Quantifying Achilles tendon shear wave velocity following high-intensity versus low-intensity endurance training regimens

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Abstract

In the realm of sport, lower extremity injuries fail to discriminate. A twisted truth to these maladies reside within their causation, triggering traumas having an unparalleled level of variance. One universal commonality does however link this ailed athletic pool, sustained stress on integrity-depleted structures can disseminate to other neighboring tissues. A second detrimental distinction, predominantly among damaged Achilles tendons, can be noted in their adverse effect on function, coupled with moderate reinjury risk. Countless professional athletes have ended their careers prematurely, or experienced relegation in play-minutes, due to an inability to reattain peak performance.

Researchers collectively acknowledge a lack of well-devised prospective studies highlighting Achilles tendon function following an overuse, or overexertion, injury. The study aimed to address this existing research insufficiency via evaluating the shear wave velocity of injured Achilles tendons. The study's purpose was to investigate if a correlation between workout intensity and damaged tissue reconditioning exists.

The foundation of this research endeavor was formed by a mutual partnership between Jyväskylä University of Applied Sciences and the University of Jyväskylä, JYU permitting the data transfer. Achilles tendon stiffness was calculated via ElastoGUI, a French shear wave velocity software. All gathered data was then quantified in SPSS.

Results showed an inconsistent correlation between regimen intensity and Achilles stiffness. With a p-value of 0.007, there is a significant correlation between control and intervention group shear wave velocity in the right foot ($p<0.05$). Oddly, this trend is not as evident in left foot testing.

Keywords/tags (subjects)

Achilles tendon, high-intensity interval training vs. low-intensity interval training, shear wave elastography, Achilles tendon stiffness

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1. Introduction

Since the dawn of competition, originating during the Panhellenic Games of 776 BC, humanity has raved behind the shear, mesmerizing hurdles the human body can surpass. Attaining feline-degree acrobatics and agility, to brute strength, requires habitual exposure to performance-enhancing stimuli. Similar to how Michelangelo sculpted the statue of David in the early sixteenth century, the stressors a musculoskeletal system is exposed to will chisel said athlete’s physique. Fueled by thorough, compounding scientific research in fields such as sport nutrition, strength and conditioning, and post-competition recovery, the parameters to success in sport shift drastically with every passing decade. This need for continuous improvement carries a precarious cost no matter how resilient our anatomical structures are at their core. Achilles, renowned in Greek mythology as the greatest warrior of his time, experienced a similar fate when an arrow penetrated his heel. The sole part of his body unblessed by the River Styx’s power of invulnerability.

The fundamentals of endurance sports prioritize sustaining undulating phases of acceleration and deceleration, energy efficiency, and aerobic capacity in the form of VO2 max. Swift changes in direction in the form of cutting, or short bursts of explosive speed, do not apply. From a physiological point of view, endurance exercise is typically performed at submaximal intensity with the main purpose of progressively moving the anaerobic threshold, i.e. the beginning of anaerobic metabolism and lactate production, towards higher exercise intensity. This occurs through complex modifications in muscle metabolism, with increased mitochondrial density and oxidative enzymes (i.e. the machinery necessary for energy production), shifts in fibre type, and increased capillarisation of muscle fibres (Morici et al., 2016).

Compared to baseball, hockey, and football, endurance sports tout a low barrier to entry. In most cases, an aspiring athlete's sole equipment requirement is a pair of running shoes. Couple this with soaring epidemics of obesity and loneliness, only exacerbated by Covid-19, participation in aerobic sports continues to rise annually in all age demographics and competition levels. Generally, the relationship between exercise and tendon adaptation is symbiotic. As tendons become accustom to new movement patterns and differing angles of force, they inherently learn how to optimize themselves for fluid force transmission. Studies exploring biomechanical changes are supported by Magnusson & Kjaer (2003), finding there was a difference in tendon cross-sectional area (CSA) between experimental groups, such that runners had a greater CSA (36%) than non-runners at the most distal part of the tendon ($P<0.05$). This trend continues in a longitudinal study concluding Achilles tendon adaptation to injury resilience occurs in cross-country runners. A positive adaptation in AT structural integrity was observed over the XC (cross-country) season, with a ~10% shift from Type II to Type I muscle fibers, suggesting AT resilience to a competitive season of repetitive loading in highly trained runners (Stanley et al., 2018).

The Achilles, the largest and strongest tendon in the entire musculoskeletal system, plays a pivotal role in mankind's ability of ambulation. The sheer power of this tissue is not however locked to pure locomotion, as its true potential is unlocked in high-exertion activities. At running speed, the Achilles may encounter forces up to 12.5 times that of one's bodyweight (Altchek, 2012). Knowledge of situational and biomechanical patterns contributing to an Achilles tendon injury are important for early, on-field, diagnosis and for the development of prevention programmes (Cooper, 2015). However, researchers unconditionally concede an incomplete comprehension to Achilles tendon overuse, academia quite devoid of well-devised prospective studies highlighting the adaptive capabilities of an Achilles. Studies examining the changes in tendon cellular matrix composition and anatomical properties following acute Achilles injuries are uniformly under-published.

The primary focus of this study is to quantify how regimen intensity, either high or low, changes tendon stiffness. The broad vision consisting of a two-week preparatory period (phase 1), a one-week recovery period (phase 2), a two-week training period utilizing high- or low-intensity training (phase 3), capped off by a second recovery week (phase 4). So, what happens when either a mechanical stimulus, or uncontrollable stimuli, affects this critical anatomical structure?

2. Dissecting the Achilles Tendon

2.1 Anatomical makeup and function

To understand the Achilles tendon, it is important to outline its histology first. Derived from a fusion of three individual subtendons, the lateral and medial heads of the Gastrocnemius plus the Soleus, the Achilles tendon travels approximately fifteen centimeters along the posterior side of the leg, inserting itself onto the calcaneal tuberosity. To bolster its own attachment via surface area, the triad's individual fascicles attach to various calcaneal facets. Four centimeters from its insertion, it flattens, then expands and becomes cartilaginous, to insert into a rough area on the middle of the lower part of the posterior surface of the calcaneus (O'Brien, 2005). Contraction of the triceps surae permits one's foot to apply force in a downward direction, otherwise known as plantar flexion. The primary function of the Achilles tendon is to generate nearly 95% of all plantar flexion force, propelling oneself forward (Moore et al., 2011). Its thick, elastic structure can additionally help in shock-absorption.

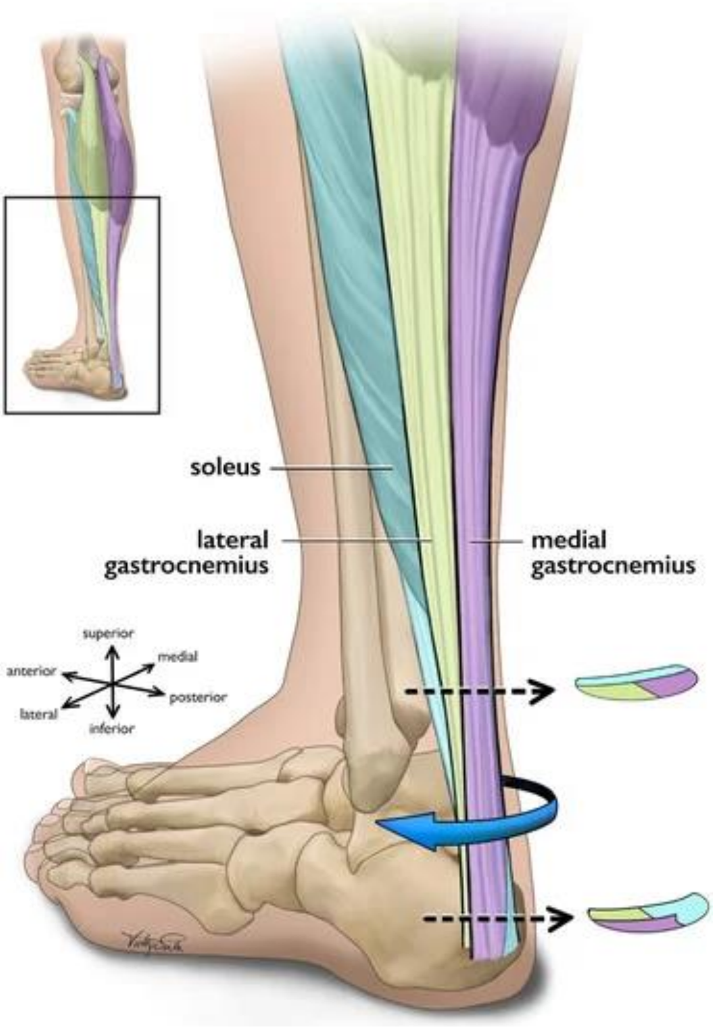


Figure 1. Morphology of the Achilles tendon. Adapted from Merry et al., (2022).

