compared to the SX_AT and ASX_AT groups. The differences between the control group and the SX_AT and ASX_AT groups irrespective of set number suggest that symptomatic participants were less efficient in their response to SSC demands, as they demonstrated a lower RSI equating to a slower SSC (McMahon et al., 2018).

In the SX_AT group, RSI also decreased between set 1 and set 3, with no significant differences found in the ASX_AT or control groups. The differences suggested a rapidly declining SSC function within the SX_AT which could be explained by fatigue, which was unlikely based upon the RPE scores, a declining efficiency of the musculotendinous unit or altered SLH strategy which may have affected SLH height and GCT (McMahon et al., 2018; Oliver, Lloyd, & Whitney, 2015).

Hopping at 2.5Hz is a slow SSC action, with a mean GCT across the groups of 0.29s (Flanagan & Comyns, 2008; Turner & Jeffreys, 2010). A pre-requisite of an efficient Achilles

tendon is a stiff muscular attachment and a tendon that can stretch and recoil, with importance being placed on the transition time between the two, with delays to this leading to energy being lost via hysteresis (Gruber et al., 2019). GCT in the control group was quicker by 0.02s when compared to the SX_AT and ASX_AT groups, leading to a larger RSI. It could be possible that this may explain why the SX_AT and ASX_AT's were less efficient, as the longer GCT's could allow for greater dissipation of energy (Abdelsattar et al., 2018). Longer GCT in the single-leg hop would increase the metabolic cost on the Gastrocnemius-Soleus musculature, which would lead to decreased RSI. Combined with the known reduction in stiffness with Achilles tendinopathy (Finnamore et al., 2019; Maquirriain, 2012), this could suggest greater hysteresis from the Achilles tendon (Lichtwark & Wilson, 2007).

However, this would not necessarily explain why there were no differences in RSI between the SX_AT and ASX_AT groups. Often in people suffering from tendinopathy, neuromuscular adaptations are present in both the ipsilateral and contralateral limb (Rio et al., 2016). It is possible that the lack of differences between the SX_AT and ASX_AT's demonstrated inhibition of the contralateral (ASX_AT) limb. This could also be evidenced by the mean peak GRF results.

#### 6.1.5.8 SLH mean peak GRF

There were no statistically significant two-way set x group interactions, however, there were statistically significant differences in mean peak GRF's between group's, irrespective of set number. The control group displayed mean peak GRF's 0.19 times bodyweight higher than the SX_AT group and 0.13 times bodyweight higher than the ASX_AT group, both with large effect sizes (d=1.1 and d=0.8 respectively). Caution should be drawn when interpreting these results as the values did not exceed the MDC value of 0.25 times bodyweight, therefore it cannot be said with certainty that these differences were not attributed to random error and hypothesis 14 was not accepted. No statistically significant differences existed between the SX_AT and ASX_AT groups. A previous systematic review has highlighted that no differences existed in the magnitude of GRF during running in symptomatic versus control participants (Munteanu & Barton, 2011), so finding these changes during SLH may be significant and reflect the importance of the healthy AT functioning as an optimal spring-like unit in SLH tasks. However, other studies have contradicted this and not identified any statistically significant changes in vertical GRF magnitude in those suffering from tendinopathy, but they have identified differences in both kinetics and kinematics (Azevedo et al., 2009; Becker et al.,

2017), It could be possible that NM inhibition occurred resulting in the symmetry between the SX_AT and ASX_AT's but presented statistically significantly different to controls as suggested by Rio et al. (2016). It is important to re-emphasise that the differences did not exceed the MDC values when compared to the control group and it cannot be said with certainty that they reflected true change however it warrants further investigation.

It is unlikely that tendon stiffness properties are responsible for the differences between the two groups, based on the work conducted by Chang & Kulig (2015). They found that pathological tendons were significantly more compliant than non-pathological. Previous work has shown a relationship between stiff AT's and shorter GCT (Abdelsattar et al., 2018). Other research has suggested that when stiffness increases at higher hop frequencies, peak GRF reduces due to a shorter GCT (McMahon, 2015; Wong, Chaouachi, Dellal, & Smith, 2012). Therefore, it would be expected that more compliant SX_AT tendons would experience larger GRF than ASX_AT and control due to the longer GCT displayed. However, it could be possible that symptomatic participants adopted a different hop strategy, such as stiffer overall limb (Debenham et al., 2016) which may have prolonged GCT but reduced the overall GRF by using the knee joint muscles to absorb some of the force during the braking phase of hopping. Further, the findings from the control group do not fit with the research from McMahon, (2015) and Wong, Chaouachi, Dellal, & Smith, (2012) as they had higher GRF's with shorter GCT's. This finding highlights the need to conduct kinetic and kinematic analysis on vertical SLH between symptomatic and asymptomatic Achilles tendinopathy patients.

Another possibility is that muscle weakness may have contributed to the difference in RSI between the SX/ASX_AT and control group, but not between the SX_AT and ASX_AT groups. Again, this could be explained by neuromuscular inhibition (Rio et al., 2016). Additionally, due to the severity of symptoms, symptomatic participants may have altered their normal training regimes, which may have led to reduced strength levels, which has previously been found in those with midportion tendinopathy (O'Neill, Barry, et al., 2019).

#### 6.1.5.9 Limitations

This study was not without limitation. The COVID-19 outbreak affected the recruitment of control participants. Initially, the aim was to recruit 38 participants (19 per group). The SX recruitment process was ceased at 21 SX participants and 17 control

participants were recruited before the national lockdown. 4 control participants were lost due to the outbreak which would have created equal sample sizes in each group.

A second limitation was that participants had to walk from the hopping area to the thermal testing area and have their markers reattached before the POST0 thermal images being taken. This was a distance of 3m and the time taken was less than 60 seconds. It is possible that there was TSK change within that time. It was not possible to conduct the hopping trials with the anatomical markers in place as they often fell off during pilot testing, which created a hazard if they landed on the force plate. It could be possible that future methods that are developed may be able to reduce this timeframe and capture any immediate thermal changes post-hopping.

### 6.1.6 Conclusion

To conclude this section, there were no statistically significant between-group differences in absolute or ΔTSK despite a decrease in AT midportion TSK in the SX_AT and ASX_AT when compared to the control group. There appeared to be a statistically significant rise in absolute TSK following the SLH intervention for 5 minutes before TSK began to decrease and all further differences then lay within the MDC value of the IRC.

There were no between-group ΔTSK differences following the SLH intervention. Despite there being no statistically significant differences between groups, there appeared to be a different profile between the symptomatic participants compared to the control. As no existing data is available, at this moment in time it is not clear whether this is clinically meaningful. Therefore, it is necessary to further this research to see the absolute and ΔTSK response following a rehabilitation intervention.

Significant differences between sets and groups existed for some kinetic and kinematic variables associated with SLH. GCT between the SX_AT and control group, and ASX_AT and control group, flight time between the SX_AT and control group during sets 2 and 3 and for RSI in the SX_AT versus the control group and ASX_AT versus the control in sets 2 and 3. Significant differences did not exceed the MDC for hop height and GRF. Kinetic and kinematic variables must be assessed in those suffering from chronic midportion Achilles tendinopathy in response to a rehabilitation intervention.

## 6.2 A comparison of skin temperature and symptom response during SLH task between matched controls and Achilles tendinopathy patients exposed to a 12-week HSR training programme

### 6.2.1 Introduction

In the previous section, it was identified that despite there being no statistically significant differences between the groups in terms of absolute and ΔTSK response, with small effect sizes, there was a trend for a decrease in TSK when compared with the control group and when compared with the TSK response following the 15-minute running intervention in section 5.1.

Several theories for why the immediate decrease occurred have been proposed; hysteresis, blood flow changes and temporary blockages of blood vessels due to tensile forces. In section 5.2 following a 12-week HSR programme, there was a "more normalised" absolute and ΔTSK response following the 12-week HSR programme. As a contrasting TSK response was identified in the previous section following SLH activity, it will be interesting to investigate TSK once the 12-week HSR rehabilitation has been completed in the hopping participants, alongside monitoring symptom change, to see if both normalise.

The present study (section 5.3), has highlighted its success in managing runners with Achilles tendinopathy with a mean 20.4 ± 8.3 point clinically significant improvement in VISA-A scores. Despite the success in managing symptoms, little is known about the physiological effects of HSR on the AT, however, it may be possible to identify physiological changes that are represented at the surface of the skin via heat, using infrared thermal imaging. Further, little is known about how a 12-week HSR programme affects kinetic and kinematic variables that are associated with SLH in those who have been rehabilitated from Achilles tendinopathy which will be addressed in section 6.3.

Therefore, this study aimed to establish the TSK response of the midportion of the AT in response to a SLH intervention following a 12-week HSR rehabilitation programme for Achilles tendinopathy.

### 6.2.2 Hypotheses

1. There would be a statistically significant difference in absolute TSK of the midportion of the AT from timepoint BL to POST0 in each of the groups

2. There would be a statistically significant difference in absolute TSK of the midportion of the AT from timepoint POST0 to CD10 in all groups
3. There would be a statistically significant difference in absolute TSK values between the SX_AT and ASX_AT's in response to the SLH intervention
4. There would be a statistically significant difference in TSK between the SX_AT and control AT's in response to the SLH intervention
5. There would be a statistically significant difference in TSK between the ASX_AT and control AT's in response to the SLH intervention
6. There would be a statistically significant difference in ΔTSK response between the SX_AT and control AT's in response to the SLH intervention
7. There would be a statistically significant difference in ΔTSK response between the ASX_AT and control AT's in response to the SLH intervention
8. There would be a statistically significant difference in ΔTSK response between the SX_AT and ASX_AT's in response to the SLH intervention

### 6.2.3 Methods

The methods used in this section follow the methods outlined in chapter three unless otherwise stated.

#### 6.2.3.1 Sample size calculation

The sample size calculation was as stated in section 5.2.3.1.

#### 6.2.3.2 Participant recruitment

As stated in section 3.6.2.2. A CONSORT flowchart detailing recruitment can be seen in figure 6.2.1. Participant anthropometrics can be seen in table 6.2.1. Control participants were age and gender-matched to the n=9 participants who completed the HSR programme. There were no statistically significant differences in participant anthropometrics as assessed by independent samples t-tests ($p>0.05$). WK0 mean VISA-A, NPRS during and after activity and RPE scores can be seen for the SX and control participants in table 6.2.2. Participant exercise hours can be seen in table 6.2.3.

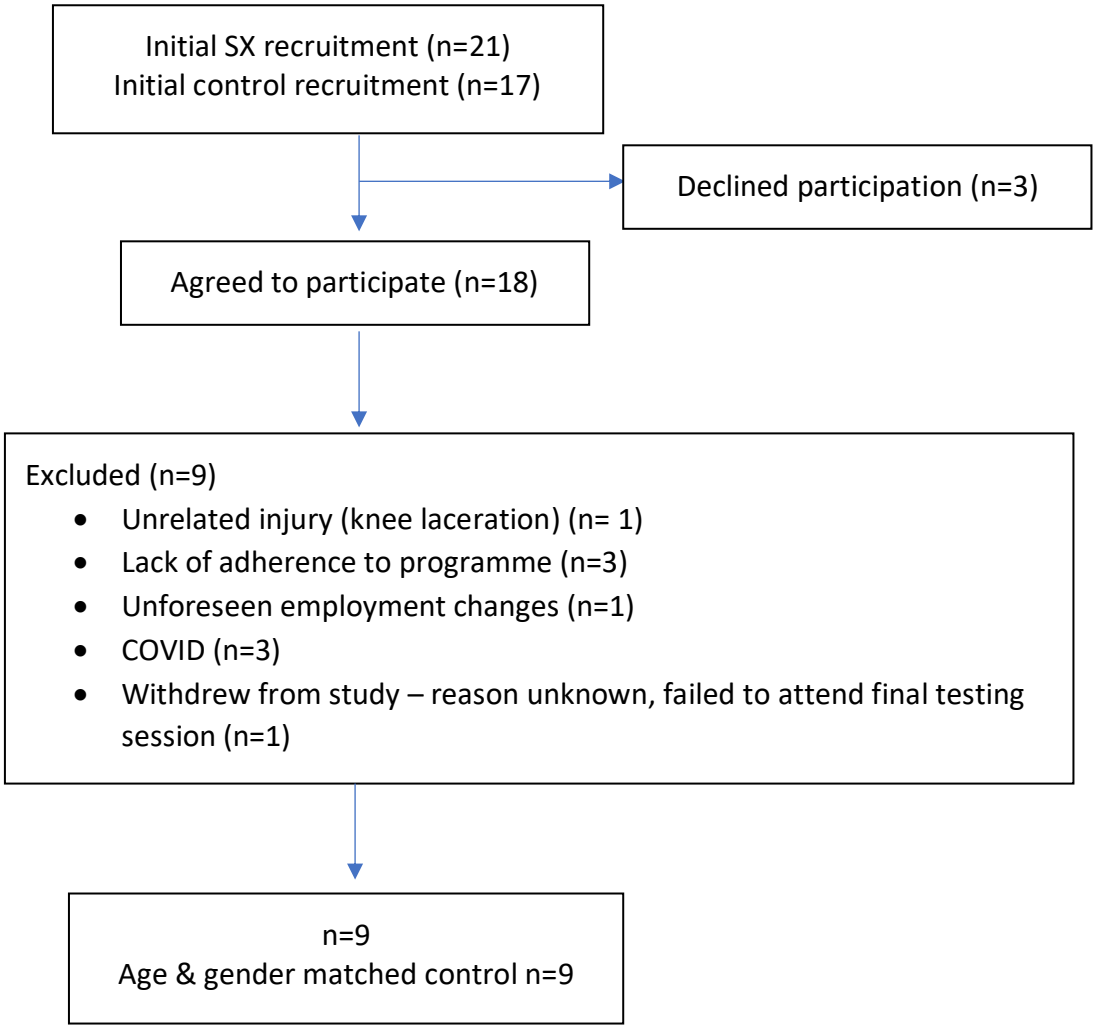



Figure 6.2.1: CONSORT flowchart outlining participant recruitment

Table 6.2.1: Participant anthropometrics

| Group | Mean age ± SD (years) | Mean height ± SD (cm) | Mean mass ± SD (kg) |
|---|---|---|---|
| SX | 40.8 ± 11.0 | 174.6 ± 8.6 | 76.1 ± 14.8 |
| Control | 39.6 ± 12.0 | 178.0 ± 10.0 | 74.0 ± 11.9 |

Table 6.2.2: Mean and SD data for VISA-A, NPRS and RPE for SLH participants at baseline

| Outcome measure | SX mean ± SD | Control mean± SD |
|---|---|---|
| VISA-A | 81.4 ± 11.5 | 100.0 ± 0.0 |
| NPRS During | 2.9 ± 2.9 | 0.0 ± 0.0 |
| NPRS After | 1.3 ± 1.7 | 0.0 ± 0.0 |
| RPE | 3.1 ± 2.4 | 3.6 ± 0.9 |

Table 6.2.3: SLH participant exercise hours

| **Hours** | **SX** | **Control** |
|---|---|---|
| 3-6 | 5 | 3 |
| 6-9 | 2 | 5 |
| 10+ | 2 | 1 |
| **Total Number** | **9** | **9** |

#### 6.2.3.3 Room temperature

Measured as stated in section 3.6.2.5. The mean room temperature during week 12 testing was 21.1 ± 0.8°C and the mean humidity was 41.6 ± 8.0%.

#### 6.2.3.4 Clinical assessment

Participants underwent a repeat clinical assessment during week 4, week 8 and week 12. The assessment was a repeat of the subjective and objective clinical examination that was outlined in section 3.6.

#### 6.2.3.5 SLH task

Participants returned on a second day (within 7 days) of testing following their clinical assessment to conduct the SLH intervention. They underwent a 15-minute acclimatisation period, as outlined in section 3.6.2.7, before conducting 3 sets of 20 barefoot hops at a frequency of 2.5Hz as stated in section 6.1.3.5.

#### 6.2.3.6 Thermal data capture

Thermal data capture was conducted as stated in section 3.6.2.10. Thermal images were taken at 8 time points per participant (BL, POST0, CD2, CD4, CD5, CD6, CD8 and CD10). In total, 72 infrared thermal images were taken for the SX hoppers, and 72 images were used for analysis from the age and gender-matched control participants.

#### 6.2.3.7 Statistical analysis

Normality was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise($p>0.05$). Homogeneity of variances was assessed using Levene's test and the assumption was met unless stated otherwise ($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

Data were not normally distributed ($p<0.05$). Separate non-parametric Mann-Whitney U tests were run for each variable to assess if there were differences in scores between SX and control participants.

A factorial mixed ANOVA (8x3) was used to assess the differences in TSK values following the hopping intervention, with timepoint (BL, POST0, CD2, CD4, CD5, CD6, CD8, CD10) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subjects independent variable. Mauchly's test of sphericity was violated ($x^2$ (27) = 236.472, $p<0.001$) therefore Greenhouse-Geisser corrected results were reported.

ΔTSK scores were calculated by subtracting the absolute TSK value from BL. A factorial mixed ANOVA (7x3) was run on ΔTSK response for each of the 7 pairs of time points, to see if the responses differed between groups, with timepoint (POST0-BL, CD2-BL, CD4-BL, CD5-BL, CD6-BL, CD8-BL, CD10-BL) as the within-subjects independent variable and group (SX_AT, ASX_AT, Control) as the between-subject independent variable. Mauchly's test of sphericity was violated ($x^2$ (20) = 219.840, $p<0.001$) therefore Greenhouse-Geisser corrected results were reported.

### 6.2.4 Results

#### 6.2.4.1 HSR adherence

There was a 55.6% (5/9) success rate for participants returning their HSR exercise log at the end of the 12 weeks. 3 out of 9 participants did not return their log of exercise following

the programme. At each of the 4-weekly clinical follow-up sessions, the adherence to the programme was checked and these participants were following the programme as outlined through discussion or visual checking of the participant log.

Out of the 5 returned exercise log forms, there were a total of 173 out of 180 completed rehab sessions as outlined in the programme. There was a total of 11 modified HSR sessions and 7 non-completed. 5 of the modified sessions were as a result of increased pain in the AT at the start of week 6, when the block changed, and repetitions reduced to 4x8 but the weight increased. As a result of this, the participant reduced the weight increment, although they remained higher than the previous block. The remaining modified sessions were due to either broken or unavailable equipment at their respective gyms.

Mean RPE and NPRS data for each block of the HSR programme can be seen in table 6.2.4.

Table 6.2.4: Mean RPE and NPRS data for the 12-week HSR programme

| **Block** | **Mean RPE ± SD** | **Mean NPRS ± SD** |
|---|---|---|
| 1 (Week 1) | 3.9 ± 1.5 | 2.6 ± 1.2 |
| 2 (Weeks 2 & 3) | 4.3 ± 1.3 | 3.2 ± 1.3 |
| 3 (Weeks 4 & 5) | 4.2 ± 1.5 | 3.1 ± 1.3 |
| 4 (Weeks 6, 7 & 8) | 4.3 ± 1.5 | 2.7 ± 1.4 |
| 5 (Weeks 9, 10, 11 & 12) | 3.9 ± 2.4 | 1.7 ± 1.3 |

#### 6.2.4.2 VISA-A, NPRS and RPE

The results from the Mann Whitney U-test for VISA-A, NPRS and RPE can be seen in table 6.2.5

Table 6.2.5: Mean and SD data for VISA-A, NPRS and RPE for SLH participants at week 12

| Outcome measure | SX mean ± SD | Control mean± SD | SX median | Control median | p-value |
|---|---|---|---|---|---|
| VISA-A | 96.6 ± 7.4 | 100.0 ± 0.0 | 100.0 | 100.0 | 0.436 |
| NPRS During | 1.1 ± 2.0 | 0.0 ± 0.0 | 0.0 | 0.0 | 0.258 |
| NPRS After | 0.6 ± 1.7 | 0.0 ± 0.0 | 0.0 | 0.0 | 0.730 |
| RPE | 1.8 ± 1.9 | 3.6 ± 0.9 | 1.0 | 4.0 | **0.014*** |

***Denotes significance (p>0.05)**

There was no statistically significant difference in VISA-A scores between SX and control participants at the week 12 testing session, U=49.500, z=1.455, p=0.436. The results can be seen in table 6.2.5.

There were statistically significant differences in mean RPE score between the SX and control participants at the week-12 testing session U=68.000, z=2.522, p=0.014. The results can be seen in table 6.2.5.

There were no statistically significant differences in NPRS score during the SLH activity in the week 12 testing session, U=27.000, z=-1.835, p=0.258. The results can be seen in table 6.2.5.

There were no statistically significant differences in NPRS scores recorded after activity at the week 12 testing session between the SX and control groups U=36.000, z= -1.000, p=0.730. The results can be seen in table 6.2.5.

#### 6.2.4.3 Absolute TSK

Table 6.2.6 shows the mean TSK results from the week 12 testing session. Figure 6.2.2 shows a graphical representation of the mean TSK response of each group.

Table 6.2.6: Mean TSK data for SLH participants week 12

| Time | Group | Mean TSK (°C) | SD (°C) | ΔTSK from BL (°C) | SD (°C) |
|---|---|---|---|---|---|
| BL | SX | 26.8 | 2.2 | - | - |
| | ASX | 27.1 | 2.2 | - | - |
| | Control | 26.9 | 2.3 | - | - |
| | Mean | **26.9** [a] | 2.2 | - | - |
| POST0 | SX | 25.4 | 2.3 | -1.4 | 2.5 |
| | ASX | 24.5 | 2.9 | -2.6 | 3.5 |
| | Control | 26.8 | 1.9 | 0.0 | 0.8 |
| | Mean | **25.9** [a] | 2.4 | -1.0 | 2.4 |
| CD2 | SX | 26.7 | 2.0 | -0.1 | 1.8 |
| | ASX | 26.2 | 2.4 | -0.9 | 2.4 |
| | Control | 26.8 | 2.1 | -0.1 | 0.5 |
| | Mean | 26.6 | 2.1 | -0.3 | 1.5 |
| CD4 | SX | 26.8 | 2.1 | 0.0 | 1.9 |
| | ASX | 26.2 | 2.3 | -0.9 | 2.0 |
| | Control | 27.0 | 1.9 | 0.1 | 0.9 |
| | Mean | **26.8** [b] | 2.0 | **-0.2** [c] | 1.5 |
| CD5 | SX | 26.7 | 2.1 | -0.1 | 1.9 |
| | ASX | 26.1 | 2.2 | -1.0 | 1.9 |
| | Control | 26.8 | 2.0 | -0.1 | 0.8 |
| | Mean | 26.6 | 2.0 | -0.3 | 1.5 |
| CD6 | SX | 26.6 | 2.3 | -0.2 | 1.9 |
| | ASX | 26.1 | 2.3 | -1.0 | 2.0 |
| | Control | 26.7 | 1.9 | -0.2 | 0.9 |
| | Mean | 26.5 | 2.0 | -0.4 | 1.5 |
| CD8 | SX | 26.4 | 2.3 | -0.5 | 1.8 |
| | ASX | 26.0 | 2.2 | -1.1 | 1.7 |
| | Control | 26.6 | 2.0 | -0.2 | 0.9 |
| | Mean | **26.4** [b] | 2.1 | **-0.5** [c] | 1.4 |
| CD10 | SX | 26.5 | 2.1 | -0.3 | 1.8 |
| | ASX | 26.3 | 1.9 | -0.8 | 1.6 |
| | Control | 26.6 | 1.9 | -0.2 | 0.9 |
| | Mean | 26.5 | 1.9 | -0.4 | 1.4 |

[a] [b] denotes statistical significance for mean absolute TSK (irrespective of group) between timepoints ($p<0.05$)

[c] denotes statistical significance for mean ΔTSK (irrespective of group) between timepoints ($p<0.05$)


**Key: BL (baseline), POST0 (Immediately post activity), CD (cooldown + minute)**

Figure 6.2.2: Age and Gender matched controls week 12 TSK response to SLH

The two-way mixed ANOVA revealed that there was no statistically significant group x time two-way interaction on TSK values of the midportion of the Achilles tendon in response to a SLH intervention, following a 12-week HSR rehabilitation programme ($F_{(5.186,85.563)}$ = 2.159, p=0.064, partial $\eta^2$ = 0.116). The main effect of time showed a statistically significant difference irrespective of group ($F_{(2.593,85.563)}$ = 5.958, p=0.002, partial $\eta^2$ = 0.153). Pairwise comparisons revealed statistically significant TSK differences between timepoints BL and POST0 (p=0.037). Timepoint CD4 was statistically significantly different than timepoint CD8 (p=0.027).

There was no statistically significant main effect of group, irrespective of timepoint ($F_{(2,33)}$ = 0.379, p=0.688, partial $\eta^2$ = 0.022).

#### 6.2.4.4 ΔTSK

Mean ΔTSK response can be seen graphically in figure 6.2.3 and numerically in table 6.2.6. The results of the two-way mixed ANOVA for ΔTSK response revealed no significant two-way group x timepoint interaction following the SLH intervention ($F_{(3.440,56.757)}$ = 2.243, p=0.085, partial $\eta^2$ = 0.120). The main effect of time showed a statistically significant difference irrespective of group ($F_{(1.720,56.757)}$ = 6.138, p<0.001, partial $\eta^2$ = 0.157). Pairwise comparisons revealed statistically significant (p=0.020) TSK differences between timepoints CD4 and CD8.

There was no statistically significant main effect of group for ΔTSK response, irrespective of timepoint ($F_{(2,33)}$ = 0.379, p=0.688, partial $\eta^2$ = 0.022).

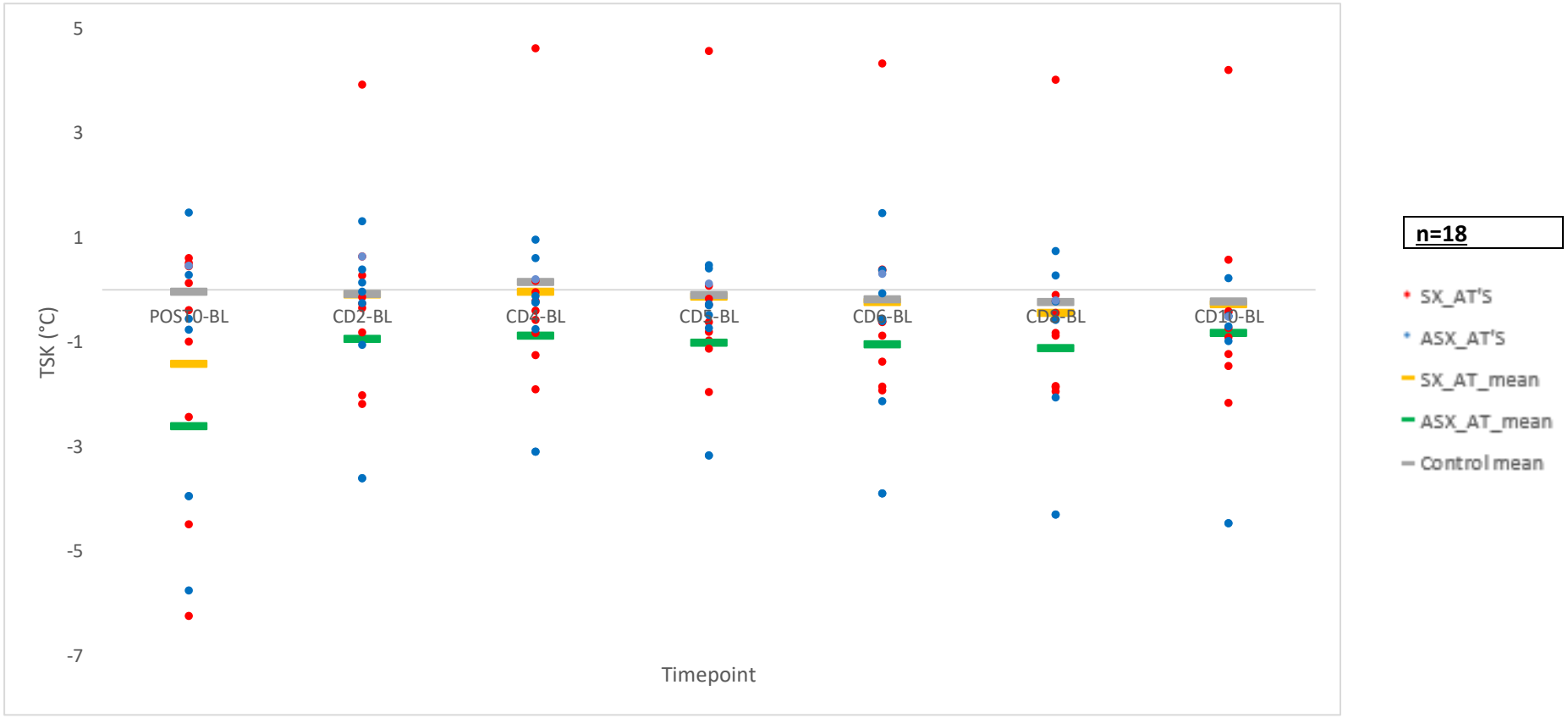



Figure 6.2.3: Age and Gender matched controls week 12 ΔTSK response to SLH

### 6.2.5 Discussion

The main purpose of this study was to establish the effect of a 12-week HSR programme on the TSK response of the AT midportion to a SLH task. The main findings of this study were:

1. There was a statistically significant TSK decrease following the SLH task between timepoints BL and POST0 irrespective of group.
2. There were no between-group differences in absolute TSK response of the midportion of the AT in response to the SLH task.
3. There were no significant between-group differences in ΔTSK response of the midportion of the AT in response to the SLH task.
4. There was a statistically significant difference in RPE scores between the SX and control participants.
5. There were no significant differences between the SX and control participants in VISA-A scores or NPRS scores during and after activity.

#### 6.2.5.1 Absolute TSK

There was no statistically significant two-way group x timepoint interaction following the SLH intervention. The results revealed that there was a main effect of timepoint, with pairwise comparisons showing a statistically significant difference in absolute TSK of 1.4°C (95% CI 0.0°C – 2.7°C) between BL and POST0 with a large effect size (d=0.8), which led to the acceptance of hypothesis 1. Hypothesis 2 was rejected as there was not a statistically significant decrease in absolute TSK across the cooldown period. There was a statistically significant difference between timepoint CD4 and CD8, with a mean difference of 0.4°C (95% CI 0.0°C 0 0.7°C), with a small effect size (d=0.2). This difference also fell within the MDC of the camera therefore this may not represent true change. There were no between-group differences for absolute TSK between any of the groups, therefore this led to the rejection of hypotheses 3, 4 and 5.

The response demonstrated following the SLH activity led to the acceptance of hypothesis 1, that there was a statistically significant difference in absolute TSK irrespective of group, however, the larger decrease in TSK was unexpected. Based on the results of the running cohort (section 5.2), it was expected that following the 12-week HSR training

programme an increase in TSK would have been seen and following the programme there would have been a more “normalised” TSK response in comparison to the control group.

In section 6.1, one of the first explanations for an initial but statistically insignificant TSK decrease was that the level of exercise may not have been high enough to elicit a significant increase in temperature. Whilst this may be true, it is unlikely to be the case for the greater decrease in TSK seen between timepoints BL and POST0 in the current section.

Another suggestion made was that the immediate reduction in TSK over the AT midportion was due to changes in blood flow, with increased metabolic demand from the Gastrocnemius-Soleus musculature in the symptomatic AT’s. However, following the 12-week HSR programme the decrease in absolute TSK between the two-time points was statistically significant, irrespective of the group. It, therefore, seems unlikely that metabolic demand from the Gastrocnemius-Soleus musculature was responsible for the decrease as slow sustained loading should have led to a more efficient musculotendinous unit and thus reduce the demand on the musculature to do work during the SSC action (Docking & Cook, 2019).

The theory by Li & Hua (2016) regarding tensile forces creating a temporary block to blood flow through neovessels which are already hyperpermeable and lack proper perfusion (Järvinen, 2020), could still explain the decreases seen in the SX_AT and ASX_AT groups compared with the initial control group response. Achilles tendinopathy is closely linked to hypoxia, with elements of the histopathology and high levels of lactate only being present in hypoxic environments, which have not been found in healthy control tendons (Järvinen, 2020). Therefore, despite positive symptom change as a result of the 12-week HSR programme, it could be possible that the hypoxic environment was not improved, possibly reflected by decreased TSK, and may point towards biomechanical properties being responsible for the increased functional change, opposed to physiological ones. However, this is speculative and would need further investigation of both physiological and biomechanical properties to confirm and could shape future study.

#### 6.2.5.2 ΔTSK

There was no statistically significant group x time two-way interaction for ΔTSK response following the SLH intervention at week 12. The main effect of timepoint was statistically significant (p=0.020) for timepoints CD4-BL and CD8-BL with a mean difference of 0.3°C, however, the effect size was small (d=0.3) and the change fell within the MDC. It is

unknown why there was a statistically significant difference between these two time points, but the general trend in the SX_AT and ASX_AT groups was that the ΔTSK response at timepoint CD4-BL was the closest to BL values, whereas there were greater differences at timepoint CD8-BL in all groups. There were no between-group differences for ΔTSK response, which led to the rejection of hypotheses 6 and 7.

#### 6.2.5.3 VISA-A, NPRS and RPE

There were no statistically significant differences in VISA-A or NPRS score during or after activity. This is a different finding to section 6.1, and it suggested that symptoms of Achilles tendinopathy have reduced significantly in SX participants following the 12-week HSR programme. Interestingly, the RPE scores were significantly different, with SX participants finding the SLH task a mean of 1.8 points easier than the control group, in contrast to week 0 when there were no differences present.

The HSR programme may alter the biomechanical and physiological properties of the AT in SX participants. Kongsgaard et al. (2010) found that the stiffness of the patella tendon decreased following a 12-weeks HSR programme. It is possible that if stiffness changes occurred in the AT as a result of the programme, it could have created greater mechanical efficiency of the AT leading to a reduction of pain and increased function (Groeber et al., 2019). Beyer et al. (2015) found decreased A-P thickness and neovascularisation properties of the AT following a 12-week HSR programme, both of which could also lead to decreased pain in the region, however, this link needs further investigation due to the lack of relationship found between neovascularisation and clinical symptoms in previous research (De Jonge et al., 2014).

#### 6.2.5.4 Limitations

A limitation of this study was that the control participants did not complete the 12-week HSR programme. The main reason for this was it was extremely difficult to get them to commit to the gym-based programme as many of them were not members of local gyms. With many of the participants, conversations were had about the benefit of strength training for runners, however many still did not want to pay monthly membership costs or reduce their number of running hours. This highlighted an area that could be addressed with future study.

### 6.2.6 Conclusion

To conclude this section, following the 12-week HSR programme for midportion Achilles tendinopathy, there were significant immediate decreases in TSK in response to the SLH intervention which exceeded the MDC value, irrespective of group, between timepoints BL and POST0. No between-group differences existed for absolute TSK response of the midportion of the AT across any timepoints. No significant between-groups differences existed for ΔTSK response.

The results following the 12-week HSR rehabilitation programme changed the TSK response in the SX_AT and ASX_AT groups, with more timepoint main effects being present at week 0 than at week 12.

The results revealed that there were no significant differences between the groups in VISA-A scores or NPRS scores during or after activity. A significant difference was observed between RPE scores, with the control group finding that SLH activity was more difficult than the SX group who had undergone the 12-week HSR programme.

## 6.3 A comparison of kinetics and kinematics during SLH task between matched controls and Achilles tendinopathy patients exposed to a 12-week HSR training programme

### 6.3.1 Introduction

Section 6.1 identified differences in kinematic and kinetic variables in those suffering from chronic midportion Achilles tendinopathy. Those suffering from the condition are thought to have negative pathological (Cook et al., 2016; Dakin et al., 2018; Klatte-Schulz et al., 2018) and biomechanical changes to the tendon (Arya & Kulig, 2010; Chang & Kulig, 2015).

HSR training has been used as an exercise-based rehabilitation programme to successfully manage tendinopathy of the Achilles and Patella tendons (Beyer et al., 2015; Kongsgaard et al., 2010). The present study (section 5.3), has highlighted its success in managing runners with Achilles tendinopathy with a mean 20.4 ± 8.3 point statistically and clinically significant improvement in VISA-A scores, as well as improving NPRS scores during activity close to statistical significance (p=0.06).

Beyer et al. (2015) identified that a 12-week programme of resistance exercise significantly decreased AT A-P thickness over time, but this did not differ between HSR or eccentric exercise groups. Similarly, Kongsgaard et al. (2010) identified patella tendon cross-sectional area and stiffness changes in symptomatic patients who had undergone the 12-weeks HSR programme. With physiological adaptations occurring to AT's as a result of HSR training, this may lead to biomechanical and functional changes with regards to patient performance.

Despite the success in managing symptoms clinically, little is known about the biomechanical effects of HSR on the AT. However, it may be possible to identify biomechanical changes that occur through the measurement of kinetic and kinematic variables that are associated with SLH in those who have been rehabilitated from Achilles tendinopathy.

Therefore, this study aimed to assess kinetic and kinematic variables associated with SLH following the 12-week HSR programme.

### 6.3.2 Hypotheses

1. There would be a statistically significant difference in SLH frequency between the SX and control participants in response to the SLH intervention

2. There would be a statistically significant difference in SLH GCT between the SX and control participants in response to the SLH intervention
3. There would be a statistically significant difference in SLH flight time between the SX and control participants in response to the SLH intervention
4. There would be a statistically significant difference in SLH height between the SX and control participants in response to the SLH intervention
5. There would be a statistically significant difference in SLH RSI between the SX and control participants in response to the SLH intervention
6. There would be a statistically significant difference in SLH GRF between the SX and control participants in response to the SLH intervention

### 6.3.3 Methods

The methods used are as stated in section 6.2. The only addition to this section is the statistical approach for analysis hopping kinetic and kinematic data. This followed the approach outlined in section 6.1.3.9 for each SLH characteristic.

### 6.3.4 Results

#### 6.3.4.1 SLH frequency

Mean hopping frequencies can be seen in table 6.3.1. There was no statistically significant two way set x group interaction for hopping frequency ($F_{(4,66)}$ = 1.946, p=0.113, partial $\eta^2$ = 0.105). There were no statistically significant simple main effects for group ($F_{(2,66)}$ = 0.647, p=0.527, partial $\eta^2$ = 0.019) or set number ($F_{(2,33)}$ = 1.539, p=0.046, partial $\eta^2$ = 0.003).

#### 6.3.4.2 SLH GCT

Mean hopping GCT's can also be seen in table 6.3.1. There was no statistically significant two-way interaction between set number and group for hopping GCT ($F_{(4.66)}$ = 1.831, p=0.133, partial $\eta^2$ = 0.100). There was a statistically significant main effect for set number on GCT during the hopping trials ($F_{(2,66)}$ = 5.559, p=0.006, partial $\eta^2$ = 0.144). Pairwise comparisons revealed a statistically significant mean difference in GCT between set 1 and set 2 (p=0.023) and set 1 and set 3 (p=0.044). Mean hop GCT was higher in set 1 than in set 2 and 3 by 0.006s (d=0.4).

There were no statistically significant simple main effects for group ($F_{(2,33)}$ = 0.183, p=0.833, partial $\eta^2$ = 0.011).

Table 6.3.1: Mean week 12 SLH characteristics

| Set Number | Group | Mean Freq. (Hz) | SD Freq. (Hz) | Mean GCT (s) | SD GCT (s) | Mean Flight Time (s) | SD Flight Time (s) | Mean Hop Height (m) | SD Hop Height (m) | Mean RSI | SD RSI | Mean peak GRF (BW) | SD peak GRF (BW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SX_AT | 2.51 | 0.09 | 0.29 | 0.02 | 0.11 | 0.02 | 0.01 | 0.01 | 0.05 | 0.03 | 2.28 | 0.26 |
| | ASX_AT | 2.52 | 0.05 | 0.29 | 0.01 | 0.11 | 0.01 | 0.01 | 0.00 | 0.05 | 0.01 | 2.30 | 0.26 |
| | Control | 2.50 | 0.06 | 0.29 | 0.01 | 0.11 | 0.01 | 0.02 | 0.01 | 0.06 | 0.01 | 2.41 | 0.09 |
| | Mean | 2.51 | 0.07 | **0.29**[ab] | 0.01 | **0.11**[cd] | 0.01 | **0.01**[ef] | 0.01 | **0.05**[gh] | 0.02 | **2.33**[i] | 0.20 |
| 2 | SX_AT | 2.49 | 0.09 | 0.29 | 0.03 | 0.11 | 0.02 | 0.02 | 0.01 | 0.06 | 0.03 | 2.33 | 0.29 |
| | ASX_AT | 2.49 | 0.06 | 0.28 | 0.02 | 0.12 | 0.03 | 0.02 | 0.01 | 0.06 | 0.03 | 2.36 | 0.27 |
| | Control | 2.52 | 0.06 | 0.28 | 0.01 | 0.12 | 0.01 | 0.02 | 0.00 | 0.06 | 0.01 | 2.45 | 0.14 |
| | Mean | 2.50 | 0.07 | **0.28**[a] | 0.02 | **0.12**[c] | 0.02 | **0.02**[e] | 0.01 | **0.06**[g] | 0.02 | **2.38**[i] | 0.23 |
| 3 | SX_AT | 2.51 | 0.07 | 0.29 | 0.03 | 0.11 | 0.03 | 0.02 | 0.01 | 0.06 | 0.05 | 2.32 | 0.33 |
| | ASX_AT | 2.50 | 0.04 | 0.28 | 0.03 | 0.12 | 0.03 | 0.02 | 0.01 | 0.07 | 0.05 | 2.37 | 0.31 |
| | Control | 2.50 | 0.03 | 0.29 | 0.01 | 0.12 | 0.01 | 0.02 | 0.01 | 0.06 | 0.02 | 2.44 | 0.12 |
| | Mean | 2.50 | 0.05 | **0.29**[b] | 0.02 | **0.12**[d] | 0.02 | **0.02**[f] | 0.01 | **0.06**[h] | 0.04 | 2.38 | 0.25 |
| Mean | SX_AT | 2.50 | 0.08 | 0.29 | 0.03 | 0.11 | 0.02 | 0.02 | 0.01 | 0.06 | 0.04 | 2.31 | 0.29 |
| | ASX_AT | 2.50 | 0.05 | 0.28 | 0.02 | 0.12 | 0.02 | 0.02 | 0.01 | 0.06 | 0.03 | 2.34 | 0.28 |
| | Control | 2.51 | 0.05 | 0.29 | 0.01 | 0.12 | 0.01 | 0.02 | 0.01 | 0.06 | 0.01 | 2.43 | 0.12 |
| | Mean | 2.50 | 0.06 | 0.29 | 0.02 | 0.12 | 0.02 | 0.02 | 0.01 | 0.06 | 0.03 | 2.36 | 0.23 |

[a b c d e f g h i] denotes statistically significant simple main effect for set number ($p<0.05$)

#### 6.3.4.3 SLH flight time

Mean hopping flight time can be seen in table 6.3.1. There was no statistically significant two-way interaction between set number and group for hopping flight time ($F_{(3.160, 52.138)} = 1.157$, p=0.338, partial $\eta^2 = 0.066$). There was a statistically significant main effect for set number on flight time during the hopping trials ($F_{(1.580,52.138)} = 8.202$, p=0.002, partial $\eta^2 = 0.199$). Pairwise comparisons revealed a statistically significant mean difference in flight time between set 1 and set 2 (p=0.003) and set 1 and set 3 (p=0.020). Mean hop flight time was longer in set 1 than in set 2 and 3 by 0.006s and 0.007s respectively (d=0.5 and d=0.4 respectively).

There were no statistically significant main effects for group ($F_{(2,33)} = 0.222$, p=0.802, partial $\eta^2 = 0.013$).

#### 6.3.4.4 SLH height

Mean hop height data can be seen in table 6.3.1. There was no statistically significant two-way interaction between set number and group for hopping height ($F_{(4,66)} = 1.762$, p=0.147, partial $\eta^2 = 0.096$). There was a statistically significant main effect for set number on hop height during ($F_{(2,66)} = 7.316$, p=0.001, partial $\eta^2 = 0.181$). Pairwise comparisons revealed a statistically significant mean difference in hop height between set 1 and set 2 (p=0.003) and set 1 and set 3 (p=0.023). Mean hop height was lower in set 1 than in set 2 and 3 by 0.004m and 0.003m respectively (d=0.7 and d=0.5 respectively).

There were no statistically significant simple main effects for group ($F_{(2,33)} = 0.085$, p=0.918, partial $\eta^2 = 0.005$).