A tendon’s composition epitomizes pliability and robustness, ornately arranged into a hierarchy of collagen molecules, fibrils, fascicles, and the tendon unit. Collagen, the primary building block of tendons, can be categorized into five primary types.

Type	Function(s)
I	Most common type; hair, skin, organs, bones, ligaments
II	Builds cartilage, maintain gut lining, joint health, immune support

III	Works in unison with I; skin and bone health, important for heart health (arterial walls)
V	Less abundant in the body; forms cell membranes and placenta tissue
X	Less abundant in the body; helps form bones

These tropocollagen proteins account for 65-80% of the dry weight mass of an Achilles tendon (O'Brien, 2005).

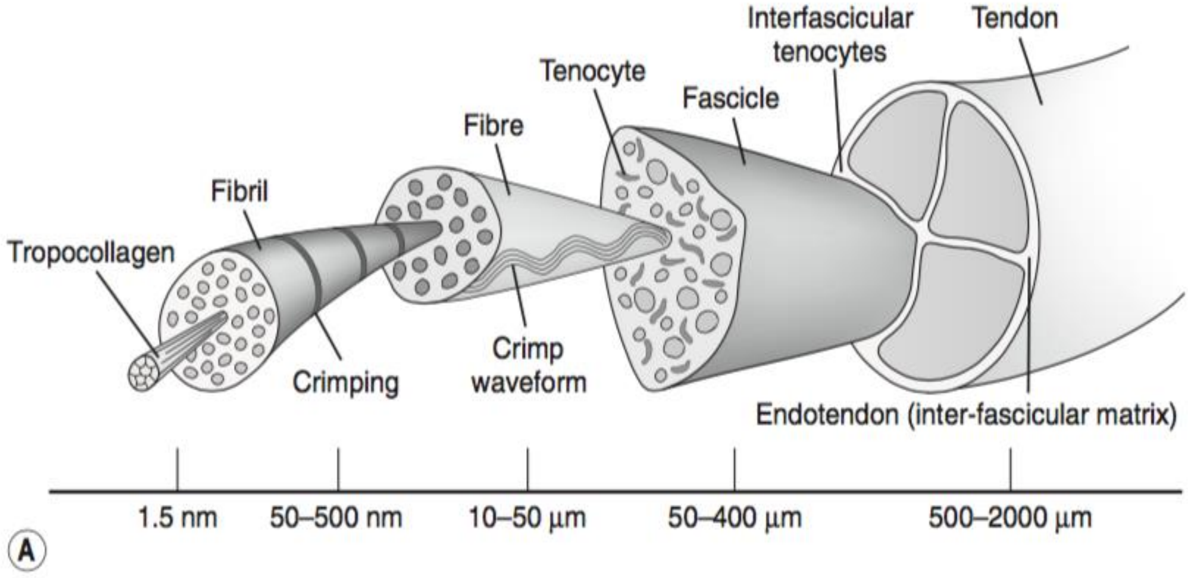


Figure 2. Microscopic breakdown of a tendonous structure. Adapted from Physiopedia, (2023).

2.2 Pathology behind Achilles adaptation and injury

In accordance with Wolff's law, all tendons' elastic properties are augmented in direct correlation to the degree of mechanical loading exposure. Sport-specific demands also elicit tendon morphology and composition, as it is vital for a tendon to adapt to maintain joint mechanics. A 12-week training program containing mainly endurance-type training 2-4 h per day showed a peak in collagen synthesis after 4 weeks while still being 3 times greater than baseline value after 11 weeks of training. Importantly, collagen degradation also peaked at 4 weeks but had returned to baseline at 11 weeks (Langberg et al., 2001). Arampatzis et al.

(2007) suggest sprinters have higher AT stiffness, as counterparts training for ultra endurance events, often comprised of multistage legs and lasting six or more hours, have antithetical AT structure. A larger soleus muscle with a thicker Achilles tendon is associated with better marathon performance (Kovács et al., 2020). Shorter soleus muscle fascicles may be an adaptation to life-long endurance running (Stenroth et al., 2016). Majima et al. (2003) emphasize the importance of continued tendon loading, regardless of age, stating, frequent loading maintains an appropriately small number of tendon cells, sufficiently large collagen fibrils, and correctly oriented collagen.

Disregarding proper pillars to conditioning, primarily an adequate warm-up prior to competition, often foreshadows Achilles irritation. In warm-up routines, prolonged static stretching is to be avoided since it can decrease tendon stiffness reducing elastic capacity (Obst et al., 2013). Imperfections in force transfer and biomechanics need to be corrected too. Overloading and abnormal gait including features such as prolonged eversion have been identified as risk factors for AT injuries (Becker et al., 2017; Hannigan & Pollard, 2021). These oversights often do not have an immediate effect on the athlete, rather the true, insidious consequences reside at a microscopic level. As the Achilles exerts power, its molecular microcosm is tasked to endure multiplanar forces and shear tension. When insufficient training principles are utilized, the body's autonomous ability to recover and repair damaged structures is significantly compromised. This results in cumbersome disorders which can evolve into persistent stints of discomfort, or worse.

2.2.1 Risk factors

The mechanisms of injury for an Achilles injury are well-documented, typically forcible dorsiflexion in a closed-chain movement.

> Most injuries (94%) occur through indirect or non-contact mechanisms. The kinematic analysis revealed characteristic joint positions at the time of injury consisting of hip extension, knee extension, ankle dorsiflexion, foot abduction, and foot pronation in most cases. The underlying direction of movement was from flexion to extension (knee) and from plantarflexion to dorsiflexion (ankle). Player actions identified as main injury patterns were

stepping back (26%), landing (20%), running/sprinting (18%), jumping (13%), and starting (10%) (Hoenig et al., 2023).

Although the use of performance enhancing drugs, PEDs, is strictly enforced and tested in the world of sport, house-hold names annually devolve into sources of shame following a positive steroid test. An unnatural increase in fat free mass coupled with strict dietary intake, the latter often implemented during in-season play, both act as synergists to Achilles trauma. Team physicians in the National Football League, National Basketball Association, and the Fédération Internationale de Football Association sometimes administer steroids via injection to aching joints and musculature. These nerve-blocking agents can diffuse, seeping into otherwise healthy tissues, thus negatively impacting their structural integrity. Sex and age have also been flagged as unavoidable catalysts. People in their 30's and 40's fall into the most at-risk demographic, with men being 5x more likely to injure their AT than women (higher sport participation, reduced flexibility and different hormones can be partially blamed for this) (Canadian Academy of Manipulative Physiotherapy, 2024). Females typically have a greater degree of deficit in heel-rise height, an indicator of Achilles vitality, irrespective of treatment (Silbernagel et al., 2015). Medical history, predominantly auto-immune disorders such as Arthritis and one's circulatory system function, nettle joints and ligaments. The Achilles tendon has a generally poor blood supply throughout its length, as measured by the number of vessels per cross-sectional area; a relative region of hypovascularity exists in its midsection which usually happens to be the site around which most injuries occur. This has been attributed as a contributing factor to diminished healing after trauma (Wong et al., 2023). Blood supply, along with nutrient delivery, to peripheral structures further diminishes with age.

2.2.2 Tendonitis

Also referred to as a strain, Achilles tendonitis stems from ephemeral episodes of inflammation and micro-tearing. The cause is predominantly linked to overuse, often an increase in workout frequency, time, or intensity. Due to an uptick in activity, micro-injury sustained during previous training is not allocated enough time to heal correctly. Training errors account for 60-80% of noninsertional Achilles Tendonitis (Altchek, 2012). Recent studies linked B cells, T cells, macrophages, mast cells and/or natural killer cells, naturally occurring inflammatory agents, to defective tenocyte function (Behzad et al., 2013). This fusion of highly aggressive immune cells can lead to symptoms including AT tenderness and stiffness. Failure to hinder the swelling can ultimately spawn Altchek's tendinosis cycle (Figure 3). Perhaps the mildest ailment form, tendonitis still requires ample intervention as it is a precursor to tendonosis.

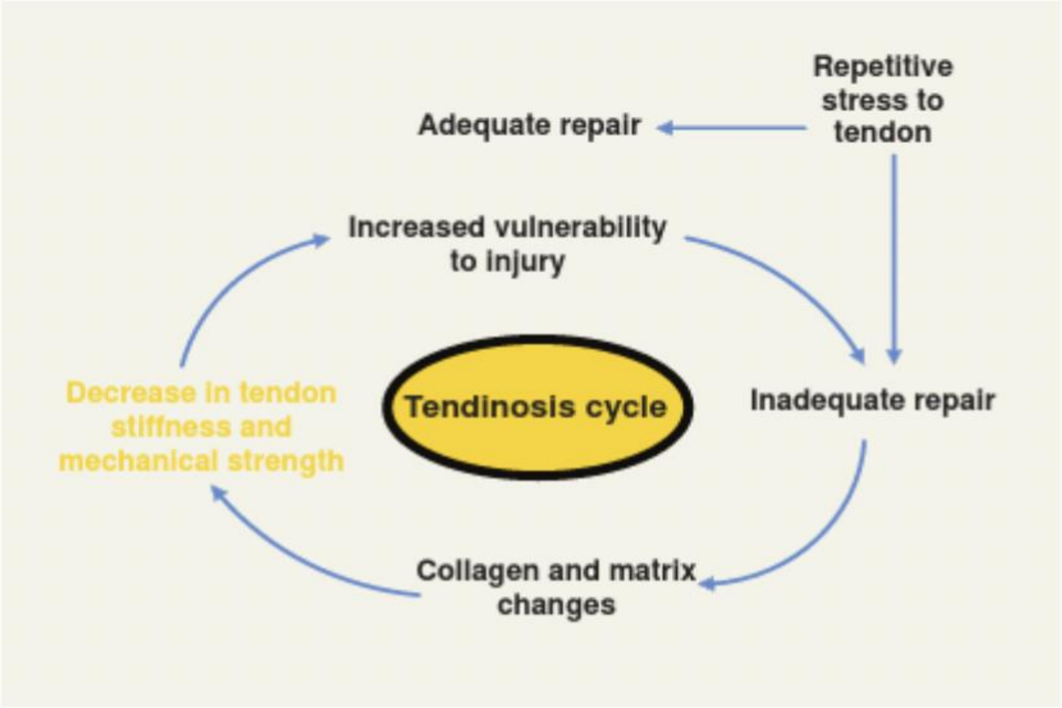


Figure 3. Altchek's infinite tendinosis cycle. Adapted from Altchek, (2012).

2.2.3 Tendinosis

Fixated in the thickest part of the tendon, Achilles tendinosis has a deteriorative histology. Lopez and Jung (2015) define tendinosis as a failure of the cell matrix to adapt to repetitive trauma caused by an imbalance between the degeneration and synthesis of the matrix. Prolonged, scanty repair to fascicles and connective tissue responsible for blood supply create a turbulent environment in the Achilles. Biopsies of diseased tendons reveal that there is cellular activation evidenced by an increase in cell numbers and ground substance, collagen disarray, and neovascularisation (Lopez & Jung, 2015). Like atherosclerosis, Achilles tendinosis appears as a yellowish, thickened tendon from accumulation of mucinous material within the diseased area. This condition can occur at higher prevalence in runners and patients with systemic diseases such as lupus or rheumatoid arthritis (Weinfeld, 2014). This malady causes irreparable damage at a macro- and microscopic level.

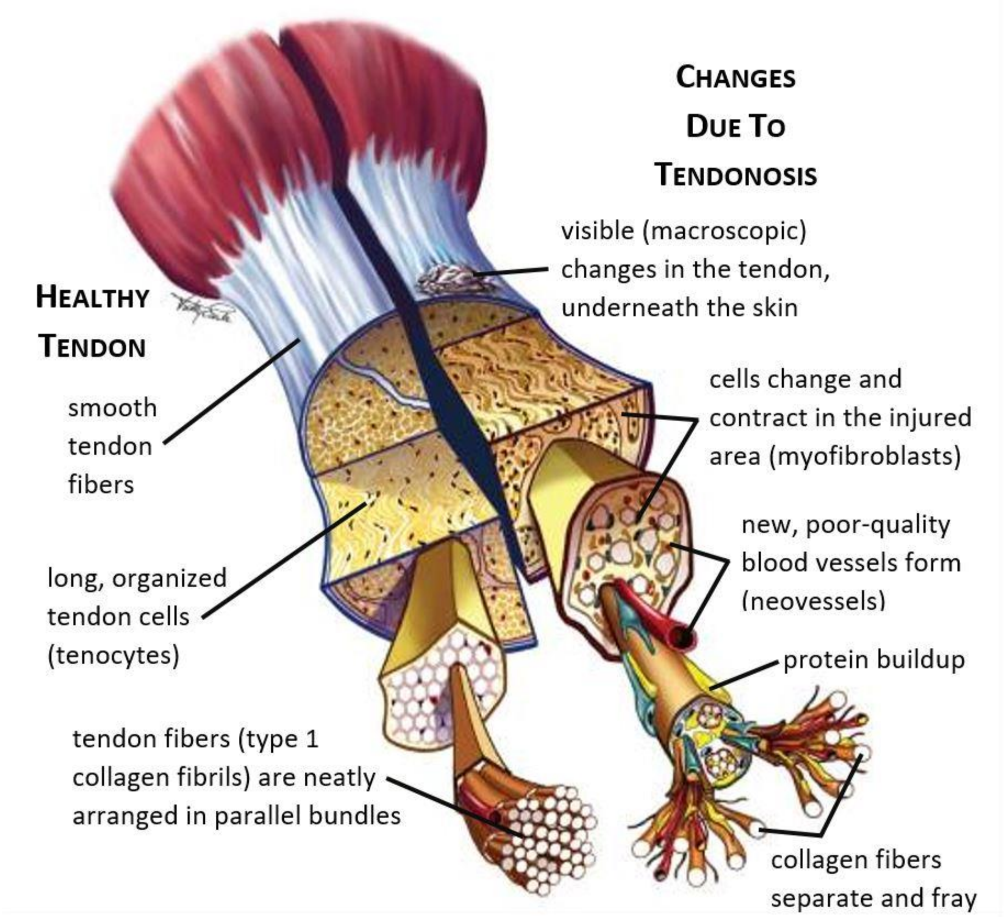


Figure 4. How chronic tendonosis ravages elastic tissue. Adapted from UNC Orthopaedics, (2024).

2.2.4 Retrocalcaneal Bursitis

Nestled between the Achilles and the calcaneus, retrocalcaneal bursitis is the inflammation of a fluid-filled sac, or bursa. Filled with synovial fluid to function as a cushion under mechanical loading, and abating friction between tendons and bones, swollen bursae can induce sharp, shooting pain in the calcaneum. Biomechanical abnormalities, joint stiffness, and proximal soft tissue tightening can exacerbate an anatomical predisposition to retrocalcaneal bursitis (Brukner & Khan, 2006).