#### 6.3.4.5 SLH RSI

Mean hopping RSI can be seen in table 6.3.1. There was no statistically significant two-way set x group interaction ($F_{(2.541,41.925)} = 1.226$, p=0.310, partial $\eta^2 = 0.069$). There was a statistically significant main effect of set number ($F_{(1.270,41.925)} = 7.496$, p=0.001, partial $\eta^2 = 0.185$). Pairwise comparisons revealed statistically significant differences between set 1 and set 2 (p=0.003), with set 1 being lower by a mean of 0.008 (d=0.4) and set 1 and set 3 (p=0.028) with a mean difference of 0.010 (d=0.4).

There were no statistically significant main effects of group ($F_{(2,33)} = 0.126$, p=0.882, partial $\eta^2 = 0.008$).

#### 6.3.4.6 SLH mean peak GRF

Mean GRF can be seen in table 6.3.1. There was no statistically significant two-way set x group interaction ($F_{(4,66)}$ = 0.118, p=0.976, partial $\eta^2$ = 0.007). There was a statistically significant main effect of set number ($F_{(2,66)}$ = 3.897, p=0.025, partial $\eta^2$ = 0.106). Pairwise comparisons revealed a statistically significant difference (p=0.042) between set 1 and set 2, a mean difference of 0.04 times body weight (d=0.3).

There were no statistically significant main effects of group ($F_{(2,33)}$ = 1.228, p=0.306, partial $\eta^2$ = 0.069).

### 6.3.5 Discussion

The main purpose of this study was to establish the effect of a 12-week HSR programme on the kinetic and kinematic variables at the AT in response to a SLH task. The main finding of this study was:

1. There was a significant change in RSI throughout the SLH sets, irrespective of group.

#### 6.3.5.1 SLH frequency

There were no statistically significant differences in hopping frequency between the groups or across the sets which led to the acceptance of hypotheses 8. This emphasises that the test frequencies were similar across the SX_AT and ASX_AT groups at the week 12 testing sessions in comparison to the control group and that all participants were able to meet the frequency demands of the SLH intervention.

This was an unexpected finding. Wang et al. (2012) suggested that symptomatic AT's became more compliant through a loss of midportion stiffness and increased MTJ compliance. Kongsgaard et al. (2010) found that 12-weeks of HSR training causes decreases in patella tendon stiffness. Based upon this, it was expected that frequency across the three sets between the groups would differ due to the assumed increased tendon compliance combined with the short GCT would make it difficult to meet the high-frequency hop. However, this was not the case and it may be possible that the musculotendinous unit adapts its function based upon tendon compliance as suggested by Uchida, Hicks, Dembia, & Delp (2016). It could have been possible that there were increases in muscular or tendon stiffness as a result of the HSR

programme. A recent review has identified that this area needs further work to fully understand (Groeber et al., 2019).

#### 6.3.5.2 SLH GCT

There was not a significant two-way interaction effect for hopping GCT between set number and group in response to the SLH intervention following the 12-week HSR programme. There were no statistically significant between-group differences irrespective of set number, however, there were statistically significant main effects for set number irrespective of group. Mean hop GCT was longer in set 1 than in set 2 and 3 by 0.006s, however, the effect size was small. The mean GCT did not exceed the MDC value therefore it is possible that the differences seen between the sets are due to chance and may not represent clinically significant change.

#### 6.3.5.3 SLH flight time

There was not a statistically significant two-way set number x group interaction for SLH flight time, nor was there a statistically significant difference between the groups. There was a statistically significant main effect for set number, irrespective of the group there was a mean difference between set 1 and 2, and set 1 and 3. Flight time was higher by 0.006s and 0.007s with a moderate and small effect size respectively. These values both exceeded the value for SEM, but not for MDC, therefore it cannot be concluded that these values truly represented clinically significant change.

#### 6.3.5.4 SLH height

No statistically significant two-way set number by group interaction was found for mean hop height and there were no main effects for group. However, there were statistically significant main effects for set number, with mean differences indicating a lower hop height of 0.004m in set 1 compared to set 2, and 0.003m between set 1 and set 3, both with moderate effect sizes. The difference between set 1 and set 2 met the value for SEM, however the difference between set 1 and set 3 did not, therefore random error cannot be excluded. Both values did not exceed the value for MDC, therefore it cannot be concluded that these differences were clinically significant.

#### 6.3.5.5 SLH RSI

There was not a statistically significant two-way interaction between set number and group for SLH RSI following the 12-week HSR programme, nor were there any statistically significant differences between the groups irrespective of set number. However, the results suggested that there were statistically significant main effects for set number, with mean increases of 0.008 between set 1 and 2 and 0.010 between set 1 and 3, both with small effect sizes. These values both exceeded the values for SEM and MDC, therefore it can be concluded that these values represented clinically significant change. The change in RSI was reflected by the reduced GCT and higher hop height seen, despite these individual variables being clinically insignificant when viewed in isolation. A larger RSI indicated a faster SSC, which suggested a more efficient AT throughout the latter sets (McMahon et al., 2018).

To the author's knowledge, this novel finding is the first to assess the RSI in patients with Achilles tendinopathy. It is evident when visually comparing these results to those found in section 6.1 that there is an improvement in RSI following the 12-week HSR programme. This difference will now be explored in section 6.4.

#### 6.3.5.6 SLH mean peak GRF

The results revealed that there was not a statistically significant two-way set number by group interaction for SLH mean GRF, nor were there differences between the groups irrespective of set number. There were statistically significant main effects for set number, with a mean difference of 0.04 times body weight between set 1 and set 2, with a small effect size. This difference did not exceed the values for SEM or MDC; therefore, it cannot be concluded that this represented a truly significant change.

#### 6.3.5.7 Limitations

Angular kinematic analyses were not conducted at the ankle, knee or hip to address whether participant SLH strategy changed between the weeks. Future study may address this alongside a 12-week HSR programme, which could indicate whether the programme is beneficial to the AT or whether it encourages kinematic change for the participant to cope with the demands of the task. It could explore whether there are differences in hop strategy between symptomatic and asymptomatic individuals.

### 6.3.6 Conclusion

There were no significant two-way set number by group interactions for SLH frequency, GCT, flight time, hopping height, RSI or GRF's. However, there were some statistically significant main effects for set number, with a diminishing GCT and an increased flight time, hop height and RSI between sets 1 and 2 and set 1 and 3. However, only the change between sets for RSI exceeded the MDC values that were calculated in section 5.1.

It was apparent that there were changes to the kinetic and kinematic SLH hopping data between week 0 and 12. At week 0, there were statistically significant two-way interactions for flight time, hopping height and RSI, with between-group differences also seen for GCT and GRF's. Due to these differences being present, it is now necessary to compare the responses seen between the weeks.

## 6.4 TSK and symptom response to a SLH task in Achilles tendinopathy patients prior to and following a 12-week HSR intervention

### 6.4.1 Introduction

The individual responses to the 15-minute SLH interventions have now been established, and it appeared that there were differences in TSK response and vertical hopping kinematic and kinetics between the weeks. In both weeks, there was an immediate decrease in TSK following the SLH intervention, however, at week 12 this was statistically significant for timepoint interactions (irrespective of group). During week 0, the overall pairwise comparisons revealed more statistically significant change between time points, indicating a more fluctuated TSK response when compared to the response seen during week 12. There was a significant two-way interaction during week 0, with simple main effects revealing statistically significant timepoint changes in the control group opposed to the SX_AT or ASX_AT, however from a clinical standpoint, it is known that this is a normal response, with these significant changes from BL falling within the values for MDC that were calculated section 5.1.

Therefore, this section aimed to establish whether there were any changes in absolute or ΔTSK response, SLH kinetic and kinematic responses and VISA-A, NPRS and RPE scores, by comparing week 0 vs week 12 TSK data.

### 6.4.2 Hypotheses

1. There would be a statistically significantly different VISA-A score between week 0 and week 12
2. There would be a statistically significantly different NPRS_DURING score between week 0 and week 12
3. There would be a statistically significantly different NPRS_AFTER score between week 0 and week 12
4. There would be a statistically significantly different RPE score between week 0 and week 12
5. There would be a statistically significantly different absolute TSK response between week 0 and week 12 in the SX_AT group
6. There would be a statistically significantly different absolute TSK response between week 0 and week 12 in the ASX_AT group

7. There would be a statistically significantly different ΔTSK response between week 0 and week 12 in the SX_AT group
8. There would be a statistically significantly different ΔTSK response between week 0 and week 12 in the ASX_AT group
9. There would be a statistically significantly different hop frequency between week 0 and week 12 in the SX_AT group
10. There would be a statistically significantly different hop frequency between week 0 and week 12 in the ASX_AT group
11. There would be a statistically significantly different hop GCT between week 0 and week 12 in the SX_AT group
12. There would be a statistically significantly different hop GCT between week 0 and week 12 in the ASX_AT group
13. There would be a statistically significantly different hop flight time between week 0 and week 12 in the SX_AT group
14. There would be a statistically significantly different hop flight time between week 0 and week 12 in the ASX_AT group
15. There would be a statistically significantly different hop height between week 0 and week 12 in the SX_AT group
16. There would be a statistically significantly different hop height between week 0 and week 12 in the ASX_AT group
17. There would be a statistically significantly different RSI between week 0 and week 12 in the SX_AT group
18. There would be a statistically significantly different RSI between week 0 and week 12 in the ASX_AT group
19. There would be a statistically significantly different GRF between week 0 and week 12 in the SX_AT group
20. There would be a statistically significantly different GRF between week 0 and week 12 in the ASX_AT group

### 6.4.3 Methods

The data used in this section were obtained using the methods outlined in section 6.1 and 6.2. It is a combination of the TSK data from week 0 and the TSK data obtained at week 12, following the 12-week HSR intervention for the SLH cohort.

#### 6.4.3.1 Statistical Analysis

Normality of the data was assessed using the Shapiro-Wilk's test and was normally distributed unless stated otherwise($p>0.05$). The assumption of sphericity was assessed using Mauchly's and was met unless otherwise stated ($p>0.05$).

VISA-A scores from week 0 to week 12 were analysed using a paired samples t-test. Due to non-normal distribution, RPE and NPRS scores both during and after the hopping activity were analysed using the Wilcoxon signed-rank test, the nonparametric alternative to the paired samples t-test.

Separate two-way repeated measures ANOVA's with Bonferroni correction were used to assess both absolute and ΔTSK for the SX_AT and ASX_AT groups, with week number and timepoint as the within-subject variables.

Separate two-way repeated measures ANOVA's were also used to assess for differences in hopping kinetic and kinematic variables between week 0 and week 12, with set number and week number as the within-subject variables.

### 6.4.4 Results

#### 6.4.4.1 VISA-A

The paired samples t-test for VISA-A revealed that there were statistically significant improvements scores between week 0 and week 12 $t_{(8)} = 6.502$, $p<0.001$, $d=2.2$. The mean difference in VISA-A scores between the weeks was 15.1 ± 7.0 (95% CI 9.8, 20.5). There were no detrimental changes in VISA-A score in any of the 9 participants.

#### 6.4.4.2 NPRS during SLH

The Wilcoxon signed-rank test revealed that there were statistically significant improvements in median NPRS scores during activity between the weeks ($z=-2.060$, $p=0.039$). The median score improvement can be seen in table 6.3.1. The results showed that 5 out of the 9 median scores improved and the remaining 4 were unchanged.

#### 6.4.4.3 NPRS after SLH

The Wilcoxon signed-rank test revealed that there were no statistically significant improvements in median NPRS scores post-activity between the weeks ($z=-1.841$, $p=0.066$).

The results showed that 4 out of the 9 median scores improved and the remaining 5 were unchanged. The median change in scores can be seen in table 6.3.1.

#### 6.4.4.4 RPE

The Wilcoxon signed-rank test revealed that there were statistically significant improvements in median RPE scores between the weeks (z=-2.032, p=0.042). The median score improvement can be seen in table 6.4.1. The results showed that 5 out of the 9 median scores improved and the remaining 4 were unchanged. There were no increases in SLH effort scores following the 12-week HSR programme.

Table 6.4.1: Mean and median VISA-A, NPRS and RPE results

| Outcome measure | WK0 mean ± SD | WK12 mean± SD | WK0 median | WK12 median | p-value |
|---|---|---|---|---|---|
| VISA-A | 81.4 ± 11.5 | 95.6 ± 7.4 | - | - | **<0.001*** |
| NPRS During | 2.9 ± 2.9 | 1.1 ± 2.0 | 2.0 | 0.0 | **0.039*** |
| NPRS After | 1.3 ± 1.7 | 0.6 ± 1.7 | 1.0 | 0.0 | 0.066 |
| RPE | 3.1 ± 2.4 | 1.8 ± 1.9 | 2.0 | 1.0 | **0.042*** |

***Denotes statistically significant finding (p>0.05)**

#### 6.4.4.5 Absolute TSK

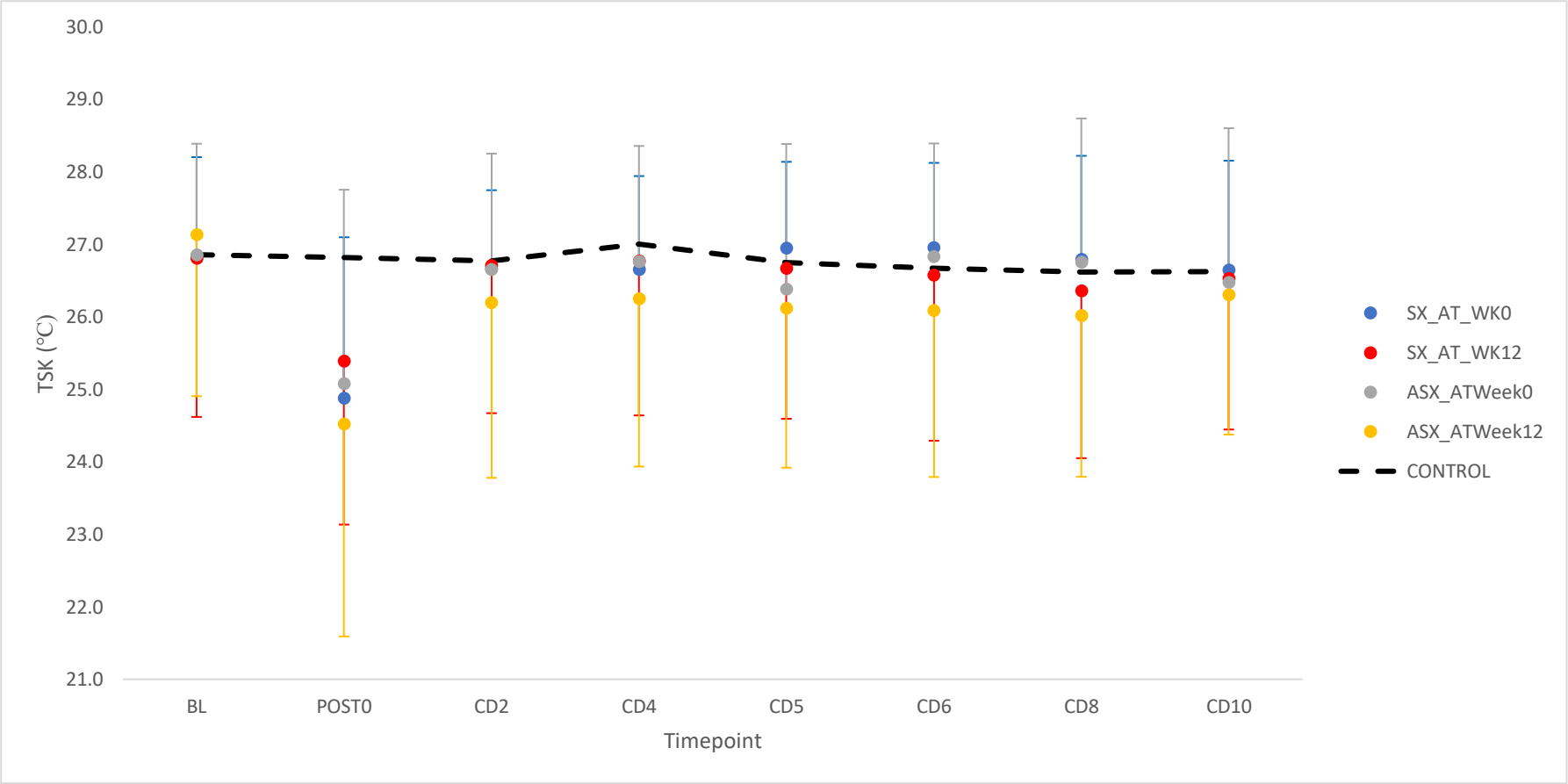
The results of the two-way repeated measures ANOVA revealed that there was no statistically significant two-way week number by timepoint interaction in the SX_AT group ($F_{(1.972,15.774)}$ = 0.258, p=0.773, partial $\eta^2$ = 0.031), and the mean values can be seen in table 6.4.2 and graphically in figure 6.4.1. There was no main effect of week number ($F_{(1.000,8.000)}$ = 0.013, p=0.912, partial $\eta^2$ = 0.002). There was a statistically significant main effect of timepoint ($F_{(2.138,17.100)}$ = 6.433, p=0.007, partial $\eta^2$ = 0.446). However, the pairwise comparisons with Bonferroni correction showed no statistically significant interactions between any of the time points.

The results of the second two-way repeated measures ANOVA revealed that there was no statistically significant two-way week number by timepoint interaction in the ASX_AT group ($F_{(1.662,13.296)}$ = 0.227, p=0.700, partial $\eta^2$ = 0.028). The mean TSK values can be seen in table 6.3.2 and graphically in figure 6.3.1. There was no main effect of week number ($F_{(1.000,8.000)}$ = 0.496, p=0.501, partial $\eta^2$ = 0.058). There was a statistically significant main effect of timepoint

($F_{(2.118,16.940)}$ = 4.685, p=0.023, partial $\eta^2$ = 0.369). However, the pairwise comparisons with Bonferroni correction showed no statistically significant interactions between any of the time points.

Table 6.4.2: Mean SLH participant absolute TSK ± SD (°C) week 0 vs week 12

| | **Week 0** | | **Week 12** | |
|---|---|---|---|---|
| **Timepoint** | **SX_AT** | **ASX_AT** | **SX_AT** | **ASX_AT** |
| BL | 26.8 ± 1.4 | 26.9 ± 1.5 | 26.8 ± 2.2 | 27.1 ± 2.2 |
| POST0 | 24.9 ± 2.2 | 25.1 ± 2.7 | 25.4 ± 2.3 | 24.5 ± 2.9 |
| CD2 | 26.7 ± 1.1 | 26.7 ± 1.6 | 26.7 ± 2.0 | 26.2 ± 2.4 |
| CD4 | 26.7 ± 1.3 | 26.8 ± 1.6 | 26.8 ± 2.1 | 26.2 ± 2.3 |
| CD5 | 26.9 ± 1.2 | 26.4 ± 2.0 | 26.7 ± 2.1 | 26.1 ± 2.2 |
| CD6 | 27.0 ± 1.2 | 26.8 ± 1.6 | 26.6 ± 2.3 | 26.1 ± 2.3 |
| CD8 | 26.8 ± 1.4 | 26.8 ± 2.0 | 26.4 ± 2.3 | 26.0 ± 2.2 |
| CD10 | 26.6 ± 1.5 | 26.5 ± 2.1 | 26.5 ± 2.1 | 26.3 ± 1.9 |




**n=18**

Figure 6.4.1: Age and gender-matched SX_AT and ASX_AT TSK response to SLH week 0 vs week 12

#### 6.4.4.6 ΔTSK

The mean ΔTSK data can be seen in table 6.4.3 and graphically on figure 6.4.2. The results of the two-way repeated measures ANOVA for ΔTSK response in the SX_AT group between week 0 and week 12 revealed no statistically significant two-way week number by timepoint interaction ($F_{(1.408,11.263)}$ = 0.319, p=0.658, partial $\eta^2$ = 0.038). There was no significant main effect of week number ($F_{(1,8)}$ = 0.004, p=0.952, partial $\eta^2$ < 0.001).

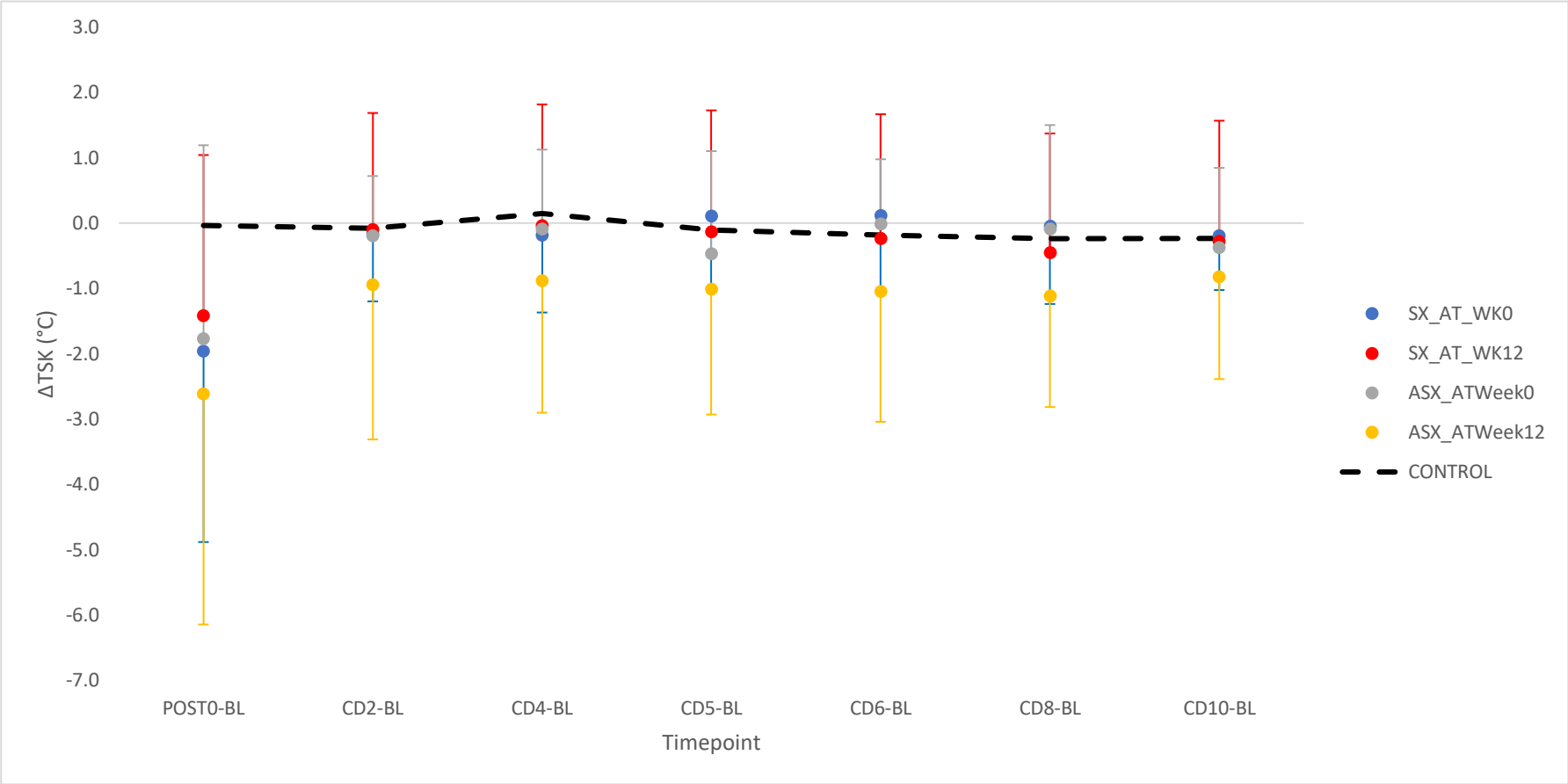
There was a statistically significant main effect of timepoint ($F_{(1.508,12.063)}$ = 7.641, p=0.011, partial $\eta^2$ = 0.489). However, once Bonferroni correction was applied, there were no significant pairwise comparisons between the timepoints, irrespective of group.