2.2.5 Achilles Tendon Rupture

An Achilles Tendon Rupture, or ATR, occurs at a frequency of thirty-seven persons per one hundred thousand (Altchek, 2012). Although this is a minuscule percentage of injury risk for the general public, they account for thirty to fifty percent of all sports-related injuries; recovering from such a devastating injury may require up to an entire year (Mahieu et al., 2006). A study by Saarensilta et al. (2020) identifies badminton, floorball, and football accounting for over 50% of all ATR's. This 'traumatic trident' may contain interchangeable sports however depending on geography, as floorball's popularity is heavily centralized in Scandinavia. Järvinen et al. (2001) suggest insertional issues account for 25%-35% of ATR cases. Unfortunately, once an AT suffers such a devastating lesion the risk of reinjury skyrockets. The prevalence of Achilles tendon (AT) injury is high in various sports, and AT rupture patients have been reported to have a 200-fold risk of sustaining a contralateral rupture (Kongsgaard et al., 1985).

2.2.6 Intrinsic risk factors

A hyperfocus on achievement has manufactured a concerning phenomenon in recent decades. Whereas international sporting events such as the Olympics used to celebrate diversity among athletes, overcoming adversity, and friendly competition, the narrative has strongly tilted to one ideal, winning. Upper echelon athletes can rarely afford to take more than a two-month hiatus from training, even when their competitive season is one to four months on average. Physical attributes conducive to performance, wingspan in endurance swimmers for example, are being aggressively scouted by recruiters in increasingly younger age blocks to ensure future medaling prospects. The trend toward early sports specialization and year-round training, has led to a similar increase in athletically developed injuries (Egger et al., 2019).

Elite-level sporting organizations typically possess a blank check when it comes to investing in their athletes. Not a single penny is saved when hiring the top 1% of strength coaches, team physios, and nutritionists. All these individuals are paid to boost competitive ability, whilst a greater emphasis of their collaborative expertise is tactically focused on injury mitigation. Variables ranging from training terrains to appropriate footwear, rate of perceived exertion prior to competition, and landing surfaces for aerial sports require precise, methodical planning.

No matter how credentialed an organization’s staff is, certain anatomical predispositions can increase the risk of sustaining an Achilles-related injury. Preexisting degenerative tendon, cavus foot, tibia vara, increased femoral anteversion, leg length discrepancy, or underdeveloped hamstrings increase the risk of AT incidents (Kader et al., 2002). Over- or underpronating is linked with poor shock absorption and may increase stress on the AT (Hess, 2010). According to Green et al. (2018), the Gastrocnemius-soleus complex’s unproportional size to the rest of the muscle located in the lower extremity causes imbalances when producing force, an underlying factor for overexertion.

It is imperative for athletes’, and their mentors', minds to meld into one collective hive mind. Only then can peak performance be achieved.

2.3 Implications from injury

When any form of trauma happens to tissue, the human body possesses an arsenal of neurotransmitters, hormones, and biological bypasses to decisively abate the damage. Inflammation, for example, is the product of white blood cells, histamine, and intravenous fluid choreographed together to immobilize an injured body part, thus reducing further damage. Harm to tendons can trigger a similar reaction, although lacking a key organic material in their composition.

The significant contrast between typical tissues and tendons in terms of self-repair is the prioritization of blood flow. Due to their necessity for hypermobility, ligaments are peppered with a limited amount of blood vessels to negate continuous vascular damage; this results in their white appearance. In lieu of direct blood supply, a tendon’s nutritional delivery relies on synovial fluid diffusion over vascular perfusion. Specialized microfibrils called the endotenon house these capillaries.

Earning its distinction through clinical efficacy and facile degree of completion, the Matles test has become a universal evaluation tool for suspected AT injury. Originally drafted in 1975, the test is conducted by having an athlete lie prone and having him/her flex their knees to 90 degrees while simultaneously keeping the feet in a passive position. An intact Achilles tendon will keep the foot in constant, slight plantar flexion, thus the presence of dorsiflexion is a positive indication of a non-operative Achilles. The simplistic design of the

Matles test makes it ideal for acquiring a quick prognosis without having to move an athlete post-injury, as it can be conducted immediately wherever the competitor went down.

2.4 Treatment and rehabilitation options

Even with exceptional training staff injuries are always unforeseen and incalculable. Following a positive Matles test, the AT injury needs confirmation via magnetic resonance imaging. If the MRI verifies a tear, either a surgical or non-surgical intervention can be performed. Regardless of which avenue is chosen, a recent shift in research has focused on the vital importance of preoperative rehabilitation. Van Melick et al. (2016) state full knee range of motion before ACL reconstructive surgery may prevent postoperative arthrofibrosis. Preoperative exercise intervention before TKA could improve knee flexion and flexibility, reduce inflammatory pain and stiffness, and improve muscle strength and joint function, thereby improving the quality of life of patients (Wang et al., 2021). Higher pre-injury performance level and neuromuscular capacity may accelerate the rehabilitation process (Niederer et al., 2018).

Valkering et al. (2017) found direct post-operative weight-bearing and functional mobilization resulted in an early improved healing response compared to non-weight-bearing and immobilization. Weight-bearing resulted in an upregulation of glutamate, an important excitatory neurotransmitter linked to early-stage tendon healing. In addition, early ankle range of motion was improved without the risk of Achilles tendon elongation and without altering long-term functional outcome (Valkering et al., 2017). Research attempting to quantify whether nonoperative or operative Achilles tendon repair excels in clinical outcomes has reached an impasse.

2.4.1 Nonoperative intervention

Conservative techniques for AT trauma are collectively categorized into three primary mediums: nerve-blocking injections and corticosteroids, expensive wave therapies, and topical agents. Though the traditional non-invasive methods are readily available and give most patients short-term pain relief, 30% of them still find these alternatives as ineffective (Lopez & Jung, 2015).

The cardinal core of physiotherapy touting exercise as a natural, holistic approach to rehabilitation in lieu of prescription drugs continues its merit in Achilles tendon betterment. Dynamic rehabilitation has been suggested to be an important part of nonoperative treatment of acute Achilles tendon injury that results in functional outcome and rerupture rates comparable with those of operative treatment (Barfod et al., 2014). Non-invasive Achilles tendon repair is accompanied by certain grey areas. Optimal non-operative treatment protocol remain to be clarified, particularly the role of weight-bearing during early rehabilitation (Barfod, 2014).

2.4.2 Surgical intervention

When performing Achilles tendon reconstructive surgery, the Krackow suture has earned the moniker of being the gold standard (Myhrvold et al., 2022). This interlacing technique provides a robust, artificial backbone for a spliced Achilles. Upon comparison to its nonintrusive counterpart, operative repair has been found to significantly decrease rerupture rate (Risk Ratio of 0.36, 95% CI 0.21-0.64; P = 0.0005) (Reda et al., 2020). The mainstay of postoperative management is initial rigid immobilization in an equinus cast, followed by a supervised rehabilitation focused on recovery of motion and power (Strom & Casillas, 2009).

Overall risk management favors the former, as any break in the skin exposes tissues to foreign pathogens. Meticulous pre-operative scrubbing and sterilization of medical personnel and surgical tools is to diminish wound infection, as it can act as a precursor to severe complications. Wound breakdown should be treated aggressively to prevent deep infection if not already present (Liles & Adams, 2019). Endoscopic surgery has risen as a valid option if delayed wound healing is present. Achilles tendon total scores were excellent, and the American Orthopedic Foot and Ankle Society scores were satisfactory, indicating improvements in Achilles tendon function and movement in patients after surgery (Yang et al., 2021). This corrective surgery further expunges the need to reopen the wound, shortening healing time. Immunocompromised patients, or those with a higher proclivity to susceptible disease, require an increased degree of consultation prior to operation. An undiagnosed infection could lead to Herpes Zoster, which if left untreated can end in necrotic tissue and limb amputation.

When deciding on which intervention to choose, neither can be crowned superior. There was no clinically important difference between groups with regard to strength, range of motion, calf circumference, or Leppilahti score...there were thirteen complications in the operative group and six in the nonoperative group, with the main difference being the greater number of soft-tissue-related complications in the operative group (Willits et al., 2010). No statistically significant difference between the two groups in functional outcome scores and range of motion (Reda et al., 2020). In patients with Achilles' tendon tear, surgery (open repair or minimally invasive surgery) was not associated with better outcomes than nonoperative treatment at 12 months (Myhrvold et al., 2022). A meta-analysis by Ochen et al. (2019) states nonoperative treatment might be the preferred treatment for acute Achilles tendon injury, owing to the higher risk of other complications after operative treatment and the relatively small benefit in rerupture rate. As controversy remains regarding which patients who sustain an acute Achilles injury should be treated nonoperatively and which would benefit most from surgical repair, a better understanding of postoperative complication rates and associated risk factors may enhance the decision-making processes in treating these injuries (Stavenuiter et al., 2019).