The results of the two-way repeated measures ANOVA for ΔTSK response in the ASX_AT group between week 0 and week 12 revealed no statistically significant two-way week number by timepoint interaction ($F_{(1.548,12.388)}$ = 0.088, p=0.871, partial $\eta^2$ = 0.011). There was no significant main effect of week number ($F_{(1,8)}$ = 1.849, p=0.211, partial $\eta^2$ = 0.188).

There was a statistically significant main effect of timepoint ($F_{(1.570,12.557)}$ = 4.828, p=0.034, partial $\eta^2$ = 0.376). However, once Bonferroni correction was applied, there were no significant pairwise comparison between the timepoints, irrespective of group.

Table 6.4.3: Mean ΔTSK ± SD (°C) for SLH participants week 0 vs week 12

| | **Week 0** | | **Week 12** | |
|---|---|---|---|---|
| **Timepoint** | **SX_AT** | **ASX_AT** | **SX_AT** | **ASX_AT** |
| POST0-BL | -2.0 ± 2.9 | -1.8 ± 3.0 | 1.4 ± 2.5 | 2.6 ± 3.5 |
| CD2-BL | -0.2 ± 1.0 | -0.2 ± 0.9 | -0.1 ± 1.8 | -0.9 ± 2.4 |
| CD4-BL | -0.2 ± 1.2 | -0.1 ± 1.2 | 0.0 ± 1.9 | -0.9 ± 2.0 |
| CD5-BL | 0.1 ± 1.1 | -0.5 ± 1.6 | -0.1 ± 1.9 | -1.0 ± 1.9 |
| CD6-BL | 0.1 ± 1.2 | 0.0 ± 1.0 | -0.2 ± 1.9 | -1.0 ± 2.0 |
| CD8-BL | 0.0 ± 1.2 | -0.1 ± 1.6 | -0.5 ± 1.8 | -1.1 ± 1.7 |
| CD10-BL | -0.2 ± 0.8 | -0.4 ± 1.2 | -0.3 ± 1.8 | -0.8 ± 1.6 |




**n=18**

Figure 6.4.2: ΔTSK response for age and gender-matched SX_AT week 0 and week 12

#### 6.4.4.7 SLH frequency

There was no significant two-way interaction between week number or set number for SLH frequency in the SX_AT group ($F_{(2,16)}$ = 2.309, p=0.132, partial $\eta^2$ = 0.224). There was no main effect of week number ($F_{(1,8)}$ = 1.716, p=0.227, partial $\eta^2$ = 0.177), or set number ($F_{(2,16)}$ = 0.190, p=0.829, partial $\eta^2$ = 0.023).

There was no significant two-way interaction between week number or set number for SLH frequency in the ASX_AT group ($F_{(2,16)}$ = 0.391, p=0.683, partial $\eta^2$ = 0.047). There was no main effect of week number ($F_{(1,8)}$ = 0.006, p=0.940, partial $\eta^2$ = 0.001), or set number ($F_{(2,16)}$ = 0.756, p=0.486, partial $\eta^2$ = 0.086).

#### 6.4.4.8 SLH GCT

There was no significant two-way interaction between week number or set number for GCT in the SX_AT group ($F_{(1.216,9.724)}$ = 0.877, p=0.394, partial $\eta^2$ = 0.099). There was no main effect of week number ($F_{(1,8)}$ = 0.006, p=0.940, partial $\eta^2$ = 0.001), or set number ($F_{(1.775,14.203)}$ = 0.090, p=0.895, partial $\eta^2$ = 0.011)..

There was no significant two-way interaction between week number or set number for GCT in the ASX_AT group ($F_{(2,16)}$ = 2.517, p=0.112, partial $\eta^2$ = 0.239). There was no main effect of week number ($F_{(1,8)}$ = 0.171, p=0.690, partial $\eta^2$ = 0.021), or set number ($F_{(1.238,10.060)}$ = 1.353, p=0.283, partial $\eta^2$ = 0.145).

#### 6.4.4.9 SLH flight time

There was a significant two-way week number by set number interaction for SLH flight time in the SX_AT group ($F_{(1.127,9.013)}$ = 11.862, p=0.006, partial $\eta^2$ = 0.597). There were no statistically significant simple main effects for week number during set 1 ($F_{(1,8)}$ = 1.455, p=0.262 , partial $\eta^2$ = 0.153 ), set 2 ($F_{(1,8)}$ = 0.033, p=0.860 ,partial $\eta^2$ = 0.004 )or set 3 ($F_{(1,8)}$ = 1.474, p=0.259, partial $\eta^2$ = 0.156).

There was a statistically significant simple main effect of set number during week 0 ($F_{(2,16)}$ = 4.750, p=0.024, partial $\eta^2$ = 0.372), but not during week 12 ($F_{(2,16)}$ = 1.600, p=0.233, partial $\eta^2$ = 0.167). Pairwise comparisons for week 0 revealed no statistically significant differences between sets once Bonferroni correction had been applied.

There was no significant two-way week number by set number interaction for SLH flight time in the ASX_AT group ($F_{(2,16)}$ = 3.473, p=0.056, partial $\eta^2$ = 0.303). There were no statistically significant main effects for week number ($F_{(1,8)}$ = 0.017, p=0.899 , partial $\eta^2$ = 0.002). There was no statistically significant main effect of set number ($F_{(2,16)}$ = 2.598, p=0.105, partial $\eta^2$ = 0.245).

#### 6.4.4.10 SLH height

There was no significant two-way interaction between week number or set number for SLH height in the SX_AT group ($F_{(2,16)}$ = 2.800, p=0.091, partial $\eta^2$ = 0.259). There was no main effect of week number ($F_{(1,8)}$ <0.001, p=1.000, partial $\eta^2$ <0.001), or set number ($F_{(2,16)}$ = 0.182, p=0.835, partial $\eta^2$ = 0.022).

There was a significant two-way week number by set number interaction for SLH height in the ASX_AT group ($F_{(2,16)}$ = 4.558, p=0.027, partial $\eta^2$ = 0.363). There were no statistically significant simple main effects for week number during set 1 ($F_{(1,8)}$ = 3.368, p=0.104 , partial $\eta^2$ = 0.296 ), set 2 ($F_{(1,8)}$ = 2.00, p=0.195 ,partial $\eta^2$ = 0.200) or set 3 ($F_{(1,8)}$ = 1.333, p=0.282, partial $\eta^2$ = 0.143).

There was no statistically significant simple main effect of set number during week 0 ($F_{(2,16)}$ = 0.571, p=0.576, partial $\eta^2$ = 0.067), but there was a statistically significant simple main effect of set number during week 12 ($F_{(2,16)}$ = 6.049, p=0.011, partial $\eta^2$ = 0.431). Pairwise comparisons for week 12 revealed a statistically significant (p=0.012) difference between set 1 and 2 following Bonferroni correction, with a mean difference of 0.007m (95% CI 0.002m-0.012m).

#### 6.4.4.11 SLH RSI

There was no significant two-way interaction between week number or set number for RSI in the SX_AT group ($F_{(2,16)}$ = 3.038, p=0.076, partial $\eta^2$ = 0.275). There was no main effect of week number ($F_{(1,8)}$ = 0.135, p=0.723, partial $\eta^2$ = 0.017), or set number ($F_{(1.204,9.631)}$ = 0.151, p=0.861, partial $\eta^2$ = 0.019).

There was a significant two-way week number by set number interaction for RSI in the ASX_AT group ($F_{(2,16)}$ = 3.854, p=0.043, partial $\eta^2$ = 0.325). Pairwise comparisons with Bonferroni correction revealed that there were no statistically significant simple main effects

for week number during set 1 ($F_{(1,8)}$ = 0.690, p=0.430, partial $\eta^2$ = 0.079 ), set 2 ($F_{(1,8)}$ = 1.391, p=0.272 ,partial $\eta^2$ = 0.148) or set 3 ($F_{(1,8)}$ = 1.455, p=0.262, partial $\eta^2$ = 0.154).

There was no statistically significant simple main effect of set number during week 0 ($F_{(2,16)}$ = 0.036, p=0.965, partial $\eta^2$ = 0.004) or during week 12 ($F_{(2,16)}$ = 3.203, p=0.110, partial $\eta^2$ = 0.286).

#### 6.4.4.12 SLH mean peak GRF

There was no significant two-way interaction between week number or set number for vertical GRF in the SX_AT group ($F_{(2,16)}$ = 0.2.239, p=0.139, partial $\eta^2$ = 0.219). There was no main effect of week number ($F_{(1,8)}$ = 1.094, p=0.326, partial $\eta^2$ = 0.120), or set number ($F_{(1.775,14.203)}$ = 0.605, p=0.558, partial $\eta^2$ = 0.070).

There was no significant two-way interaction between week number or set number for vertical GRF in the ASX_AT group ($F_{(2,16)}$ = 0.166, p=0.848, partial $\eta^2$ = 0.020). There was no main effect of week number ($F_{(1,8)}$ = 0.957, p=0.357, partial $\eta^2$ = 0.107), or set number ($F_{(1.195,9.556)}$ = 1.310, p=0.290, partial $\eta^2$ = 0.141).

### 6.4.5 Discussion

This was the first study to assess the effects of a strengthening intervention on the TSK response of the midportion of the AT. This section aimed to establish whether a 12-week HSR programme influenced the absolute or ΔTSK responses of the midportion of the AT. Secondary aims were to determine whether SLH kinetic and kinematic data was affected by the HSR programme. The main findings of this section were:

1. There were no statistically significant changes in absolute TSK following the 12-week HSR programme in either the SX_AT or ASX_AT groups.
2. There were no statistically significant changes in ΔTSK following the 12-week HSR programme in either the SX_AT or ASX_AT groups.
3. There were no significant changes that exceeded MDC values for any of the kinetic or kinematic variables measured during SLH activity.
4. There were improvements in VISA-A, RPE and NPRS scores during activity.

#### 6.4.5.1 Absolute TSK

There were no statistically significant two-way week number x timepoint interactions in the SX_AT or ASX_AT for absolute TSK which led to the rejection of hypotheses 5 and 6, nor were there any statistically significant main effects of week number. There were statistically significant main effects for time in both groups, however, once Bonferroni correction was applied, there were no significant pairwise differences. Bonferroni correction was applied to reduce the chance of type 1 error, the incorrect rejection of the null hypothesis, which in this case was that there were no significant differences in absolute TSK between the SX_AT and ASX_AT groups. Therefore, this suggested that the 12-week HSR programme did not affect the absolute TSK response of the midportion of the AT. The same response was also seen when the data was viewed as ΔTSK which led to the rejection of hypotheses 7 and 8.

#### 6.4.5.2 SLH frequency

There were no statistically significant two-way interactions or main effects for the SX_AT or ASX_AT groups when considering SLH frequency, which led to the rejection of hypotheses 9 and 10. This finding suggested that Achilles tendinopathy did not affect that ability of participants to hop unilaterally at a high frequency for 3 x 20 repetitions, which has previously been suggested to be a provocative movement (Hutchison et al., 2013; Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006). However, a limitation existed with the method in that knee flexion or ankle dorsiflexion angles were not measured, therefore it is not implausible that the participants altered their SLH strategy to account for pain experienced at the AT by flexing the knee or adopting a heel hop strategy in an attempt to stiffen the limb and meet the 2.5Hz SLH frequency. Previous research has found that there is reduced limb stiffness in symptomatic Achilles tendinopathy patients, particularly through the ankle joint (Maquirriain, 2012). Current evidence would suggest that these alterations would be to combat pain rather than deficits in stiffness, as HSR training has been shown to be beneficial for improving Achilles tendinopathy symptoms, yet has been shown to reduce the stiffness in the patellar tendon (Kongsgaard et al., 2010). Future research could be directed to assessing this from a kinetic and kinematic perspective.

#### 6.4.5.3 SLH GCT

No interactions or main effects existed for GCT in either of the groups, which led to the rejection of hypotheses 11 and 12. As decreased compliance results in an overall lower leg

stiffness (Maquirriain, 2012), it was expected that GCT would be significantly longer during the week 0 SLH trials. Previous work has shown that increased leg and joint stiffness led to quicker GCT's in SLH trials at 1.5Hz and 3.0Hz frequencies, although this difference was not statistically significant at 3.0Hz. This was an interesting finding considering that 3.0Hz is a fast SSC action and it reduced the difference between endurance and power trained athletes. It would be expected that the rapid storage and release of energy at the faster SLH speeds would be more substantially affected in a compliant AT as it is a more ankle dominant exercise (McMahon, 2015). Differences may not have existed for GCT between the weeks in the current study due to the speed of the SLH action. Despite 2.5Hz being classed as a slow SSC action (Flanagan & Comyns, 2008), hopping at that frequency may not be affected by AT compliance as suggested by (Maquirriain, 2012). However, the adaptation of SLH hopping strategy towards a more dorsiflexed ankle position to stiffen the compliant AT could be responsible. Future study may look to understand this further.

#### 6.4.5.4 SLH flight time

There was a statistically significant two-way set number by week number interaction for flight time in the SX_AT group, but not the ASX_AT group. There was no simple main effect of week number in any of the sets, however, there was a statistically significant simple main effect of set number during week 0. However, once Bonferroni correction was applied, these pairwise comparisons were no longer significant. Therefore, hypotheses 13 and 14 were both rejected.

#### 6.4.5.5 SLH height

There were no significant differences in the SX_AT group for hop height, which led to the rejection of hypothesis 15. However, there was a significant two-way week number by set number interaction in the ASX_AT group. No simple main effects existed for week number during any of the sets or for set number during week 0 which led to the rejection of hypothesis 16. However, there were statistically significant differences in hop height between set 1 and set 2 during week 12. This difference was 0.007m (95% CI 0.002m, 0.012m) higher in set 2 meaning that the differences exceeded the SEM value but not the MDC value suggesting that the difference may not be clinically meaningful.

#### 6.4.5.6 SLH RSI

There was no statistically significant two-way set number by week number interaction for RSI is the SX_AT which led to the rejection of hypothesis 17. There was however a significant interaction in the ASX_AT, however, when Bonferroni correction was applied to account for the possibility of type 1 error, there were no simple main effects for week number in any of the sets, or set number during either of the weeks which led to the rejection of hypothesis 18.

#### 6.4.5.7 SLH mean peak GRF

No statistically significant differences existed in either group for GRF's across any of the sets or weeks, which led to the rejection of hypotheses 19 and 20. This finding matched the conclusions of a previous systematic review and meta-analysis (Munteanu & Barton, 2011) and in a previous running study conducted by Becker et al. (2017). This indicated that despite positive changes in participants symptoms across the 12-weeks, there were no changes to the peak forces that participants experienced during the SLH hopping trials following the HSR intervention.

#### 6.4.5.8 VISA-A

A positive clinical finding was that there was a significant improvement in VISA-A scores of 15.1 ± 7.0 for the participants following the 12-week HSR programme, representing clinically significant improvement (Murphy et al., 2018). This finding is consistent with the results reported by Beyer et al. (2015), who found an improvement of 22.0 ± 2.7. It is possible that one of the reasons for the increased improvement seen in their study was that for the first 3 weeks of the intervention, their participants were not allowed to engage in their sporting activities which differed in the present study. All exercises were guided by NPRS and RPE scores in the present study and subjects were instructed to reduce their running load should their symptoms increase in severity with the onset of the HSR programme alongside guiding their weighted load during the exercises. The reason for not stopping the activity of the runners in the present study was that they were all already continuing to run within their pain tolerance scores and many of them were not regular gym attendees. All of the runners were keen to continue running and it is likely that suggesting 3 weeks' worth of rest from running would have greatly affected recruitment and adherence to the programme.

#### 6.4.5.9 NPRS

Another positive finding was that NPRS scores during the SLH activity, which is known to be a highly provocative movement for those suffering from Achilles tendinopathy (Hutchison et al., 2013; Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006), were significantly reduced. There was a 55% improvement rate in median NPRS scores during the activity, with the remaining 45% of median scores remaining the same. The mean improvement in NPRS scores during the activity had dropped from 2.9 ± 2.9 to 1.1 ± 2.0, which fell below the 2.0 improvement needed for clinically significant change which has been established previously for chronic pain (Farrar et al., 2001). However, the latter authors also stated that a percentage improvement score (raw score change/baseline score x 100) of 27.9% represented a clinical improvement, the percentage improvement in the current study was a mean of 62% which could be perceived as clinically significant. The results were similar to those found by Beyer et al. (2015), who found a 22-point visual analogue scale improvement (VAS) during the single-leg heel raise exercise following the 12-week HSR programme. The slightly greater improvement in score could be attributed to the fact that the load passing through the AT during the SLH activity was much greater in the present study compared to a single leg heel raise. Despite this, the results of the present study did suggest that the 12-week HSR programme was successful for reducing pain during SLH activity.

No significant differences were found between the weeks for NPRS score following the SLH activity. The mean score of 1.3± 1.7 during week 0 was classed as mild (Boonstra et al., 2016) and this reduced by 0.7 to 0.6 ± 1.7 following week 12, which was not classed as a clinically significant improvement in score. Despite not being statistically or clinically significant, the mean and median reductions in the scores are still positive for the individuals concerned and suggest a trend of improvement in residual pain following SLH activity following a 12-week HSR programme.

#### 6.4.5.10 RPE

There were also statistically significant improvements in RPE scores following the 12-week HSR programme, with a mean difference of 1.3. It is unknown whether this relates to clinically significant change as there are a range of MDC values across the literature relating to various types of activity. In elderly participants exercising at self-selected treadmill speed, it has been calculated at 0.8 (Lins-Filho et al., 2019), however, for a range of gym-based

exercises, it ranges from 1.8-2.4 (Steele et al., 2017). Despite not knowing whether the change is clinically significant, again it is a positive trend and suggests that the 12-week HSR programme improves the perceived effort required to SLH in those suffering from unilateral Achilles tendinopathy.

#### 6.4.5.11 Limitations

A limitation of this study was that only the vertical single leg hopping kinetic and kinematic data was assessed even though the participants were free-standing. It could have been possible that there may have been differences in anteroposterior and mediolateral variables between the weeks. Future study could address this.

### 6.4.6 Conclusion

To conclude this chapter, the 12-week HSR programme did not affect absolute TSK or ΔTSK values in response to a SLH trial. There were no significant changes to most kinetic and kinematic SLH variables, with significant changes being found in flight time and hop height of the ASX_AT group during the week 12 testing session between sets 1 and 2. However, this did not exceed the value for MDC.

There were positive changes in VISA-A, NPRS scores during SLH activity and RPE scores following the 12-week HSR programme, which suggested that it was successful in reducing the pain of symptomatic participants and reducing the perceived effort of the hopping activity. These results support the findings of Beyer et al. (2015) by implying that a 12-week HSR programme is a useful rehabilitation programme for those suffering from chronic midportion Achilles tendinopathy. The results of the present study also suggested that the 12-week HSR programme can be introduced alongside normal training regimes if NPRS and RPE scores are carefully monitored and still elicit an improvement in the symptoms of Achilles tendinopathy.

# Chapter SEVEN

## General Discussion

## 7.1 Key findings

This purpose of this thesis was to establish whether a smartphone-compatible infrared thermal imaging camera could be used as an objective assessment tool to monitor the reaction to the loading of AT's with chronic midportion Achilles tendinopathy. The primary aims of this thesis were:

1. To develop a reliable method of determining AT midportion TSK
2. To establish the normal baseline TSK of symptomatic and asymptomatic individuals
3. To establish the normal absolute and ΔTSK of symptomatic and asymptomatic individuals in response to running or hopping tasks
4. To establish the effect of a 12-week HSR training programme on absolute and ΔTSK change response in symptomatic individuals

### 7.1.1 Methodological considerations for AT IRT

The purpose of chapter three was to establish a robust methodology for thermal imaging assessment of the midportion of the AT. The first aim of the thesis was to ascertain the intra-rater and inter-rater reliability of the method of analysis with associated SEM and MDC values, as the construct validity of the tool had already been assessed by the supervisory team using specialist equipment from another institution, that could not be accessed as part of the current project. The minimum focus distance of the FLIR E8 was 0.5m, therefore this distance was chosen for comparison of the agreement between this and the smartphone compatible FLIR ONE. As a variety of distances had been used within the wider literature (Bach, Stewart, Minett, & Costello, 2015; Choi, Lee, & Nahm, 2013; Guirro et al., 2017; Fernandes et al., 2014), it was deemed important to understand the effect that the distance of the camera from the ROI and subsequently the angle in relation to the ROI had on TSK readings. Finally, the repeatability of the camera needed to be investigated to ensure that it was able to consistently measure TSK across time.