2.4.3 Plasma and tissue engineering, a new pathway

Platelets play an important role during the multistage process of tendon repair. On activation, platelets release an ordered sequence of growth factors, cytokines, and an array of bioactive proteins. Subsequently, this leads to recruitment of leucocytes, local stem cells and tenocytes to initiate the healing process (Alsousou et al., 2019). Modern advances in macro and micro-medicine have provided tinder for ongoing trials searching to unlock the true potential in autologous platelet-rich plasma.

Tissue engineering is an advancing field that can either augment surgical repair or provide an alternative method for Achilles tendon repair (Sahni et al., 2015). Human acellular dermal matrices (ADMs), along with bovine collagen matrices, are also being tailored to decrease surgical complications. A histology analysis by Bertasi et al. (2017) demonstrated that the healing process during a tendon reconstruction procedure is like that of wound healing. Likewise, studies by Gürler et al. (2021) indicate that a bovine collagen matrix can be used to prevent tendon adhesion; however, larger studies are needed to verify these findings. NFAH, nanostructured fibrin-agarose hydrogel, and GP-NFAH, genipin cross-linked nanostructured fibrin-agarose hydrogel, also have the potential to improve tendon healing following a surgical repair. However, future studies are needed to determine the clinical usefulness of these engineered strategies (González-Quevedo et al., 2020). Absorbable oxidised regenerated cellulose merits further evaluation as a potential treatment to inhibit the formation of peritendinous adhesions (Temiz et al., 2008).

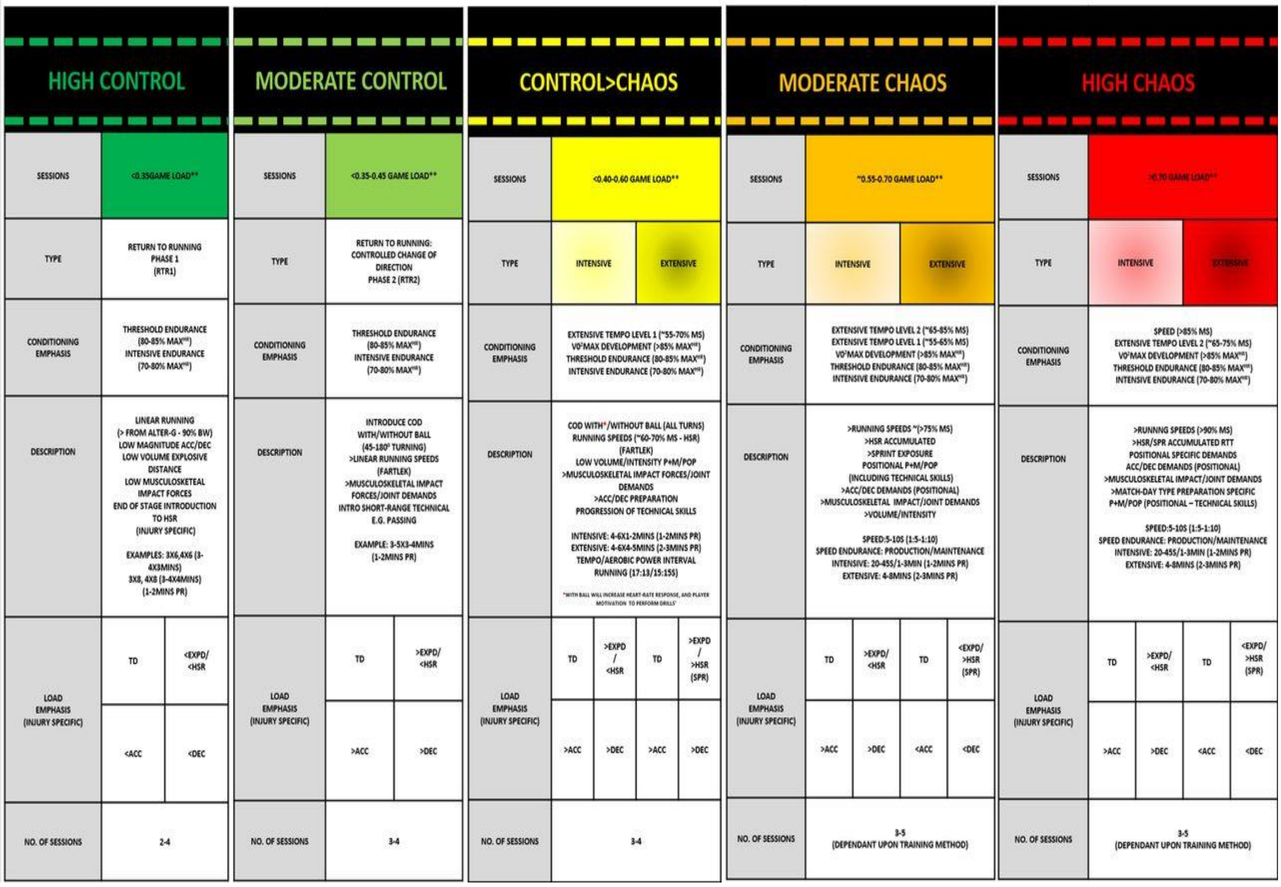
2.5 Return to sport

Rarely does an athlete who experiences an AT injury return to competition in the same season. Attempts to define the timetable for return-to-play (RTP) have been made, with some groups recommending 16 weeks for non-contact athletes and 20 weeks for contact athletes (Caldwell & Vosseller, 2019). This hypothetical time frame can be labeled as overly optimistic due to surgical intervention, as it requires prolonged rehabilitation and reconditioning. Still, elite athletes see this as the preferred corrective intervention.

Return to sport protocols should exhibit gradual progression, guided by functional criterion, and specificity based on sport-related tasks. RTS among professional leagues elicit high variability. Multiple studies have reported RTP rates in elite athletes following surgical AT repair, with RTP defined as a return to at least one game unless noted otherwise below (LaPrade et al., 2022). Rates in the NBA range from 61% to 80%, with studies reporting that 44%–64% returned for at least 2 years postoperatively (Lemme et al., 2019; Amin et al., 2013). In the NFL, studies have reported RTP rates between 61% and 73% (Trofa et al., 2017; Mai et al., 2016; Yang et al., 2019). Professional soccer players have reported RTP rates of 71%–96% (Trofa et al., 2018). In the MLB, RTP rates are reported to be 62%–100%, although one study used a return of 81 games (half a season) as their measure for RTP (Saltzman et al., 2017). No studies have evaluated elite hockey athletes after Achilles tendon injury.

Receiving medical clearance to resume training must epitomize diligence from all functional facets, and collaborative dialogue between a multidisciplinary team. AT-specific requirements such as ankle mobility, repetitive shock absorption, and powerful plantarflexion force production should be biomechanical markers when assessing RTS. The horizontal hop has cemented itself as a reliable test when analyzing Achilles tendon recovery, as 43% of horizontal hop distance is dependent on the Achilles tendon's propulsive properties (Kotsifaki et al., 2021). Achieving full symmetry in gastrocnemius girth, plantar flexor strength, and ankle range of motion are additional indicators of ideal recovery.

Per Taberner et al. (2019), figure 5 illustrates an in-depth example of progressive overload in sport-specific skills. Each tier in this 'chaos control-continuum' increases exertion parameters gradually, starting from controlled and reacclimating sport actions, crescendoing to high RPE drills.