The method of analysis using a freeform line ROI from the calcaneal to the MTJ markers was deemed to have excellent intra-rater reliability at a distance of 0.5m, with low SEM (0.2°C) and MDC (0.5°C) values. However, with taller participants, the superior MTJ marker was on occasion borderline being out of view on the captured thermal image. This could have potentially created a problem with taller participants moving through subsequent studies.

However, when the distance of the camera was moved backwards to 1m from the ROI, the clarity of the thermal images decreased making it harder to identify the midportion of the AT. Despite the intra-rater reliability values remaining excellent, the inter-rater reliability values were deemed good. The intra-rater SEM (0.1°C) and MDC (0.4°C) values improved, possibly due to the lower pixel count contained within each ROI, but the inter-rater SEM (0.6°C) and MDC (1.6°C) values dramatically worsened. Based upon this and work conducted by Ammer (2008), it was recommended that as much of the ROI as possible was incorporated into each image.

Therefore, the effect of distance and angle of the camera in relation to the ROI were assessed. Due to the wide LoA found between angles at the same distances, it was recommended that these were kept consistent between participants. As there were no statistically significant differences found between angles at the same distances, the camera was placed perpendicular to the midline of the body so that both ROI's could be captured in the same image.

Wide LoA were found with 0.5m and 1m distances, therefore it was recommended that distance was also kept consistent between participants. As a result of the anthropometric limitations that were found, it was proposed that moving the camera back to 0.6m from the ROI would be more suitable, and thus new SEM and MDC values were calculated for that distance. Therefore, a camera placement adjustment to 0.6m from the ROI was made and new SEM (0.2°C) and MDC (0.5°C) values were obtained that were the same as at a 0.5m distance. There were no longer any issues with image capture and participant anthropometrics, therefore a 0.6m distance was recommended for the assessment of the midportion of the AT when using the FLIR ONE.

Finally, chapter three evidenced that the FLIR ONE demonstrated acceptable repeatability over time, consistently measuring AT TSK of participants who were at rest. All of this underpinned the robust final methodology that was employed for assessing TSK at the midportion of the AT. In summary, the key methodological implications for the remaining studies were:

- The FLIR ONE should be placed 0.6m from the ROI which has shown to produce reliable and repeatable TSK readings.

- The placement of the FLIR ONE should be standardised to being perpendicular with the midline of the body.
- Line analysis can be used by drawing a freeform ROI from the calcaneal marker to the marker at the MTJ with acceptable intra-rater and inter-rater reliability

### 7.1.2 Baseline TSK

The following three chapters assessed TSK of the midportion of the AT between symptomatic and asymptomatic individuals. Chapter four assessed aim number two, which was to establish the normal baseline TSK of the midportion of the AT in symptomatic and asymptomatic individuals. It revealed that baseline AT TSK values did not significantly differ between SX_ATs and ASX_ATs, or between those and the ATs of asymptomatic participants.

It was necessary to establish this as the literature review in chapter two revealed that previous researchers have attempted to identify pathology based on TSK asymmetry (Ioannou, 2020; Rodriguez-Sanz et al., 2018; Rodríguez-Sanz et al., 2017), whereas non-pathological limbs have demonstrated TSK symmetry (Fernando Sanz-López et al., 2016; Tumilty et al., 2019). Other authors had suggested that TSK change greater than 0.5°C (Hildebrandt et al., 2010; Vardasca, Ring, & Plassmann, 2012; Zaproudina et al., 2008) indicated abnormality, however, due to regional variations in physiology (Tansey & Johnson, 2015), these figures should not be applied arbitrarily.

The results of this study contradicted these previous findings with no differences being found between SX_AT's, ASX_AT's or control AT's. It could be possible that due to the chronic nature of the pathology, local TSK values were not affected when participants were at rest following an acclimatisation period, due to the lack of a typical inflammatory response. The previous research cited viewed conditions more acute in presentation, which would likely have displayed the cardinal signs of inflammation (D'Addona, Maffulli, Formisano, & Rosa, 2017).

This chapter was novel as it was the first to assess for TSK differences in the midportion of the AT in those suffering from chronic midportion Achilles tendinopathy using a smartphone-compatible infrared thermal imaging camera. The hypotheses for the chapter were all rejected as the results of the study indicated that there were no significant differences between any combination of the AT's from the symptomatic and asymptomatic participants. The results supported findings from two previous studies which both found no significant

differences in baseline AT TSK in participants suffering from functional ankle equinus (Rodriguez-Sanz et al., 2018; Rodríguez-Sanz et al., 2017).

In summary, the novel results of chapter four meant that the FLIR ONE cannot be used clinically to screen participants when at rest and before exercise. The changes that were found during chapter four are not due to the technology of the FLIR ONE, as acceptable construct validity and repeatability have been found, along with acceptable intra-rater and inter-rater reliability of the method of analysis. It is therefore concluded that there were no TSK changes present in the midportion of the AT in those suffering from chronic tendinopathy when compared to ASX_AT's or asymptomatic participants AT's at rest.

### 7.1.3 TSK change in response to running

Chapters five and six both addressed aims three and four. Specifically, chapter five aimed to understand the TSK response in relation to running. Running populations are a cohort of individuals that have a high incidence of chronic midportion Achilles tendinopathy (Kujala et al., 2005; O'Neill, 2016), but despite this many continue to run moderately large weekly distances and push through tolerable pain (Rasmussen et al., 2013). One of the characteristics of this pain is that it starts and quickly ceases upon the initiation of activity following rest, which suggests that there are both biomechanical and physiological responses that occur in rapid succession for the pain to cease (D'Addona et al., 2017; Dakin et al., 2018; Knobloch et al., 2006; Wang et al., 2012). It was therefore important to explore TSK change beyond rest and investigate the TSK response over the tendon with activity. It may be possible that physiological or biomechanical changes that are known to occur in pathological AT's may cause local heat change; these are changes such as increases in metabolic demand of the Gastrocnemius-Soleus musculature, changes in AT intratendinous blood flow, increased neovascularisation or increased hysteresis (D'Addona et al., 2017; Knobloch et al., 2006; Kubo et al., 2017; Wang, Lin, Su, Shih, & Huang, 2012).

The results of chapter five section one revealed that there was a statistically significant increase in midportion AT TSK in response to a 15-minute treadmill running intervention at an individual self-selected 10k running race pace. The novelty factor was that it highlighted significant differences between the SX_AT's and the control AT's and between the ASX_AT's and control AT's, but not between the SX_AT's and ASX_AT's. The reason for these findings is unknown and it was beyond the scope of this thesis to explain these changes from an

evidential standpoint. However, there are several theories for these changes which can be proposed based on existing literature.

Previous literature has highlighted that pathology of the AT can lead to changes in local blood volume (Boesen et al., 2006; Knobloch et al., 2006; Kubo et al., 2017; Pingel et al., 2013; Praet et al., 2018). Kubo et al., (2017) showed that intra-tendinous blood flow decreased with isometric contraction and elevated during the subsequent recovery, but unfortunately the Gastrocnemius-Soleus blood flow was not measured. If future studies seek to measure this alongside, it could provide some insight as to whether Gastrocnemius-Soleus blood flow changes correlate with TSK changes. It may also reflect changes in metabolic demand of the region between SX and ASX individuals with chronic midportion Achilles tendinopathy. It may be possible that intratendinous changes in blood flow are not reflected through surface TSK change. However, previous suggestions have arisen that due to stiffness changes in symptomatic AT's, there was an increased demand on the Gastrocnemius-Soleus musculature (Katayama & Saito, 2019; Lichtwark & Wilson, 2007), which in turn may have resulted in a redistribution of skin blood flow which could have the potential to reduce the warming rate of the skin (Lenasi, 2014). Greater TSKs may have been seen in the control group over the midportion of the AT as less metabolic demand may have been required from the Gastrocnemius-Soleus musculature, and greater efficiency in the SSC may have been seen due to a stiffer musculotendinous unit (Gruber et al., 2019; Lichtwark & Wilson, 2007; Wang et al., 2012). This could be supported by the results seen in chapter 6.2, with RSI improving significantly across the latter sets, which was a finding not identified before the 12-week HSR programme in chapter 6.1 and indicated a faster SSC (McMahon et al., 2018).

SX_AT's have been shown to have greater hysteresis than ASX_AT's (Wang et al., 2012). This theory provided part of the rationale for studying surface TSK change at the midportion of the AT originally. It is unlikely based on the results of chapter five section one that hysteresis was responsible for the TSK change seen in the midportion of the AT. It would have been expected that surface TSK would have risen with increased heat emitted from the AT and thus the SX_AT's would have been hotter than the ASX_AT's and control AT's. This theory would also be supported with the theory of heat shock proteins that are present in tendinopathy, which are known to play a role in the early regulation of tenocytes to repair or degenerate (Millar & Murrell, 2012). Further, the results of the study support previous work by Wezenbeek, Willems, Mahieu, Muynck, et al., (2018) who found that diminished blood flow

resulted in a higher risk of developing Achilles tendinopathy, therefore based on this it would be expected that SX_AT's have a lower TSK than healthy controls, again suggesting that hysteresis is not responsible for thermal change. When combined with the findings of chapter five section two, specifically the normalisation of absolute TSK in the SX_AT (further increase in TSK) post-HSR programme, it makes hysteresis an unlikely explanation for the TSK changes seen.

It was interesting that differences were not present between SX_AT's and ASX_AT's in chapter five section one. Due to previous literature highlighting differences in both physiological and biomechanical AT characteristics in symptomatic tendons (D'Addona et al., 2017; Dakin et al., 2018; Knobloch et al., 2006; Wang et al., 2012), it was hypothesised that the TSK responses between SX_AT's and ASX_AT's would be statistically significantly different. However, research by Rio et al. (2016) could explain why differences did not exist. They suggested that tendon pain resulted in imbalances between motor neurons at a spinal level and noted that contralateral limbs may display negative adaptational changes in relation to unilateral tendon pain. This theory could explain why the same bilateral physiological responses were seen in the current study, however, no literature exists to draw a meaningful conclusion about this in lower limb tendinopathy and would require further study.

The 12-week HSR programme was chosen for a rehabilitation intervention based upon the results of Beyer et al., (2015). There were statistically significant differences between the ASX_AT and the control group AT's, however, there were no longer significant differences between the SX_AT and control group AT's. This suggested that there was a more normalised TSK response at the week 12 time point for SX_AT's following the rehabilitation programme and it coincided with improvements in mean VISA-A scores. Beyer et al., (2015) found that there were reductions in both A-P thickness and neovascularisation following HSR training. The results of the current study supported this by suggesting that there were physiological changes that occurred at the skin surface in response to the HSR rehabilitation programme, in response to a 15-minute treadmill run.

It is possible that AT adaptation may have been responsible for the differences noted between the SX_AT and ASX_AT groups (Docking & Cook, 2019). Docking & Cook (2019) stated that tendon adaptation, positive or negative, is regulated by exposure to or lack of exposure from load, which was evidenced by Beyer et al., (2015). It is known that pathological AT's display biomechanical and physiological maladaptation, however, these changes are often not

noted in the contralateral limb (Karamanidis & Epro, 2020; Magnusson & Kjaer, 2019; Sunding et al., 2016). Exposure to the HSR programme may have provoked a structural adaptational response in the SX_AT's (Ackermann, 2013) which may have resulted in positive physiological adaptation within the 12-weeks as found by Beyer et al., (2015). Exposure to load in a pathological tendon triggers a healing response which results in complex chemical reactions (Ackermann, 2013). As participants were conducting dynamic exercise as normal, it is feasible that negative tendon adaptations did not occur in the ASX_AT's or they occurred on a much smaller scale as there was no prolonged lack of exposure to a mechanical stimulus (Ackermann, 2013; Docking & Cook, 2019; Magnusson & Kjaer, 2019). It could be possible that there is a link between structural adaptation, the resultant chemical influx, and the neuronal homeostasis outlined by Rio et al. (2016). If so, it could be possible that there is a lag phase in the ASX_AT before physiological adaptations occurred in the absence of structural maladaptation which may explain why there were no statistically significant TSK differences between the SX_AT's and ASX_AT's, and none between the ASX_AT's and control, but there were between the SX_AT's and control AT's. This statement may be supported by results from Kumar et al. (2017) who found that UTC and shear wave elastography could distinguish pathological from non-pathological AT tissue.

The final section of chapter five revealed that there were no significant absolute or ΔTSK changes within the SX_AT or ASX_AT groups across the 12-week programme. The large SD's reflected the variance in the TSK data. This is a challenge of measuring TSK in chronic midportion Achilles tendinopathy. It appeared that the magnitude of the response was not consistent across individuals, however, the study was underpowered due to factors beyond control (loss of subjects to follow up due to COVID-19 pandemic restrictions). Future study could look to recruit greater numbers and match participants beyond age and gender to investigate whether this reduces the variance in the data. Sanz-López, Martínez-Amat, Hita-Contreras, Valero-Campo, & Berzosa (2016) had a much narrower inclusion criterion for their assessment of eccentric overload of 18-25-year-old university students and their SD's were much narrower than those in the current study, albeit still fairly large, again suggesting varied TSK responses between individuals.

Based on the results of chapter five, it cannot be concluded that TSK measurements can be used clinically to assess the response to load of chronic midportion Achilles tendinopathy. Despite finding a normalisation in absolute TSK values in SX_AT's in comparison

to control AT's immediately post running activity, it would be difficult to objectively assess the progress of the AT due to a combination of the variability of resting TSK between individuals (fig 5.1.2 and fig 6.1.2) and no differences existing between the SX_AT's and the ASX_AT's.

### 7.1.4 TSK change in response to SLH

Another aim of this thesis was to establish the normal changes in absolute and ΔTSK in those suffering from Achilles tendinopathy in response to vertical SLH tasks. SLH utilises the SSC through the storage and release of energy throughout the movement (Lamontagne & Kennedy, 2013). SLH is a task that is often used clinically as a functional assessment for those suffering from the condition and is often provocative for symptoms (Hutchison et al., 2013; Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006). In contrast to running where symptoms ease with activity, they tend to worsen with continued SLH repetition, which raised the question of whether TSK response would be the same in symptomatic AT's.

The results of chapter six section one revealed that during week 0 there were initial but statistically insignificant decreases in absolute TSK immediately following the SLH task. The novelty factor of the section was that this was a different TSK response to what was seen following the 15-minute treadmill running intervention. As SLH is an ankle plantar flexor dominant exercise, it was expected that the activity would have led to immediate increases in TSK.

Running at 12km/h, which was the mean speed of the symptomatic participants in the current study, and SLH both expose the AT to similar loads (Starbuck et al., 2020; Baxter et al., 2020). Starbuck et al., (2020) have reported AT loads during running at speeds of 12km/h as being 6.5 ± 0.8 times BW and Baxter et al. (2020) have reported loads of 6.7 ± 1.6 times BW during vertical SLH. Based upon this data, it is likely that the volume of activity (15-minute run vs 3 x 20 SLH) was responsible for the large discrepancies seen in TSK response over the midportion of the AT rather than the magnitude of the load.

A decrease in TSK was still unexpected, particularly in the symptomatic AT's, which have been shown to display increased levels of hysteresis (Wang et al., 2012), which would suggest a warmer local area. Increased metabolic demand from the Gastrocnemius-Soleus musculature could have been responsible for the immediate decreases. Previous work has found that skin intratendinous blood flow decreased and muscular blood flow increased with the onset of activity (Baker et al., 2017; Henry et al., 2015; Kubo et al., 2017). This, coupled

with the theory posed by Li & Hua (2016) who suggested that tensile forces generated during exercise could cause a temporary block to blood flow through neovessels, could explain why there was an immediate decrease in absolute TSK and point towards homeostasis being maintained within a two minute cooldown period. Kubo et al., (2017) also found that blood flow in the tendon also increased when activity ceased and rose during the subsequent recovery period, which may be reflected by the rise in TSK that was seen by the CD2 timepoint.

The results of chapter six section two revealed a main effect of time on absolute TSK values in response to the SLH intervention, irrespective of group, but there were no between-group differences. There was a further absolute TSK decrease when compared to week 0 (0.8°C vs 1.3°C), which also exceeded the MDC value. This was an unexpected finding, as it was assumed that with improvements in function and physiological AT properties (Beyer et al., 2015; Docking & Cook, 2019; Lichtwark & Wilson, 2007; Magnusson & Kjaer, 2019) that absolute TSK response would normalise towards control values.

It seems unlikely that metabolic demand from the Gastrocnemius-Soleus musculature would be responsible for TSK change based upon this. Slow and sustained load has been suggested to improve the efficiency of the musculotendinous unit during SSC activity, which would theoretically reduce the demand on the musculature during SLH (Docking & Cook, 2019). If this was the case, it would have been expected that TSK over the midportion of the AT would have normalised towards the values of the control AT's.

The theory posed by Li & Hua (2016) of tensile forces causing temporary neovessel blockages during activity may still explain why there was further TSK decrease over the midportion of the AT. There is only one existing study that has found that eccentric exercise eradicated neovascularisation in tendinopathy, with 5 cases remaining from 36 (Öhberg & Alfredson, 2004). Regardless of symptom resolution, it may have been possible that the hypoxic tendon environment that is created with tendinopathy may not have improved due to poor AT blood flow (Järvinen, 2020). It may suggest that biomechanical factors are responsible for symptom improvement as opposed to physiological factors, as based on IRT alone there did not appear to be an improvement. However, this is speculative and would require future study assessing histological and physiological factors alongside.

Based on the results of chapter six, TSK of the AT in response to SLH load in those suffering from chronic midportion Achilles tendinopathy is not an appropriate outcome

measure. Despite finding a slight decrease in AT TSK following a 12-week HSR intervention, there were no between-group differences meaning that it would not be possible to differentiate between the SX_AT, ASX_AT or control AT's. Chapter six was underpowered due to factors beyond control (COVID-19 restrictions), therefore future research may look at exploring this with greater sample sizes.

### 7.1.5 SLH kinetic and kinematic variables

Although not an original key aim of this thesis, it was found that there were alterations in kinematic SLH variables during week 0. GCT was found to be longer in both the SX_AT and ASX_AT groups versus the control group. There were also shorter flight times in the SX_AT when compared to the control group during sets 2 and 3 in week 0. The RSI was larger in the control group than both the SX_AT and ASX_AT, with decreases seen across the sets in the SX_AT group. These novel findings suggested that there were biomechanical deficits present in symptomatic participants, both in the SX_AT's and ASX_AT's when compared against AT's from asymptomatic participants.

During week 12, following the HSR programme, RSI was the only kinematic variable that was statistically significantly different across sets and irrespective of group and exceeded the MDC value. Flight time and hop height both increased between sets 1 and 2 and sets 1 and 3, with GCT reducing, however, these values did not exceed the MDC.

The finding that RSI increased following the 12-week HSR programme was important. RSI describes the force production that is needed to achieve a hop height during a cycle of the SSC (Ebben & Petushek, 2010; McMahon, Suchomel, Lake, & Comfort, 2018). A higher value is representative of a more efficient SSC (McMahon, Jones, Suchomel, Lake, & Comfort, 2018). RSI is dependent on strength and the ability to stiffen the musculotendinous unit (Beattie, Carson, Lyons, & Kenny, 2017; Douglas, Pearson, Ross, & McGuigan, 2017; McMahon, 2015) and although strength and stiffness were not measured in the current study which was a limitation, it would seem to indicate that these capabilities improved based on the shorter GCT's, higher SLH heights and improved RSI values that were found. Debenham et al., (2016) found that participants suffering from Achilles tendinopathy demonstrated altered SSC behaviour with increased limb stiffness properties and altered ankle joint kinematics. In contrast, Maquirriain (2012) observed that leg stiffness was significantly reduced in those with Achilles tendinopathy. These contrasting results are interesting and may require future study

to look at strength and stiffness characteristics in those suffering from chronic midportion Achilles tendinopathy and the effect that a 12-week HSR programme has on them.

This novel finding suggested that following the HSR programme, there were positive changes to biomechanical characteristics of the AT in comparison to the AT's of asymptomatic participants. However, due to the small sample size and underpowering of the final study, these would require further investigation alongside the assessment of strength and stiffness.

### 7.1.6 HSR training for Achilles tendinopathy

The rehabilitation intervention that was used in both chapter five and six was the HSR programme, first utilised at the AT for chronic midportion Achilles tendinopathy by Beyer et al. (2015). The programme yielded positive results, with patient satisfaction scores being higher than during the Alfredson protocol, which involved eccentric only rehabilitation. A possible reason for this could have been due to the volume of exercise required, with the Alfredson protocol requiring 1260 repetitions per week. This formed the rationale for choosing the programme for the present study, along with the knowledge that tendons respond well to controlled load allowing them to maintain biomechanical properties and prevent maladaptation (Docking & Cook, 2019; Magnusson & Kjaer, 2019).

Chapter five section three and chapter six section three both revealed that the HSR programme resulted in both statistically and clinically significant improvements in VISA-A scores with values increasing from a mean of 73.4 ± 4.4 points to 93.8 ± 10.0 points ($p<0.001$) and from a mean of 81.4 ± 11.5 points to 95.6 ± 7.4 points ($p<0.001$) respectively. These results were consistent with those found by Beyer et al., (2015). The method utilised by Beyer et al., (2015) prevented participants from taking part in exercise outside of the rehabilitation programme for a 3-week period, which may explain why fewer improvements were seen in the current study despite still being clinically significant. It was expected that this would greatly affect recruitment in the current study as all of the runners involved were training as normal despite being in varying levels of pain both before and after exercise. Therefore, the HSR programme was initiated alongside normal training regimes. The novelty factor of the findings emphasised that despite this, there were still statistically and clinically significant improvements in AT function as monitored using the VISA-A, suggesting that the programme can be completed alongside normal training regimes for recreational runners. The VISA-A

findings supported existing evidence that suggests that the AT responded favourably to slow and sustained load (Docking & Cook, 2019).

Chapter five section three revealed that there were no statistically significant changes in NPRS scores in the running cohort either during or after the running activity. The mean improvement in the score during activity exceeded the MCID scores outlined by Farrar et al. (2001). After the activity, the mean improvement in scores did not exceed the MCID (Farrar et al., 2001), however, they were classed as mild/acceptable at week 0 (Silbernagel & Crossley, 2015). In contrast, in the SLH cohort (chapter six section three), there was a statistically significant mean NPRS score decrease during activity, however, this was within the MCID reported by Farrar et al., (2001). After activity NPRS scores did not significantly change in the SLH cohort but again they were classed as mild/acceptable at week 0 (Silbernagel & Crossley, 2015).