	HIGH CONTROL	MODERATE CONTROL	CONTROL>CHAOS	MODERATE CHAOS	HIGH CHAOS
SESSIONS	<0.35GAME LOAD**	<0.35-0.45 GAME LOAD**	<0.40-0.60 GAME LOAD**	~0.55-0.70 GAME LOAD**	>0.70 GAME LOAD**
TYPE	RETURN TO RUNNING PHASE 1 (RTR1)	RETURN TO RUNNING: CONTROLLED CHANGE OF DIRECTION PHASE 2 (RTR2)	INTENSIVE EXTENSIVE	INTENSIVE EXTENSIVE	INTENSIVE EXTENSIVE
CONDITIONING EMPHASIS	THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	EXTENSIVE TEMPO LEVEL 1 (~55-70% MS) V0^{2}MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	EXTENSIVE TEMPO LEVEL 2 (~65-85% MS) EXTENSIVE TEMPO LEVEL 1 (~55-65% MS) V0^{2}MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	SPEED (>85% MS) EXTENSIVE TEMPO LEVEL 2 (~65-75% MS) V0^{2}MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})
DESCRIPTION	LINEAR RUNNING (> FROM ALTER-G - 90% BW) LOW MAGNITUDE ACC/DEC LOW VOLUME EXPLOSIVE DISTANCE LOW MUSCULOSKETEAL IMPACT FORCES END OF STAGE INTRODUCTION TO HSR (INJURY SPECIFIC) EXAMPLES: 3X6,4X6 (3-4X3MINS) 3X8, 4X8 (3-4X4MINS) (1-2MINS PR)	INTRODUCE COD WITH/WITHOUT BALL (45-180° TURNING) >LINEAR RUNNING SPEEDS (FARTLEK) >MUSCULOSKELETAL IMPACT FORCES/JOINT DEMANDS INTRO SHORT-RANGE TECHNICAL E.G. PASSING EXAMPLE: 3-5X3-4MINS (1-2MINS PR)	COD WITH*/WITHOUT BALL (ALL TURNS) RUNNING SPEEDS (~60-70% MS - HSR) (FARTLEK) LOW VOLUME/INTENSITY P+M/POP >MUSCULOSKELETAL IMPACT FORCES/JOINT DEMANDS >ACC/DEC PREPARATION PROGRESSION OF TECHNICAL SKILLS INTENSIVE: 4-6X1-2MINS (1-2MINS PR) EXTENSIVE: 4-6X4-5MINS (2-3MINS PR) TEMPO/AEROBIC POWER INTERVAL RUNNING (17:13/15:15S) *WITH BALL WILL INCREASE HEART-RATE RESPONSE, AND PLAYER MOTIVATION TO PERFORM DRILLS'	>RUNNING SPEEDS ~(>75% MS) >HSR ACCUMULATED >SPRINT EXPOSURE POSITIONAL P+M/POP (INCLUDING TECHNICAL SKILLS) >ACC/DEC DEMANDS (POSITIONAL) >MUSCULOSKELETAL IMPACT/JOINT DEMANDS >VOLUME/INTENSITY SPEED:5-10S (1:5-1:10) SPEED ENDURANCE: PRODUCTION/MAINTENANCE INTENSIVE: 20-45S/1-3MIN (1-2MINS PR) EXTENSIVE: 4-8MINS (2-3MINS PR)	>RUNNING SPEEDS (>90% MS) >HSR/SPR ACCUMULATED RTT POSITIONAL SPECIFIC DEMANDS ACC/DEC DEMANDS (POSITIONAL) >MUSCULOSKELETAL IMPACT/JOINT DEMANDS >MATCH-DAY TYPE PREPARATION SPECIFIC P+M/POP (POSITIONAL – TECHNICAL SKILLS) SPEED:5-10S (1:5-1:10) SPEED ENDURANCE: PRODUCTION/MAINTENANCE INTENSIVE: 20-45S/1-3MIN (1-2MINS PR) EXTENSIVE: 4-8MINS (2-3MINS PR)
LOAD EMPHASIS (INJURY SPECIFIC)	TD <EXPD/ <HSR <ACC <DEC	TD >EXPD/ <HSR >ACC >DEC	TD >EXPD / <HSR TD >EXPD / >HSR (SPR) >ACC >DEC >ACC >DEC	TD >EXPD/ <HSR TD <EXPD/ >HSR (SPR) >ACC >DEC <ACC <DEC	TD >EXPD/ <HSR TD <EXPD/ >HSR (SPR) >ACC >DEC <ACC <DEC
NO. OF SESSIONS	2-4	3-4	3-4	3-5 (DEPENDANT UPON TRAINING METHOD)	3-5 (DEPENDANT UPON TRAINING METHOD)

Figure 5. Blueprint for returning to sport post-ATR. Adapted from Taberner et al., (2019).

2.5.1. Athletic competency, career outlook

Being sidelined from all forms of activity swiftly clouds muscle-memory pathways and weakens neural impulse feedback. These two fundamentals, along with technique, have been tediously fine-tuned over tens of thousands of hours to eclipse elite athleticism. In the case of AT, the timeline to RTS is arduous, uncertain, sport dependent. Seventy-one (72.4%) players were able to return to sport in the NFL at a mean of 339.8 ± 84.8 days (Jack et al., 2017).

Player efficiency rating, a standardised measurement tool commonly used in evaluating NBA players by using a complex formula to create a per-minute rating of a player's performance found significantly decreased PER values following injury in the first two seasons (Lemme et al., 2019; Amin et al., 2013; Trofa et al., 2017). NBA players who returned to play after Achilles tendon injury showed a significant decrease in playing time and performance. Thirty-nine percent of players never returned to play (Amin et al., 2013). In a review of elite endurance athletes across a heterogenous population, athletes had significantly lower plantarflexion strength in their ailed extremity versus the uninjured side (Maffulli et al., 2011). Regardless of the type of rehabilitation protocol or surgical management, the rate of RTP following Achilles tendon trauma remains among the lowest of all common orthopaedic procedures, and multiple investigations have suggested that athletes returning to sport after Achilles tendon tear may have difficulty returning to preinjury level of performance (Wang et al., 2017).

Adaptability and grit however play a significant role in career potential, with one to two seasons post-injury serving as an acceptable projection for future professional prowess. A report by Grassi et al. (2018) reports 82% of professional footballers were able to play in the same division as their preoperative level.

3. Stiffness and SWE

3.1 Stiffness

Tissue stiffness is measured as an elastic modulus where kilopascals, or kPa, serve as its units. Defined as the resistance to deformation, it is expressed as the magnitude of a stress (compression, elongation, or shear force, normalized to area) divided by the strain (deformation) induced by the stress (Wells, 2013). When an outside force acts on tissue, cellular actin-myosin cytoskeleton exert tension on extracellular matrix proteins via integrin attachments located within focal adhesions; stiffer tissues result in increased resistance to the pulling force exerted by cells, contributing to strengthening that force (Chen, 2008; Roca-Cusachs et al., 2012). The slope of the force-elongation curve yields an equational constant between stiffness and varying levels of force. When force is divided by the tendon cross-sectional area and tendon elongation normalized to initial length of the tendon, the slope of the stress-strain curve yields Young's modulus. Young's modulus represents the material property of tissue and is identified from the linear region of the curve. Both stiffness and Young's modulus can increase with training. Longer training periods are needed to have increases in tendon cross-sectional area (green arrow). This unique characteristic permits tissues to store elastic energy. Figure six illustrates this phenomenon.

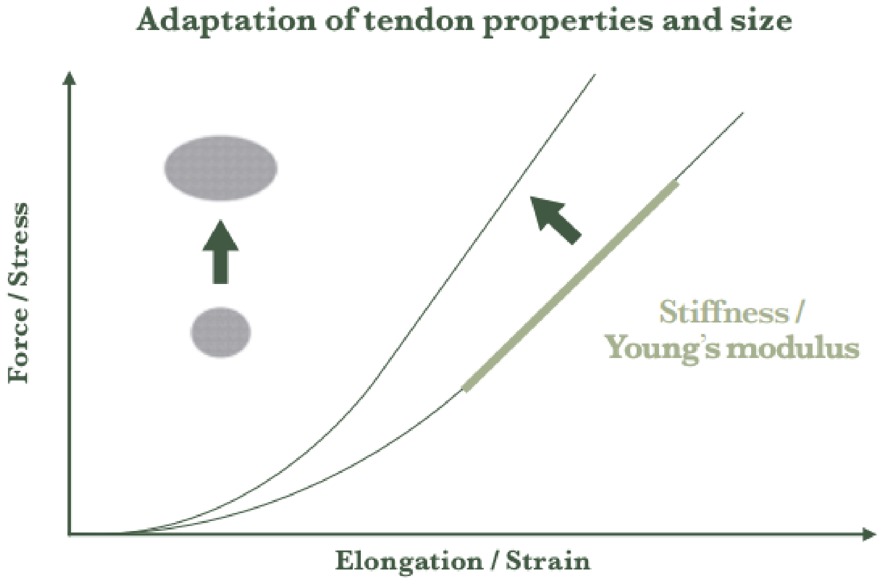


Figure 6. Stress-strain relationship. Adapted from Finni et al., (2023).