It was unexpected that significant improvements were not seen in NPRS scores during activity because of the significant improvements in VISA-A scores. A possible reason for this could be due to the small sample size and large variations in scores. These were reflected by the large SD's, in NPRS scores during activity, ranging from 0-5 at week 0, and 0-4 at week 12. Despite the lack of statistical significance seen in the running cohort, there are still positives to be taken from the results. Six out of eight participants NPRS scores during activity improved, with two worsening, neither of which exceeded the MCID value (Farrar et al., 2001). In the SLH cohort, the significant NPRS score improvement seen during the activity was positive with no scores worsening, particularly considering the provocative nature of the activity (Hutchison et al., 2013; Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006).

Chapter five section three revealed that there were no significant changes in RPE scores following the HSR rehab programme in the running cohort. However, chapter six section three revealed that there were significant improvements in RPE in the SLH cohort, but it was unknown whether this represented a clinically significant change. It is possible that, due to the provocative nature of the SLH task for those that were suffering from midportion Achilles tendinopathy, RPE scores could have improved due to the reductions in perceived pain. Participants were encouraged to differentiate between pain or RPE each time that they were asked by describing the ease of the activity to complete regardless of pain and the pain caused by the activity in the midportion of the tendon only.

It is possible that RPE scores improved significantly in the SLH group due to alterations in physiological or biomechanical AT properties as the Achilles tendinopathy symptoms had improved (Debenham et al., 2016; Maquirriain, 2012). Debenham et al., (2016) found that subjects suffering from Achilles tendinopathy displayed greater overall lower limb stiffness and hopped in a more ankle dorsiflexed position compared to healthy controls. Following an eccentric rehabilitation intervention, Debenham et al., (2017) showed that ankle kinematics had shifted toward a more plantarflexed hopping position combined with a greater overall lower limb stiffness. In contrast, Maquirriain (2012) observed that leg stiffness was significantly reduced in those with Achilles tendinopathy. Regardless of whether stiffness properties of the AT increased or decreased in response to rehabilitation from tendinopathy, it is probable that participants adopted a modified lower limb strategy to reduce the load on the AT in week 0 to protect from pain, which would reduce the SSC function (Debenham et al., 2016). One of the limitations of the study that was conducted by Debenham et al., (2016) was that the SLH was conducted on a custom-built sled, whereas Maquirriain (2012) utilised a true vertical hop. It is possible that the sled restricted the ability of the participants to switch to a knee flexed (decreased knee stiffness) hop strategy which has been suggested to reduce the peak loading on the AT (Debenham et al., 2016). As the symptoms of Achilles tendinopathy improved the hopping strategy likely normalised, increasing the efficiency of the SSC, thus reducing the RPE scores, which could be supported by previous literature seen during eccentric rehabilitation (Debenham et al., 2017). This was not reflected in the kinetic or kinematic variables assessed during the current study, therefore further study should look to explore AT/limb stiffness changes as a result of HSR rehabilitation.

One of the limitations of using HSR for rehabilitation from Achilles tendinopathy was that it required specialist gym equipment and large loads. In the running cohort, there were 28 modified sessions out of a possible 180 and a total of 12 non-completed sessions from the participants that returned their exercise logs. In the SLH cohort, there were a total of 11 modified and 7 non-completed sessions out of a possible 180. All but 5 of these sessions were due to a lack of access to gym-based equipment. It would have been ideal to account for this and conduct the rehabilitation sessions in the strength and conditioning suite at the University, however, this was not feasible for several reasons. Firstly, participants had to complete the programme three times per week for 12 weeks which created unrealistic travel demands for many of them who were attending around work. Secondly, it would have created

unrealistic time constraints from a research perspective with each individual gym session lasting approximately 40-minutes.

Participants were instructed to modify their sessions if they were not able to access equipment. The instruction that they were given was to replicate each of the exercises using free weights. They were asked to load as heavily as possible and be guided using RPE and NPRS scores. They were instructed to adhere to the 6-second repetitions and be guided by the metronome app. The rationale for this was provided by Docking & Cook (2019), AT's respond to slow and sustained load, therefore as long as the participants were able to modify this safely and in accordance with RPE, NPRS score and the metronome then this was deemed acceptable. As previously stated, this happened in 39 out of 360 rehabilitation sessions.

### 7.1.7 Clinical implications

It was found that there were no differences between SX_AT, ASX_AT or control AT's at baseline following an acclimatisation period (chapter four), which would mean that clinicians are unable to differentiate between the AT's by observing TSK. The utility of the FLIR ONE for the assessment of chronic midportion Achilles tendinopathy symptoms at rest is therefore not appropriate as it appears that there is no thermal response between symptomatic and asymptomatic participants. This may not be the case for those individuals who are suffering from reactive inflammatory exacerbations of their symptoms and would require future study in this population.

Significant differences were found between symptomatic and asymptomatic running participants (chapter five section one). However, there were no differences between SX_AT's and ASX_AT's. Clinically, it would not be possible to identify whether one AT is symptomatic in an individual compared to the contralateral one. However, future research could look to collect large scale normative data to assess whether it is possible to identify those individuals susceptible to chronic midportion tendinopathy following running activity who may have reduced absolute TSK. It may not be a simple thing to predict, as the current study revealed that there were large SDs amongst the cohort of runners involved which reflected the individual variances in TSK response to running activity.

The results of chapter five section two revealed that the TSK response of the running cohort SX_AT was no longer statistically significant when compared to the control group, however, there were still no significant differences between the SX_AT's and ASX_AT's. Again,

this would make the use of smartphone compatible infrared thermal imaging difficult in a clinical setting. A clinician would not be able to differentiate between symptomatic or asymptomatic limbs after a 12-week HSR programme before or following a running task because they have a similar thermal response. Large scale normative data with appropriate power could help to identify whether a person is at risk of Achilles tendinopathy against other individuals, but this would require further research.

Chapter five section three revealed that there were no statistically significant changes in TSK of the SX_AT's or ASX_AT's as a result of the 12-week HSR programme. Despite an insignificant shift towards normal TSK when viewing absolute and ΔTSK results, there were large SD's in the data which reflected the variance in participant TSK response. Again, this ruled the FLIR ONE out for objectively assessing the progress of midportion Achilles tendinopathy in response to a rehabilitation programme as there were no clear thermal changes between the weeks.

Chapter six section one revealed that there were no significant TSK differences between SX_AT's, ASX_AT's or control group AT's at week 0 in response to a SLH intervention. There was a decrease in absolute TSK which was the opposite reaction that was observed when compared to the running cohort, but this was statistically insignificant. Therefore, as the TSK change was clinically insignificant, the FLIR ONE should not be used clinically to distinguish between SX_AT's or AS_ AT's or between symptomatic or asymptomatic participants.

Chapter six section two revealed that irrespective of the group there were statistically significant TSK decreases immediately post SLH exercise following the 12-week HSR programme. This unexpected response did not have any clinical implications as the purpose of using the tool clinically would be to differentiate between symptomatic or asymptomatic participants, or SX_AT's and ASX_AT's.

Chapter six section three confirmed that there were no significant differences in absolute or ΔTSK found within the SX_AT or ASX_AT groups between weeks 0 and 12 following the 12-week HSR programme. This confirmed that the FLIR ONE should not be used as a clinical tool to assess chronic midportion Achilles tendinopathy following a SLH task as significant thermal changes did not occur at the surface of the skin.

Despite no thermal response existing in those with chronic midportion Achilles tendinopathy, this thesis has revealed other important clinical implications. Firstly, the use of

a 12-week HSR rehabilitation programme (Beyer et al., 2015) has been shown to be successful for the management of chronic midportion Achilles tendinopathy alongside normal training regimes in recreational runners. However, clinically it should be recognised that in some instances, it did not completely resolve the symptoms of the condition. Therefore, clinicians should consider all existing evidence before deciding which rehabilitation programme to prescribe to patients. A limitation to the programme is that it does not incorporate plyometric activity, which could expose the AT to greater and more sport-specific loads than slow-sustained contraction, however, this would need to be investigated further as there is little evidence to suggest that plyometric activity causes positive adaptations in tendinous structures (Docking & Cook, 2019). One such programme to consider has been outlined by Silbernagel & Crossley (2015) however further study is required to assess this programme against existing regimes.

Clinically, collagen synthesis and degradation must be considered, with previous studies suggesting that immediate protein degradation occurs after acute bouts of exercise, and maximum synthesis occurring 1-3 days after, however this was following a 30 km endurance run (Kjaer et al., 2006). One of the benefits of the 12-week HSR programme is that it requires 3 sessions per week to be completed, which allows greater time for collagen synthesis to occur when compared against the Alfredson or Silbernagel programmes (Alfredson & Cook, 2007; Alfredson et al., 1998; Silbernagel & Crossley, 2015). It also compliments evidence that the AT responds favourably to high strain over longer contraction durations (Arampatzis et al., 2007; Arampatzis, Peper, Bierbaum, & Albracht, 2010; Bohm, Mersmann, Tettke, Kraft, & Arampatzis, 2014). The training regimes of patients must be controlled around this using NPRS and RPE scores so that the AT's are not subjected to overload and that protein degradation does not supersede collagen synthesis (Kjaer et al., 2006) and thus worsen the tendinopathy.

Kinesiophobia must be considered when prescribing a HSR programme to those suffering from Achilles tendinopathy. Due to the nature of the heavy loading, some patients may fear the consequences of large loads through the AT due to expected pain or the possibility of further injury. Silbernagel, Brorsson, & Lundberg (2011) found that the effectiveness of a rehabilitation programme that involved loading the AT beyond body weight (Silbernagel, Thomeé, Eriksson, & Karlsson, 2007) was influenced by the level of kinesiophobia, with higher fear of movement equating to a longer recovery. On the contrary, too low levels of kinesiophobia must be recognised as potentially detrimental to recovery from Achilles

tendinopathy as they may be more likely to overload the AT which may result in maladaptation (Silbernagel et al., 2011; Magnusson & Kjaer, 2019)

The 12-week HSR programme did not significantly affect the majority of the SLH kinetic or kinematic variables once Bonferroni correction had been applied to account for type I error. SLH height was the only variable where significant differences did exist post-Bonferroni correction, however, the difference of 0.007m between sets 1 and 2 in the ASX_AT group did not exceed the SEM or MDC values meaning that it was clinically insignificant. Despite the lack of performance improvement seen with these variables, there were various improvements seen in running performance alongside the study, with several lifetime personal bests achieved in races. Although these were not monitored and are not reported in the thesis, this could inspire future study and could assess the performance benefits of the HSR programme on running performance over various distances in conjunction with or separate to clinical symptoms of Achilles tendinopathy. It is not possible to say whether it was the HSR programme alone that resulted in the running improvements, or the initiation of strength training in general, as many of the recreational athletes involved in the study were not regular gym attendees.

### 7.2 Limitations and future study

There were limitations to the current study and the consideration of these limitations has generated further questions and potential lines of future study. The method of analysis that was employed looked specifically at the TSK over the midportion of the AT using a line ROI. One of the limitations of the line being 1 pixel wide was that it analysed a small portion of the AT in a medial-lateral direction and may not have picked up TSK variations along the medial-lateral borders of the AT. However, the FLIR ONE interpolates the thermal image with the digital image, therefore there is only one temperature value per four pixels. Subsequently, this method of analysis would likely not have resulted in drastic TSK variations when the width of the AT in pixels was considered. It could be beneficial for future research to use other software which would allow a custom drawn ROI where non-linear shapes can be drawn to encompass a full AT midportion.

A philosophical theme throughout this thesis was the possible link between metabolic demand of the Gastrocnemius-Soleus musculature and the TSK of the midportion of the AT based upon existing literature (Ammer, 2017; Katayama & Saito, 2019). Future research could

look at whether there is a relationship between TSK of the Gastrocnemius-Soleus musculature compared with midportion AT TSK in those with midportion Achilles tendinopathy. This may help to provide proof of concept for physiological changes in the two different regions in response to exercise. This could be combined with tools to assess regional blood flow such as Doppler.

The emergence of COVID-19 limited the study as it affected the recruitment of control participants and led to chapter five sections two and three and chapter six sections two and three being underpowered. The reason that it only affected the control group was due to the design of the study. It was decided that symptomatic participants were going to be recruited first due to the foreseen difficulty of securing participants for a 12-week rehabilitation programme. Once it was decided that the data collection for symptomatic participants was on track, control recruitment was initiated. Ideally, a total of 17 symptomatic and 17 asymptomatic participants were required for chapter five section one and 19 symptomatic and 19 control participants were needed for appropriate power in chapter six section one. The required number of symptomatic participants was met for each of the sections; however, the control groups were two and four participants short respectively.

Ideally, it would have been beneficial to collect TSK and 12-week HSR data on the control group. However, there was a lack of interest from control participants to return to the laboratory for testing after 12 weeks. Firstly, evening sessions were limited by laboratory opening hours. For many of them, testing fell outside of working hours (mainly evenings) which were the times that they normally trained for their respective disciplines. Secondly, many of the participants for testing travelled long distances and would have to compete with large volumes of rush hour traffic to attend the laboratory on a further two occasions.

As discussed previously, the adherence rates to returning the logs of exercise were 62.5% and 55.5% in chapter five section two and chapter six section two respectively. One of the initial aims of the studies was to quantify the total loads that each of the participants lifted during the 12-week HSR programme as a way of monitoring load exposure alongside training regimes. However, due to the lack of adherence to retuning the logs and some of those that did return the logs did not complete a full diary of load lifted, it was not assessed. Participants did return for clinical assessment at 4-weekly intervals and they were questioned about their participation in programmes. All of the participants who were included in the analysis

demonstrated that they were adhering to the 12-week HSR programmes, they just failed to submit their log of exercise upon completion of the study.

The same was true with normal running regimes. Not all participants recorded their running activity as requested so could not give accurate details around the distance of their sessions, therefore this information was not accurate enough to be included for analysis.

Chapters five and six of this thesis supported existing evidence that HSR training improved the clinical symptoms of chronic midportion Achilles tendinopathy. Future study should seek to address the underlying reasons for this change. Beyer et al., (2015) found that some physiological characteristics of the AT were improved following the 12-week HSR programme, but further work could seek to address whether the programme resulted in biomechanical changes that would be beneficial to overall AT and SSC function as observed alongside this study in recreational runners.

Future study may be appropriate in those individuals with acute Achilles tendinopathy. It could be possible that there are physiological differences that exist between those with chronic and acute tendinopathy in terms of their initial adaptive responses, which unlike during chronic tendinopathy, may be reflected at the surface of the skin in acute pathology.

## 7.3 Conclusion

The overall recommendation based on the results of chapters five and six is that the assessment of TSK of the midportion of the AT is not a viable way of identifying or managing chronic midportion Achilles tendinopathy in runners. Despite TSK changes being identified in response to running and SLH tasks, there were no clear differences in the thermal responses between SX_ATs and ASX_ATs in response to the 12-week HSR programme. It is possible that the studies were underpowered which may have contributed to the lack of statistical significance found between groups.

The novel finding from this thesis is that there are no clear differences in thermal response between symptomatic or asymptomatic ATs. The suggestion that increased hysteresis would lead to increased TSK in the region of the AT was not evident, particularly in the SLH cohort, which was surprising given that SLH is an ankle dominant exercise that utilises the SSC. Given the chronic nature of the pathologies assessed in the current study, it may be that the FLIR ONE can be used for future projects looking at acute Achilles tendinopathy, or acute conditions within other lower limb joints.

The success of the HSR programme designed by Beyer et al. (2015) for the rehabilitation of chronic midportion Achilles tendinopathy should be noted. This should be considered as part of any evidence-based rehabilitation programme for patients with chronic midportion Achilles tendinopathy who can access gym facilities. The current thesis has provided evidence that this programme can be conducted effectively, without modification to normal recreational running regimes. This may improve patient adherence to long-term rehabilitation moving forward.

# Appendices

## Appendix 1: Reliability and construct validity of two commercially available thermal imaging cameras

Non-contact infrared Thermal Imaging (TI) is becoming a popular method of assessing skin temperature in sports medicine. A specialised infrared TI camera allows an individual to record a thermogram of a region of skin. This thermogram is a still picture image which allows for the calculation of skin temperature in the chosen region of interest. Infrared TI has been employed in a clinical setting since the mid-1900s and utilises the phenomenon that living and non-living objects all emit infrared radiation to some extent. This rapidly developing technology can be utilised to detect, locate and monitor thermal changes or abnormalities characterized by an increase or decrease in skin temperature and consequently, could become a valuable tool in sports medicine and research. TI could be used to diagnose injuries as it is well established that overuse injury, and several other pathophysiological injuries that affect athletes, cause inflammation and a subsequent localised increase in skin temperature around the affected region.

Currently, there are several different TI devices which are commercially available to measure skin temperature. What is lacking from the literature on TI is validity studies comparing commercially available TI devices to criterion measures such as thermocouples and also the between device reliability. Fernandes et al. (2014) measured skin temperature before during and after exercise with thermocouples and a TI device they found moderate reliability before exercise (ICC = 0.75, mean difference -0.75°C), poor correlation during exercise (ICC = 0.49, mean difference -1.22°C) and after exercise (ICC = 0.35, mean difference -1.16°C). Bach et al. (2015) reported poor agreement between TI device and thermocouples (mean difference 0.83+/-0.77°C (pre-exercise), 1.88+/-1.87°C (post-exercise)).

The primary aim of the current study is to assess the construct validity of two commercially available thermal cameras against thermocouples to measure temperatures close to body temperature. The secondary aim is to compare the reliability of temperature reading, between two commercially available thermal cameras, when measuring temperatures close to body temperature.

Method

The three thermocouples were placed in the pre-heated plastic water bath one in the middle, one on the side in the water closest to the FLIR ONE camera and one on the side closest to the FLIR I5 camera. The thermocouples (Instrutherm S-09K) had a measurement range from -70-500°C, with an accuracy of 0.5%. The smart device camera was a FLIR ONE, which has an infrared resolution of 160x120 pixels and a sensitivity of 150mK, mounted onto a third-generation iPad. The FLIR tools application was used to take images and record spot temperatures. The second camera that was used was a FLIR I5 handheld device, which has an infrared resolution of 100x100 pixels and a sensitivity of 100mK.

The cameras were held 80cm away and perpendicular to the water bath, the thermograph was captured simultaneously from both cameras every minute, for 20 minutes. The emissivity of the cameras was set at 0.94, in line with the known emissivity of clear plastic. Average ambient air temperature throughout the data collection period was 22.0+/-0.1°C. The starting temperature for the water bath was 38.0°C and the final temperature of the water bath (after 20 minutes) was 34.1°C, as measured by the central thermocouple.

**Set up**


*Yellow markers = thermocouples

*Red markers = Thermal devices

**Analysis**

The relationship between the recorded temperatures from each thermal camera was assessed using ICC (3,1) correlation and further analysed for the significance of any differences in recordings using a one-sample t-test. Agreement was assessed using Bland Altman analysis, the mean bias and 95% limits of agreement (LoA) in SPSS. The manufacturer

stated accuracy of the FLIR ONE is ±5%, therefore a priori acceptable mean bias was defined as a value within 5% of the mean absolute TSK measurement.

A one-way ANOVA was conducted to assess whether there were any differences in temperature measurements between the thermocouples.

## Results

The captured temperature values can be seen in figure 1. The inter-device reliability for temperature recorded by the thermocouple and both the handheld device and the iPad device was excellent (Table 1).

Table 1: Inter device reliability ICC's and 95% Confidence intervals (CI)

| Device | ICC | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| FLIR ONE vs I5 | 0.998 | 0.995 | 0.999 |
| FLIR ONE vs thermocouple | 0.981 | 0.955 | 0.992 |
| FLIR I5 vs thermocouple | 0.974 | 0.936 | 0.989 |

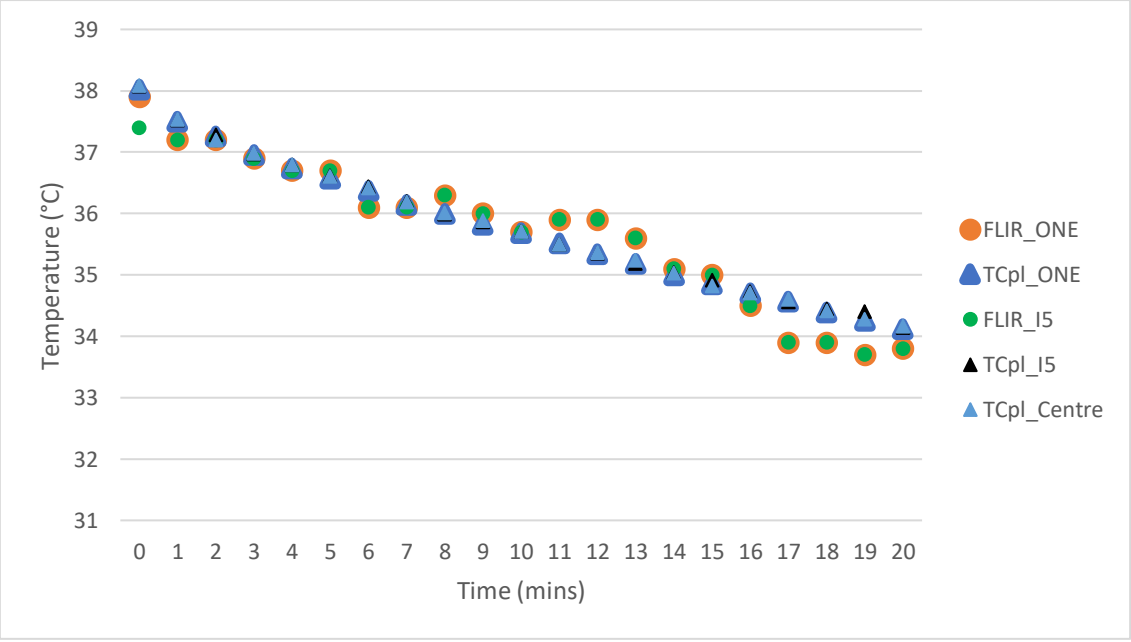



Figure 1: Temperature data from each device across the 20-min capture period.

The Bland-Altman plots for the iPad device and the associated thermocouple, the handheld device and the associated thermocouple and between the iPad and handheld devices can be seen in figures 2, 3 and 4 respectively. The mean temperature measurement for the FLIR ONE was 35.7°C, therefore acceptable bias was within 1.8°C.