Tissues however are not perfectly elastic, but are viscoelastic, meaning that, like liquids, they have a viscosity, and that the strain in response to stress changes with time (Liu & Bilston, 2000; Navajas et al., 1995). This explains why each muscle of the triceps surae has an individual passive stiffness. The fluid nature of stiffness diverges further depending on Achilles injury history. Assessments by AOFAS, the American Orthopaedic Foot and Ankle Society, suggest contralateral tendons in patients with reconstructed Achilles tendon have significantly lower stiffness than healthy individuals. Therefore, contralateral tendons in patients who suffered from injury are more prone to future ruptures (Ivanac et al., 2020).

Biomechanics and pathophysiology of surrounding structures have shown correlation to stiffness. Lorimer & Hume (2016) recall high arches and increased vertical and propulsive forces as protective for AT injuries, increasing lower body stiffness. The evidence trending towards an increase in leg stiffness, and a decrease in ankle stiffness, being detrimental to Achilles tendon health.

Few studies have investigated the link between lower body stiffness and Achilles injury. High stiffness is potentially associated with risk factors for Achilles tendon injuries although some of the evidence is controversial. Prospective injury studies are needed to confirm this relationship (Lorimer & Hume, 2016).

3.2 Shear wave elastography

Shear wave elastography (SWE) is a non-invasive, emerging diagnostic imaging technique that maps the elastic properties of tissues. It uses an acoustic radiation force pulse sequence to generate shear waves, which propagate perpendicular to the ultrasound beam, causing transient displacements (Taljanovic et al., 2017). SWE provides a measurement of shear wave velocity (m/s), which can be further expressed as shear modulus and serves as a surrogate quantification of passive tissue stiffness (Bercoff et al., 2004). As a modern research instrument, shear wave elastography offers three main innovations: the quantitative aspect, dimensional resolution, and real-time imaging ability (Zemanova, 2019). Several publications have reported its reliability in assessing muscle (Lacourpaille et al., 2012) and tendon stiffness (Schneebeli et al., 2021). Shear wave elastography is optimized for resting, rather than mechanical loading, conditions.

4. Research Objectives

4.1 Primary objective

The primary objective of this Master's thesis was to investigate Achilles tendon stiffness via shear wave velocity. This research question was approached through two different cohorts, juxtaposed by whether a certain workout intensity results in superior clinical outcomes. As outlined, the practical benefits of this study could aid in shrinking the prolonged, arduous recovery process of an Achilles tendon injury. The transfer rate between athletes and everyday people is presumed high, thus the findings of this experiment can also help physiotherapists in all facets. If the data is irrefutable, it could be a building block to creating a new paradigm in physiotherapy, i.e. rehabilitation, and athletic training programs, i.e. decreasing rate of injury.

4.2 Tested hypotheses

Alternative hypothesis: Subjects in the high-intensity aerobic training group will have higher Achilles stiffness than the low-intensity participants. (H1: $\mu 1 \neq \mu 2$)

Null hypothesis: Training intensity does not influence Achilles tendon adaptation. (H0: $\mu 1 = \mu 2$)

5. Materials & Methods

5.1 Data collection

The foundation of this research endeavor was formed by a mutual partnership between Jyväskylä University of Applied Sciences and the University of Jyväskylä. All demographic information, injury history, and ultrasound scans were previously collected by JYU in 2020 and had been archived.

This study's framework consisted of a two-week preparatory period (phase 1), a one-week recovery period (phase 2), a two-week training period utilizing high- or low-intensity training (phase 3), capped off by a second recovery week (phase 4). During the preparatory stage, participants trained normally, with zero outside input on their regimens. Phase two’s training period began with group designation where sex, 3000-m performance, maximum aortic velocity ($v_{max)}$, and baseline heart rate variability, or HRV, served as contextual variables. To mitigate bias these performance markers were then used to pair two similar scoring athletes, assigning one into the interval group (INT), the other into the volume group (VOL).

As phase three transpired, the INT group performed a total of ten 6×3-minute HIIT sessions at a frequency of five sessions per week. Meanwhile, the VOL group increased their low-intensity running volume by 70%. Exertion parameters for the HIIT and volume protocols were estimated based on previous studies examining HIIT shock microcycles (Dolci et al, 2020) or volume-based overload periods (Lehmann et al, 1992; Uusitalo et al., 1998; Le Meur et al, 2013).

5.1.2 Shear wave elastography

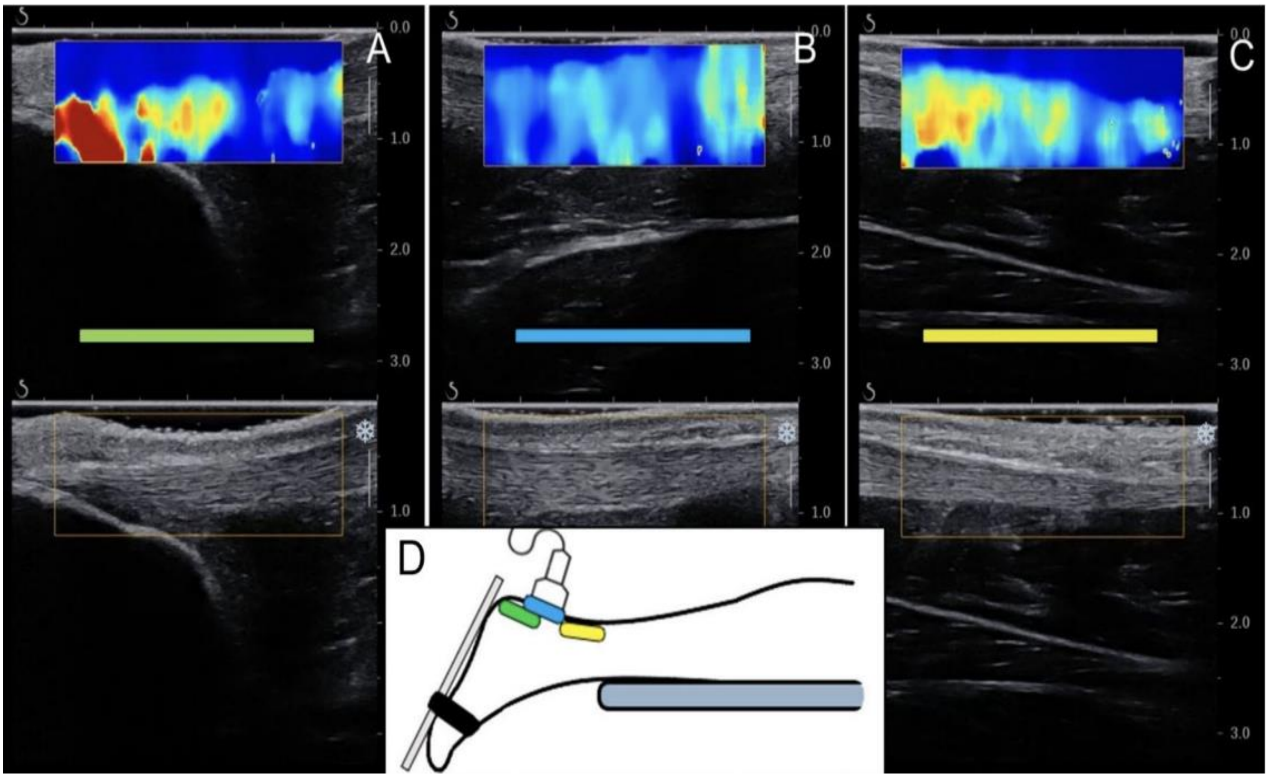
Passive muscle stiffness in the Achilles and triceps surae was approximated via supersonic shear wave elastography (Aixplorer Supersonic Imagine, v. 12.3.1, patent Aix-en-Provence, France). This technology yielded tissue shear wave velocity (SWV) and shear modulus (μ), of which the latter is calculated using the formula:

μ = ρV2 (ρ = muscle mass density 1000 kg m3) (Bercof et al. 2004; Gennisson et al. 2003). Optimal probe placement was defined as having numerous fascicles and aponeuroses, both superficial and deep, visible in the B-mode image. Reliability was authenticated by alleviating manual pressure between the probe and subject's skin.