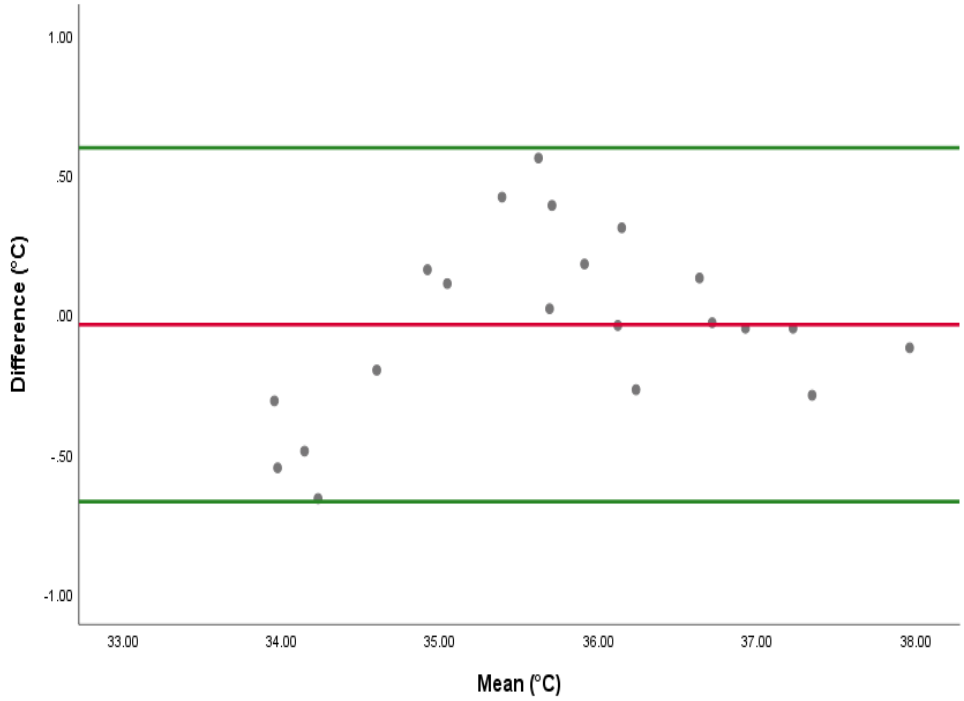



Figure 2: Bland-Altman plot for the FLIR ONE and the associated thermocouple.

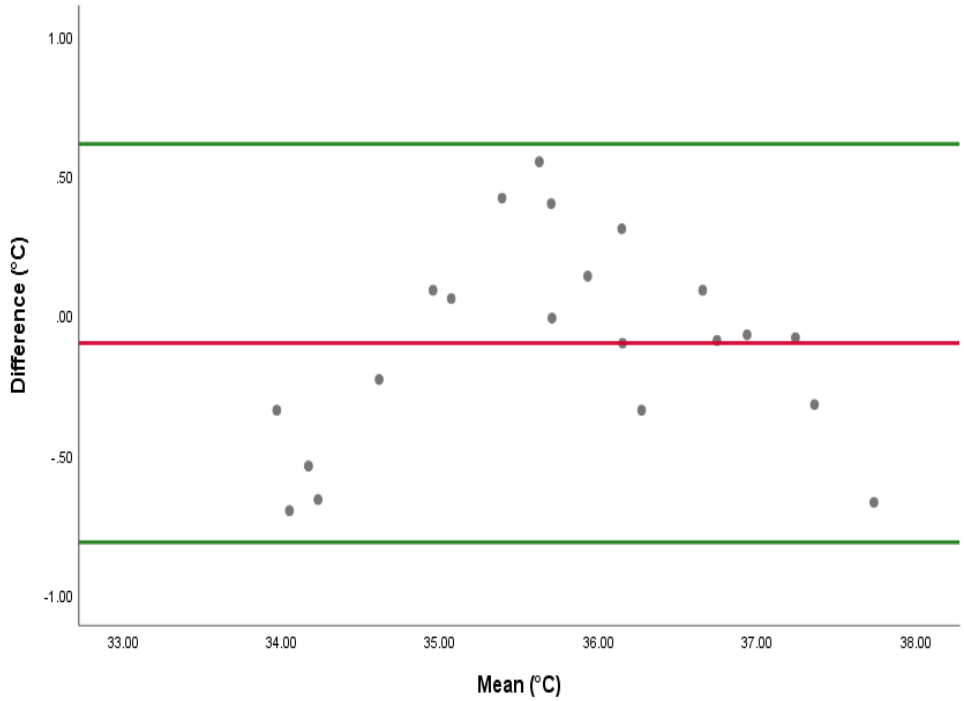



Figure 3: Bland-Altman plot for the FLIR I5 and the associated thermocouple.

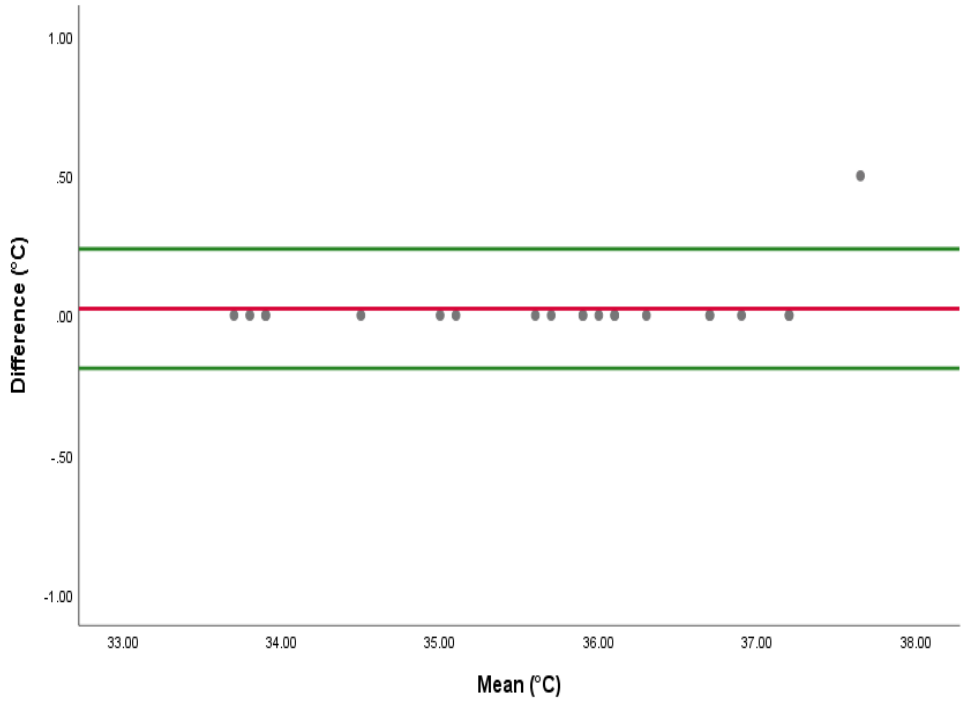



Figure 4: Bland-Altman plot for the FLIR ONE and the FLIR I5.

The one-way ANOVA revealed that there were no statistically significant differences between the temperature measurements of the three thermocouples across the 20 minutes ($F_{(2,60)}$ = 0.007, p=0.993).

**Discussion**

The results of the study support the hypothesis that the FLIR ONE and the FLIR I5 are valid measures of temperature when compared to a thermocouple control. This is evidenced by the excellent ICC figures for the FLIR ONE and the FLIR I5 (Table 1). The fact that there were no statistically significant differences (p=0.993) between each of the three thermocouples evidences that the water temperature was constant throughout the plastic container.

The results of this study contradicted findings by Bach et al. (2015) who found that poor agreement existed between conductive and infrared devices in the heat, both during rest, exercise and subsequent recovery. Evidenced by the mean bias (0.83°C +/-0.77°C), it was concluded that the infrared thermal device consistently overrated skin temperature compared to the criterion thermocouple. The a-priori limits of agreements were not exceeded in the current study between devices.

In contrast to Bach et al. (2015), Fernandes et al. (2014) found that the infrared thermal cameras used in the study consistently underrated skin temperature in comparison to the criterion thermocouple, with a mean bias of -0.75°C +/-0.75°C during a pre-exercise condition. This bias increased throughout exercise conditions in the heat. These differences may be explained when considering the attachment of the thermocouples. Fernandes et al. (2014) use a microporous tape, compared to a non-microporous sports tape in the study by Bach et al. (2015). The tape will create a local micro-environment which may affect the values of skin temperature read from the thermocouple. The infrared device does not have this issue as areas of skin can be analysed without having to place anything directly on the surface of the skin where temperature readings will be measured from. In the current study, the local environment surrounding the thermocouple was not an issue as they were not secured in the water via taped attachment, and resultantly there is a greater agreement between the infrared and conductive devices.

Unlike our study, James et al. (2014) conducted a validity test assessing a thermal imaging camera against a criterion thermistor and found that there were not acceptable limits of agreement (2.01°C +/- 0.74°C). The results of the study must be interpreted with caution

as they use a cast-iron block that is suspended in a water bath as their reference temperature point, however, they state that the camera is set at an emissivity of 0.98. This does not account for the emissivity of the iron block, with cast iron emissivity values ranging from 0.21-0.81 depending on whether it is polished, cased or oxidised ("Emissivity Values for Common Materials", 2020). This could potentially have led to erroneous absolute temperature values for the infrared thermal camera.

**Limitations**

A potential limitation of the current study is that infrared temperature measurements were taken using the spot temperature function on the outside of the plastic water tank, whereas the thermocouple reading was taken from the inside of the tank at the same level. There is the potential that the outer plastic surface may have affected the conductivity of the heat emanating from the water tank. This means that values of absolute temperature must be interpreted with caution.

**Conclusion**

To conclude, infrared thermal imaging devices demonstrate acceptable levels of agreement in assessing temperature that is close to body temperature values when compared to wired thermocouple devices. Furthermore, the smart device compatible infrared thermal imaging camera showed excellent reliability when compared with the other commercially available infrared device.

## Appendix 2: Ethical approval forms

University of Salford MANCHESTER

Research, Enterprise and Engagement
Ethical Approval Panel

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

T +44(0)161 295 2280

www.salford.ac.uk/

23 January 2018

Dear Ben,

**RE: ETHICS APPLICATION–HSR1718-032 – 'The reliability and validity of a smartphone based infrared thermal imaging camera for detecting skin temperature change of the Gastroc-Soleal muscle complex in response to dynamic exercise.'**

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-032 has been approved.

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

Yours sincerely,

Professor Sue McAndrew
Chair of the Research Ethics Panel

University of Salford MANCHESTER

**Research, Enterprise and Engagement**
**Ethical Approval Panel**

Doctoral & Research Support
Research and Knowledge Exchange,
Room 827, Maxwell Building,
University of Salford,
Manchester
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk

7 December 2018

Dear Ben,

**RE: ETHICS APPLICATION–HSR1718-014 – 'A prospective observational study to assess the skin temperature and structural response of the Achilles tendon during a tendon loading programme.'**

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-014 has been approved.

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

Yours sincerely,

Professor Sue McAndrew
Chair of the Research Ethics Panel

## Appendix 3: Chapter 3 recruitment poster

Recruitment poster v1.0 28/11/2017

University of Salford MANCHESTER

The reliability and validity of a smartphone based infrared thermal imaging camera for detecting skin temperature change of the Gastroc-Soleal muscle complex in response to dynamic exercise

Aim of project: To establish the reliability and validity of the FLIR one (smartphone based) thermal imaging camera in detecting skin temperature change against an already validated FLIR E8 thermal imaging camera in the Gastroc-Soleal region.

Future aspiration are that the mobile device can be used clinically to help detect skin temperature change that may or may not be indicative of tendon dysfunction.


Next step? If you're interested in participating in the study, aged 18-60, and injury free, contact the researcher on the email below, feel free to tear a strip off!

Researcher: Ben Oliver

Supervisor: Lee Herrington

What do you need to do? Data collection will involve a series of images being taken of your calf muscles and Achilles tendons. After this you need to hop on the spot, 3 sets of 20 hops, before a further set of images are taken. That's all!

How long will it take? No more than 30 minutes!

B.Oliver1@edu.salford.ac.uk

## Appendix 4: Chapter 3 participant information sheet

**Study Title**

**The reliability and validity of a smartphone-based infrared thermal imaging camera for detecting skin temperature change of the Gastroc-Soleal muscle complex in response to dynamic exercise**

**Invitation paragraph**

I would like to invite you to participate in a research study that is going to assess the reliability and validity of a smartphone-based infrared thermal imaging camera in assessing skin temperature change in response to exercise in the calf muscle region.

Before you decide whether or not you would like to participate, you must understand what the study involves and why it is being done, by reading the information carefully. If you would like any further information or are unsure about anything that you read, please ask, using the contact details below. I would like to make it clear that you are under no obligation to take part, it is entirely voluntary.

**What is the purpose of the study?**

The study is the first part of an overall PhD project that aims to establish levels of heat loss from the Achilles tendon during dynamic activity, using a smartphone-based infrared thermal imaging camera. Research has stated that heat loss possibly causes tendon dysfunction, but due to the expense and complexity of how it is currently measured, no data exists from a clinical perspective. The smartphone-based camera is a relatively cheap method of assessing temperature, however, its specifications are less than the recommended cameras used throughout the literature, therefore these need exploring.

The purpose of this study, therefore, is to establish the reliability and validity of the smartphone-based thermal imaging camera by comparing it to an already validated thermal imaging camera. This will be done by two researchers, who will take images and analyse the data using a software programme. It is hoped that the study will reveal the normal amounts of skin temperature change of the calf region before and in response to single-leg hopping. This will provide a benchmark for future studies to hopefully identify whether dysfunctional tendons lose more heat, which could relate to injury.

**Why have I been invited?**

You have been invited to participate in the study because you fit the inclusion criteria. You are between the ages of 18-60, you participate in a minimum of three hours of exercise per week and you have no Achilles tendon injury. If you score below 100 in section B of the PAR-Q you will be excluded from the study, however, I must stress that this is nothing to worry about, it just means that you may have a slight dysfunction of your tendon and you will be advised on where to go to get this assessed. It is estimated that the study will contain between 8-10 participants in total, all of which will be performing their testing at separate times to yourself.

**Do I have to take part?**

You decide whether or not you wish to take part. Participation or non-participation will have no ill-effect on your university status. After reading this form, if you are happy to proceed, we will then ask you to sign a consent form which outlines that you are happy to participate. You will be free to withdraw yourself and your data from the study at any time and do not have to provide a reason, up until the point of data anonymization which will occur the day after the last data collection.

**What will happen to me if I take part?**

It is estimated that the research protocol will take about 30 minutes to complete and will only involve attendance at one session. In the session, you will have your height, sitting height, weight and leg length taken. Then you will have infrared thermal images taken of your calf muscle and Achilles tendon region before you perform a series of 3x20 hops on the spot. Once this is completed you will have a few more thermal images taken. Your involvement is then complete (See below for detailed methodology).

As the study involves imagery, it is appropriate to let you know what will happen with the images. Firstly, no personal data or identifying features will be revealed in the images. They will automatically be saved onto the internal memory of the thermal imaging cameras/smartphone. Immediately after data collection, the images will be stored onto the

university F: drive in an anonymous and coded fashion and will be deleted immediately from the memory of the camera/smartphone.

**What will I have to do?**

The session will involve an approximate 5-minute period for you to read the information sheet, ask any questions and sign the consent form. Then you will have your height, sitting height, weight and leg length measured. Markers will be placed onto your lower limb so that researchers can later identify different points on your leg to help them with analysis. You will then stand for 15 minutes whilst your body acclimatises to the temperature of the room. During this time a series of images will be taken using both thermal imaging cameras to track the skin temperature and make sure that it stabilises.

After the 15 minutes, two more images per leg will be taken as baseline measures for skin temperature. You will then be asked to hop on the spot, standing on a Kistler force plate, 3 sets of 20 repetitions, before having another thermal image taken of the calf region. This will then be repeated on the opposite leg. After this, your skin temperature will be re-measured at 1-minute intervals for 10 minutes. After these 10 minutes, the experiment is over.

**What are the possible disadvantages and risks of taking part?**

As the experiment involves single leg hopping, there is a chance of injury, however, it is extremely unlikely. Single leg hopping is a demanding task, and it may be possible that you experience slight muscle soreness in the days following the hopping. This is normal with demanding activity. Surrounding the force plate, there is a custom-built wooden frame, at the same height as the force plate, to prevent you accidentally hopping off the plate. There are no other disadvantages of taking part in the study.

**What are the possible benefits of taking part?**

There is no direct benefit to yourself for taking part in the study, however, we hope that long term your contribution will help those suffering from Achilles tendon dysfunction.

**What if there is a problem?**

If you have a concern about any aspect of this study, you should ask to speak to the researcher (details anonymised for initial approval) who will do their best to answer your questions. If you remain unhappy and wish to complain formally you can do this by contacting the Research Supervisor (details anonymised for initial approval). If the matter is still not resolved, please forward your concerns to Professor Susan McAndrew, Chair of the Health Research Ethical Approval Panel, Room MS1.91, Mary Seacole Building, Frederick Road Campus, University of Salford, Salford, M6 6PU. Tel: 0161 295 2278. E: s.mcandrew@salford.ac.uk

**Will my taking part in the study be kept confidential?**

Your participation in the study will be kept entirely confidential by the research team. It is up to you if you choose to disclose your participation with anyone else. The research team will follow the procedures for handling, processing, storing and destroying data in line with the Data Protection Act 1998.

Your anthropometric data will be collected using a height measure scale and recorded into a spreadsheet on Microsoft Excel, which will be saved on the University F: drive. The data inputted into the spreadsheet will be anonymous and coded, known only to the researcher, so that your personal information is not present.

Your temperature data will be taken using the FLIR one and FLIR E8 thermal imaging cameras. The FLIR One thermal imaging camera automatically saves pictures to the smartphone device which it is attached to. Immediately after data collection, these images will be transferred to the University F: drive and stored in an anonymous and coded fashion known only to the researcher. They will then be deleted from the smartphone device. This process will be repeated with the images that are automatically stored on the internal memory of the FLIR E8 thermal imaging camera.

The researcher will hold a list of participants on the University F: drive which will identify names based on the codes. At the time of anonymization, the already anonymous data will be transferred to a separate member of the research team who will further code it to make

it unidentifiable by the researcher. This reason for this is so that the researcher cannot identify data when it comes to analysing the results.

The results of the study may be presented in a journal article or at future poster presentations, however, none of your data will be revealed and your participation in the study will remain entirely anonymous.

The data from the study will be stored for 3 years after the completion of the PhD study before being destroyed.

**Can I withdraw from the study?**

You can withdraw from the study up to 1 week of your participation and your data will be destroyed. After this, all data will be anonymised, and it will not be possible to withdraw your data.

**What will happen to the results of the research study?**

If you would like to know the results of the study, please identify this on your consent form. The researcher will email you once the study is finished to make you aware of any publications and to give you a brief outline of the findings. Any published data will be anonymous, and you are unidentifiable.

**Who is organising or sponsoring the research?**

The research is being undertaken as part of a PhD project at Salford University. No external funding has been received.

**Further information and contact details:**

Generic research information can be found on the following university website: http://www.salford.ac.uk/research

Project-specific details can be obtained by emailing the researcher on the following email address: b.oliver1@edu.salford.ac.uk

Should you need advice on whether you are fit to participate in the study can be obtained by emailing b.oliver1@edu.salford.ac.uk

**Appendix 5: Chapter 3 participant consent form**

**Title of Project: The reliability and validity of a smartphone-based infrared thermal imaging camera for detecting skin temperature change of the Gastroc-Soleal muscle complex in response to dynamic exercise**

**Ethics Ref No: HSR1718-032**

**Name of Researcher: Ben Oliver**

*(Circle as appropriate)*

| | | | |
|---|---|---|---|
| ➢ I confirm that I have read and understood the information sheet for the above study (V4.0 14/02/2018) and what my contribution will be. | **Yes** | **No** | |
| ➢ I have been allowed to ask questions (face to face, via telephone and e-mail) | **Yes** | **No** | |
| ➢ I have been made aware of the protocol in place should I be unhappy with any aspect of the study | **Yes** | **No** | |
| ➢ I am aware that there is a risk of injury/post-exercise muscle soreness due to the hopping involved in the study | **Yes** | **No** | **NA** |
| ➢ I agree to digital thermal images being taken during the research and these images will be transferred from the thermal imaging cameras to the university F: drive where they will be coded | **Yes** | **No** | **NA** |
| ➢ I agree to a separate member of the research team viewing the images in their coded format to further code them to prevent any bias during image analysis | **Yes** | **No** | **NA** |

| | | |
|---|---|---|
| ➢ I understand that my participation is voluntary and that I can withdraw from the research at any time **without giving any reason up until one week after participation** | **Yes** | **No** |
| ➢ I understand how the researcher will use my images (for analysis in FLIR tools software), that they will be seen by the research team and that the data will be stored on the university F: drive for 3 years post-graduation | **Yes** | **No** |
| ➢ Please state "YES" if you would like to receive information regarding the results of the study, and provide your email address at the end of the form | | |
| ➢ **I agree to take part in the above study** | **Yes** | **No** |

Name of participant

……

Email of participant (if wanting to receive results of the study) ……..

Signature …….

Date …….

Name of researcher taking consent …Ben Oliver……

Researcher's e-mail address …b.oliver1@edu.salford.ac.uk……

**Appendix 6: Chapter 3 participant Physical Activity Readiness Questionnaire (PAR-Q)**

This PAR-Q is designed to ascertain whether you are fit enough to participate in the study and whether you meet the inclusion or the exclusion criteria. This experiment should not cause you physical exertion, but we want to identify any potential participants who may not be able to complete this exercise safely and effectively. In section B, if you score below 70, this will be deemed that you are not fit to participate in the study based on your Achilles pathology, however, this is nothing to be concerned about. Please read the questionnaire carefully and answer yes/no appropriately, providing further explanation where necessary. Thank you.

Section A

1. Have you been told by your doctor that you have any problems with the following? If Yes, please explain:

| | | |
|---|---|---|
| Thyroid | Yes / No | |
| Heart | Yes / No | |
| Rheumatoid Arthritis | Yes / No | |
| Epilepsy | Yes / No | |
| Asthma | Yes / No | |
| Diabetes | Yes / No | |
| Allergies | Yes / No | |

2. Do you frequently have pains in your heart/chest? If yes, please explain:

| | |
|---|---|
| Yes / No | |

3. Do you often have spells of dizziness when exercising? If yes. Please explain:

| | |
|---|---|
| Yes / No | |

4. Do you suffer from high blood pressure?

| Yes / No |
|---|

5. Do you suffer from pain during impactful activity? If yes, please explain:

| Yes / No | |
|---|---|

6. Do you suffer from any lower back problems? If yes, please explain

| Yes / No | |
|---|---|

7. Have you suffered any lower limb musculoskeletal injury within the last 6 months? If yes, please explain:

| Yes / No | |
|---|---|

8. Do you smoke? If so, please state when you had your last cigarette/e-cig

| Yes / No | |
|---|---|

9. Are you currently taking any medication? If yes, please state the name and function of the medication:

| Yes / No | |
|---|---|

10. If you are female, are you currently pregnant?

| Yes / No / Not applicable |
|---|

11. How many hours per week do you participate in exercise for?

| 0-3 | 3-6 | 9+ |
|---|---|---|

12. What type of activity do you participate in?

| |
|---|

13. When did you last train/compete/play?

| Today | Within 24 hours | 24 hours + |
|---|---|---|

14. Is there any reason why you feel that you would not be able to participate in the study? If yes, please explain:

| Yes / No | |
|---|---|

15. Have you ever suffered any injury to either of you Achilles tendons? If yes please explain, then pass the form to the researcher, who will complete section B with you:

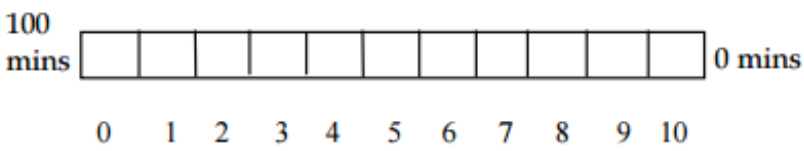
| Yes / No | |
|---|---|

Section B: VISA-A questionnaire

The VISA-A questionnaire: An index of the severity of Achilles tendinopathy

IN THIS QUESTIONNAIRE, THE TERM PAIN REFERS SPECIFICALLY TO PAIN IN THE ACHILLES TENDON REGION

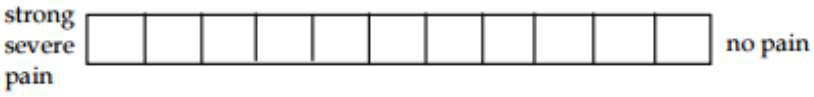
1. For how many minutes do you have stiffness in the Achilles region on first getting up?




POINTS

□

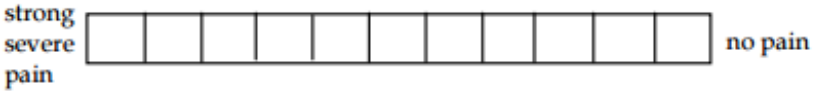
2. Once you are warmed up for the day, do you have pain when stretching the Achilles tendon fully over the edge of a step? (keeping knee straight)




POINTS

□

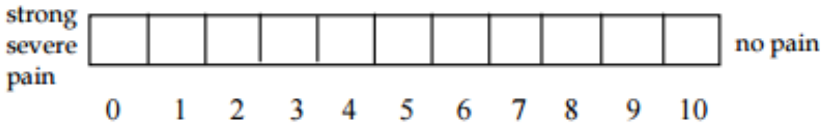
3. After walking on flat ground for 30 minutes, do you have pain within the next 2 hours? (If unable to walk on flat ground for 30 minutes because of pain, score 0 for this question).




POINTS

□

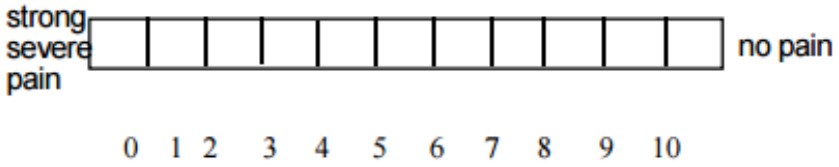
4. Do you have pain walking downstairs with a normal gait cycle?




POINTS

□

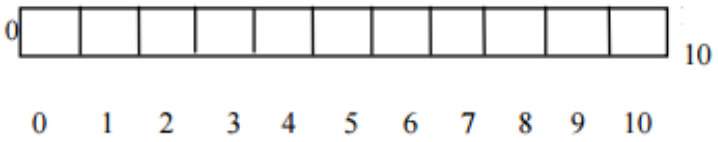
5. Do you have pain during or immediately after doing 10 (single leg) heel raises from a flat surface?




POINTS

□

6. How many single leg hops can you do without pain?




POINTS

□

7. Are you currently undertaking sport or other physical activity?

| | | | |
|---|---|---|---|
| 0 | □ | Not at all | POINTS |
| 4 | □ | Modified training ± modified competition | □ |
| 7 | □ | Full training ± competition but not at same level as when symptoms began | |
| 10 | □ | Competing at the same or higher level as when symptoms began | |

8. Please complete **EITHER A, B or C** in this question.

- If you have **no pain while undertaking Achilles tendon loading sports** please complete **Q8a only**.
- If you have **pain while undertaking Achilles tendon loading sports but it does not stop you from completing the activity**, please complete **Q8b only**.
- If you have **pain that stops you from completing Achilles tendon loading sports**, please complete **Q8c only**.

**A.** If you have **no pain** while undertaking **Achilles tendon loading sports**, for how long can you train/practise?

| NIL | 1-10 mins | 11-20 mins | 21-30mins | >30 mins | POINTS |
|---|---|---|---|---|---|
| □ | □ | □ | □ | □ | □ |
| 0 | 7 | 14 | 21 | 30 | |

**OR**

**B.** If you have some pain while undertaking **Achilles tendon loading sport**, but it does not stop you from completing your training/practice for how long can you train/practise?

| NIL | 1-10 mins | 11-20 mins | 21-30mins | >30 mins | POINTS |
|---|---|---|---|---|---|
| □ | □ | □ | □ | □ | □ |
| 0 | 4 | 10 | 14 | 20 | |

**OR**

**C.** If you have **pain that stops you** from completing your training/practice in **Achilles tendon loading sport**, for how long can you train/practise?

| NIL | 1-10 mins | 11-20 mins | 21-30mins | >30 mins | POINTS |
|---|---|---|---|---|---|
| □ | □ | □ | □ | □ | □ |
| 0 | 2 | 5 | 7 | 10 | |

**TOTAL SCORE ( /100)** □ %

Thank you for completing the PAR-Q. If you are happy to proceed with data collection, please sign below. By signing below, you are expressing that you are fit enough to participate in the study, and you are giving informed consent to participate, for your data to be collected and stored as described in the information sheet.

Name of participant: ……..

Signed: …….

Date: ……

## Appendix 7: Prospective study recruitment posters (asymptomatic and symptomatic)

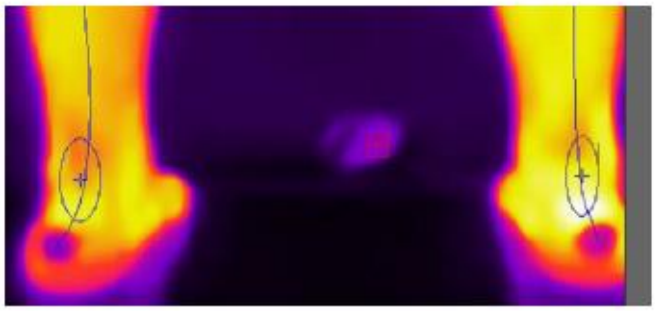
Recruitment poster v1.0 08/10/2018

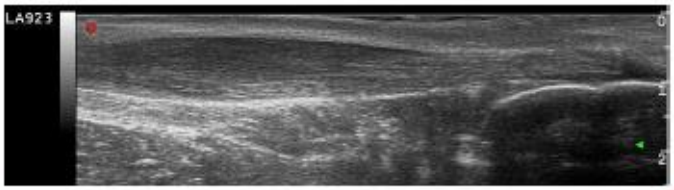
University of Salford MANCHESTER

**Establishing the normal skin temperature response to exercise of the Achilles tendon in healthy individuals**

**Aim of project:** To establish the normal skin temperature of the Achilles tendon in non-symptomatic participants in response to exercise.

Future aspirations are that thermal imaging can be used clinically to help detect skin temperature change that may or may not be indicative of tendon dysfunction.






**What do you need to do?** Data collection will involve a series of images being taken of your Achilles tendons. You will undergo a full assessment, ultrasound scans, thermal images and undertake a hopping or a running intervention. You may then be asked to participate in a loading programme before reassessment.

**How long will it take?** Each testing session may last 1 hour and you need to attend twice.

**Next step?** If you're interested in participating in the study, aged 18-60, perform 3 or more hours of exercise per week, and have not had a lower limb injury for 6 months, with no history of Achilles tendon pain, you may be eligible, so contact the researcher on the email below.

Researcher: B.oliver1@edu.salford.ac.uk

Supervisor: L.c.herrington@salford.ac.uk

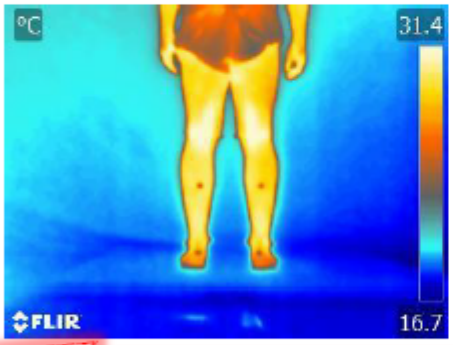
Recruitment poster v1.0 08/10/2018

University of Salford MANCHESTER

**A prospective study to assess the skin temperature and structural response of the Achilles tendon during a tendon loading programme**

Aim of project: To establish the effect that tendon loading has on the skin temperature and structure of the Achilles tendon in participants suffering with Achilles tendinopathy.

Future aspirations are that thermal imaging can be used clinically to help detect skin temperature change that may or may not be indicative of tendon dysfunction.




Achilles Pain?

You may be eligible!

What do you need to do? Data collection will involve a series of images being taken of your Achilles tendons. You will undergo a full assessment, ultrasound scans, thermal images and undertake a hopping and a running intervention. You may then be asked to participate in a loading programme before reassessment

How long will it take? Each testing session may last 1 hour. If you undertake the rehab programme, there will be 5 testing sessions, if not there will be 2. The loading programme is gym based and is 3x per week for 12 weeks.

Next step? If you're interested in participating in the study, aged 18-60, perform 3 or more hours of exercise per week, and you have Achilles tendon pain you may be eligible, so contact the researcher on the email below.

Researcher: B.Oliver1@edu.salford.ac.uk

Supervisor: L.C.Herrington@salford.ac.uk

## Appendix 8: Prospective study participant information sheet

**Study Title**

A prospective study to assess the skin temperature and structural response of the Achilles tendon during a tendon loading programme

**Invitation paragraph**

I would like to invite you to participate in a research study that is going to assess the effect of a tendon loading programme on skin temperature and Achilles tendon structure.

Before you decide whether or not you would like to participate, it is essential that you understand what the study involves and why it is being done, by reading the information carefully. If you would like any further information or are unsure about anything that you read, please ask, using the contact details below. I would like to make it clear that you are under no obligation to take part, it is entirely voluntary.

**What is the purpose of the study?**

The study is part of a PhD project that aims to establish levels of heat loss from the Achilles tendon during dynamic activity, in an attempt to link it to pathology in the long-term. Research has stated that heat loss possibly causes tendon dysfunction, but due to the expense and complexity of how it is currently measured, no data exists from a clinical perspective. Thermal imaging is a way to do this, but it will require complex investigation long-term, using diagnostic ultrasound to image muscles and tendons.

The study will reveal how a tendon loading programme affects skin temperature and the cross-sectional area, thickness and length of the Achilles tendon. The study will compare those who have symptomatic tendons to the participants who do not. Hopefully, this will help to identify whether dysfunctional tendons lose more heat and whether they respond structurally to a beneficial loading programme, which could relate to injury.

**Why have I been invited?**

You have been invited to participate in the study because you fit the inclusion criteria. If you are symptomatic (have Achilles tendon pain), you are between the ages of 18-60, you participate in 3 or more hours of running exercise per week and you have had no other lower limb injuries in the last 6 months, then you may be eligible. Equally, if you are asymptomatic (have no Achilles tendon pain), you are between the ages of 18-60, you participate in 3 or more running hours of exercise per week and you have had no other lower limb injuries in the last 6 months, then you may be eligible. It is estimated that the study will contain between 70-80 participants in total, all of which will be performing their testing at separate times to yourself.

**Do I have to take part?**

You decide whether or not you wish to take part. After reading this form, if you are happy to proceed, we will then ask you to sign a consent form which outlines that you are happy to participate. You will be free to withdraw yourself from the study up to one week after the final testing session and your data will be destroyed.

It is estimated that there will be two testing sessions, each taking about 60 minutes to complete. During the first assessment session, you will undergo a complete musculoskeletal assessment for Achilles tendinopathy. This will involve having an ultrasound scan of your tendon. In the second session, you will have infrared thermal images taken of your calf muscle and Achilles tendon region and you will be asked to perform a hopping or treadmill running task. You may then be asked to participate in a tendon loading programme which has been proven to be beneficial for strengthening the Achilles tendon.

As the study involves imagery, it is appropriate to let you know what will happen with the images. Firstly, no personal data or identifying features will be revealed in the images. They will automatically be saved onto the internal memory of the thermal imaging cameras. Immediately after data collection, the images will be stored onto the laptop of the lead researcher, in an anonymous and coded fashion, and will be deleted from the memory of the camera. After analysis, the images will be removed from the laptop and will be stored on a password-protected external hard drive to free space on the laptop.

**What will I have to do?**

During the first assessment session, you will undergo a full subjective and objective assessment for the ankle, which will rule in, or rule out, symptoms of Achilles tendinopathy. This will involve completing a VISA-A questionnaire and a series of ankle movements. You will then receive an Ultrasound scan of your Achilles tendon which will be used to assess the structure.

On a second assessment day, you will be asked to attend to receive an infrared thermal imaging picture of your tendons, followed by completing a series of dynamic tests. These tests will be single-leg hopping and a fifteen-minute treadmill run. These tests will be recorded using a digital video camera so that we can identify your foot-strike pattern and work out the time between foot contacts during movement, as these may influence tendon conditions. After these activities, you will again receive an infrared thermal image of your tendons.

After this, you will be invited to participate in a 12-week gym-based tendon loading programme at your normal gym. You do not have to participate in this if you do not want to. It will involve a series of progressive exercises which have been shown to strengthen the tendon and reduce symptoms of tendinopathy. During weeks 4, 8 and 12 you will be asked to return to the lab for a series of thermal images. At the 12-week point, you will receive a further set of thermal images and a final ultrasound scan.

**What are the possible disadvantages and risks of taking part?**

There is a risk of injury with the project as it will involve hopping, running and gym-based loading activity. However, the programme will be closely monitored, and steps have been taken to ensure that injury risk is minimal. If symptoms worsen, you will be encouraged to continue with the programme based on a numerical pain rating scale but will be asked to stop if the pain becomes intolerable. A slight provocation of symptoms is usual with rehabilitation from tendinopathy.

**What are the possible benefits of taking part?**

You will undergo a loading programme that will increase the strength of your calf muscles and the function of your Achilles tendon. This will lead to improvements in exercise.

**What if there is a problem?**

If you have a concern about any aspect of this study, you should ask to speak to the researcher (xxx) who will do their best to answer your questions. If you remain unhappy and wish to complain formally you can do this by contacting the Research Supervisor (xxx). If the matter is still not resolved, please forward your concerns to Professor Susan McAndrew, Chair of the Health Research Ethical Approval Panel, Room MS1.91, Mary Seacole Building, Frederick Road Campus, University of Salford, Salford, M6 6PU. Tel: 0161 295 2778. E: s.mcandrew@salford.ac.uk

**Will my taking part in the study be kept confidential?**

Your participation in the study will be kept entirely confidential by the research team. It is up to you if you choose to disclose your participation with anyone else. The research team will follow the procedures for handling, processing, storing and destroying of data in line with the General Data Protection Regulation 2018.

Your skin temperature and images will be first stored on the researcher's laptop before being transferred onto an external hard drive to free space on the researcher's laptop. No personal or identifying information will be stored.

The researcher will hold a list of participants on the University F: drive which will identify names based on the codes. At the time of data analysis, a separate member of the research team will re-code the data so that the researcher is blinded to participant numbers. The reason for this is so that the researcher cannot identify data when it comes to analysing the results.

The results of the study may be presented in a journal article or at future poster presentations, however, none of your personal data will be revealed and your participation in the study will remain entirely anonymous.

The data from the study will be stored for 3 years after the completion of the PhD study before being destroyed.

**Can I withdraw from the study?**

You can withdraw from the study up to 1 week after your final assessment session and your data will be destroyed. After this, all data will be anonymised, and it will not be possible to withdraw your data from the research project.

**What will happen to the results of the research study?**

If you would like to know the results of the study, please identify this on your consent form. The researcher will email you once the study is finished to make you aware of any publications and to give you a brief outline of the findings. The results will form part of my overall thesis and may be produced in a journal article. Any published data will be anonymous, and you are unidentifiable.

**Who is organising or sponsoring the research?**

The research is being undertaken as part of a PhD project at Salford University. No external funding has been received.

**Further information and contact details:**

Generic research information can be found on the following university website: http://www.salford.ac.uk/research

Project-specific details or advice can be obtained by emailing the researcher on the following email address: b.oliver1@edu.salford.ac.uk

**Appendix 9: Prospective study consent form**

**Research Participant Consent Form**

**Title of Project:** A prospective study to assess the skin temperature and structural response of the Achilles tendon during a tendon loading programme

**Ethics Ref No:**
**Name of Researcher:**

*(Circle as appropriate)*

| | | | |
|---|---|---|---|
| ➢ I confirm that I have read and understood the information sheet for the above study (V3.0 04/12/2018) and what my contribution will be. | **Yes** | **No** | |
| ➢ I have been given the opportunity to ask questions (face to face, via telephone and e-mail) | **Yes** | **No** | |
| ➢ I have been made aware of the protocol in place should I be unhappy with any aspect of the study | **Yes** | **No** | |
| ➢ I am aware that there is a risk of injury/post-exercise muscle soreness due to the hopping/running and resistance training involved in the study | **Yes** | **No** | **NA** |
| ➢ I agree to digital, ultrasound and thermal images being taken during the research and these images will be transferred from the thermal imaging cameras to the university F: drive where they will be coded | **Yes** | **No** | **NA** |
| ➢ I agree to a separate member of the research team viewing the data in their coded format to further code them to prevent any bias during image analysis | **Yes** | **No** | **NA** |

- I understand that my participation is voluntary and that I can withdraw from the research at any time **without giving any reason up until one week after the final assessment session**

| **Yes** | **No** |
|---|---|

- I understand how the researcher will use my images (for analysis in FLIR software/imageJ), that they will be seen by the research team and that the data will be stored on the university F: drive for 3 years post-graduation

| **Yes** | **No** |
|---|---|

- Please state "YES" if you would like to receive information regarding the results of the study, and provide your email address at the end of the form

| |
|---|
| |

- **I agree to take part in the above study**

| **Yes** | **No** |
|---|---|

Name of participant ……

Email of participant (if wanting to receive results of the study) ……..

Signature …….

Date …….

Name of researcher taking consent ……..

Researcher's e-mail address ……

## Appendix 10: 12-week HSR programme for the AT

Heavy, slow resistance programme (Beyer et al., 2015)

- All exercises to be performed 3 second concentric (raising onto toes), 3 second eccentric

| Week | Sets | Reps | Rest |
|---|---|---|---|
| 1 | 3 | 15RM | 2 min |
| 2 & 3 | 3 | 12 RM | 2 min |
| 4 & 5 | 4 | 10RM | 3 min |
| 6, 7 & 8 | 4 | 8RM | 3 min |
| 9, 10, 11 & 12 | 4 | 6RM | 3 min |

  (lowering to just below neutral)
- This programme should be performed 3 times per week

- In your first practice session, pick a weight that you think that you will be able to lift 15 times with both legs.
- Adjust the weight for the following set accordingly based on what you think that you can lift 15 times for a further 2 sets
    - You should be able to complete each set, but the last few repetitions should feel like an effort
    - You should still be able to complete them with proper technique
    - The pain caused by each exercise should remain tolerable
- If after the three sets you are happy that you have found your 3x15RM, begin the rehab in the next session. If not, then conduct one more practice session.
- Before each session, perform a 5-minute warm-up on the bike and progress through two warm-up sets at a lighter weight than your “RM”

Exercises

Beyer et al. (2015)

Seated Calf raises (A)

- Sit on the machine
- Place the balls of your feet on the step and your knees under the pad
- Select a weight that you feel that you will be able to lift 15 times through full range of movement
    - By the end of the set, the exercise should feel difficult, but you should be able to complete all 3 sets without altering the weight
    - The discomfort that you feel should be tolerable – it may worsen slightly the following day but should remain tolerable. If this become intolerable, contact the researcher immediately
- Push onto your toes over a duration of 3 seconds, then lower your heels just below the horizontal over 3 seconds
- Repeat the movement for the required number of repetitions

Smith machine standing Calf raises (B)

- Place a disc on the floor to act as a step
- Place weight on the Olympic bar that you feel that you will be able to lift 15 times
    - By the end of the set, the exercise should feel difficult, but you should be able to complete all 3 sets without altering the weight

    - The discomfort that you feel should be tolerable – it may worsen slightly the following day but should remain tolerable. If this become intolerable, contact the researcher immediately
- Place the balls of your feet on the edge of the disc
- Raise up onto your toes over a 3 second period
- Lower down to just below the horizontal over 3 second period
- Repeat the movement for the required number of repetitions

<u>Seated Calf raise on the Leg Press (C)</u>

- Sit on the machine
- Place the balls of your feet on the base of the Leg Press plate
- Select a weight that you feel that you will be able to lift 15 times
    - By the end of the set, the exercise should feel difficult, but you should be able to complete all 3 sets without altering the weight
    - The discomfort that you feel should be tolerable – it may worsen slightly the following day but should remain tolerable. If this become intolerable, contact the researcher immediately
- With your legs straight press up onto your toes over a 3 second period
- Lower your heels through just below the horizontal over a 3 second period
- Repeat the movement for the required number of repetitions

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