A 38 mm linear transducer (2–10 MHz, SL10-2) was used to record AT SWV and SOL shear modulus, while a 50 mm linear transducer (5–18 MHz, SL18-5) transcribed the MG and LG shear modulus. All measurements were performed with a custom musculoskeletal pre-set (penetration mode, smoothing level 5, persistence off, opacity 100%) with the probe parallel to the muscle and tendon fascicles and perpendicular to the skin (Sukanen et al., 2024).

Site-relevant preparation protocols were uniformly administered prior to any data collection. The proximal head of the calcaneus was identified utilizing B-mode ultrasound and marked as the Achilles tendon's insertion point. Elastographies of each test subject's Achilles tendon followed a methodical manner, starting from the most distal third (ATDist), gradually moving proximally toward the gastrocnemius (ATMed and ATProx). The second, and third, measurement being 18mm, and 48mm, from the AT's origin. ATMed and ATProx locales were also marked. To strengthen the evidence, elastography measurements were recorded three times, twice during the preparatory period (pre1- and pre2-measurements) and once in the recovery period (post-measurement).

The measurement protocol required the SWE range to be calibrated to 0-800 kPa, with an average depth of scan set to 2.5cm. To approximate resting Achilles tendon SWE participants were instructed to lie prone on the measurement table, with both feet manually fixed into 25° of ankle plantarflexion. Figure 7-D illustrates this step. To obtain resting Triceps surae SWE, athletes were instructed to lie prone with their feet dangling off the end of the table. Data collection for the gastrocnemius was collected from its thickest portion, i.e. highest density of muscle fibers. The soleus was imaged laterally from the area where the muscle lies superficially, distal to LG muscle–tendon junction (Sukanen et al., 2024). In Figure 7, images A-C show SWE and B-mode images of AT at three different measurement sites. D is the resting Achilles tendon SWE, achieved via physically strapping ankle in place; H-J are SWE of the medial gastrocnemius, lateral gastrocnemius, and soleus muscle. Note: J shows that although the SWE region of interest was initially placed in the middle of the muscle, changes in muscle position during dorsiflexion caused the region to overlap the aponeurosis, convoluting shear modulus in the upper part of the image. In such a case, red hued areas were omitted from ElastoGUI analysis.



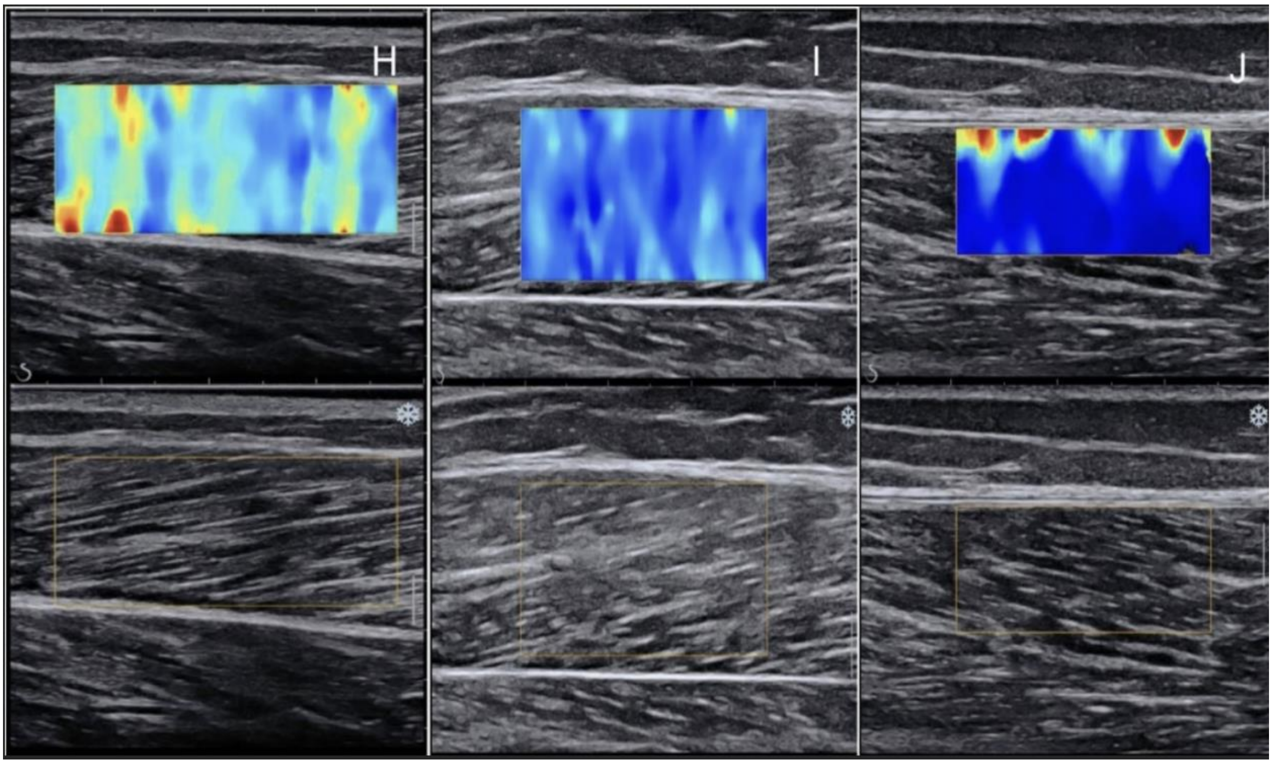


Figure 7. Measurement protocol for AT shear wave velocity. Adapted from Sukanen et al., (2024).

5.2 Non-disclosure agreement

A series of documents safeguarding the archived dataset, participants' anonymity and privacy at all stages of data interpretation, along with agreeing to Jyväskylä University's IT guidelines were drafted by doctoral researcher Maria Sukanen, and Taija Juutinen, JYU's vice dean of physical education and research. Signing the agreement legally bound both respective parties to the terms and conditions, prompting due diligence and dynamizing based scientific purpose(s). The student retrieved an entrance key from service center Clavis, granting access to a personal cubical in JYU's Neuromuscular Research Center. The workspace was provided from October 2nd, 2023, to October 31st, 2023, the JAMK affiliate shifting to virtual until thesis submission. Cisco's AnyConnect VPN service assured security. All collected and quantified data was stored in the student's personal two-phase identification cloud service, S-asema. Compliance to all ethics was ratified by the Research Ethics Committee of the Central Finland Health Care District. All study procedures were conducted according to the Declaration of Helsinki.

5.3 Study design

A one-month prospective cohort study investigating if a relationship between workout intensity and damaged Achilles tissue stiffness exists.

5.4 Athletic recruitment

Test subjects were selected from local sporting programs. Inclusion criterion required each participant competing at the national level. Exclusion criteria included candidates' inability to return to sport or underlying health conditions which sidelined him/her from play in the past competitive season. By the end of vetting, twenty endurance athletes were chosen and briefed. Each participant provided a signed informed consent prior to participation. One of the twenty subjects extricated themself from the trial following the second round of measurements. The intervention group thus had nine athletes, the remaining ten assigned to the volume, or control, population.

5.5 Covid-19 safety

In efforts to lessen the spread of Covid-19, JYU and its research staff integrated safety guidelines mirroring those set by the WHO. Upon entering the data collection workspace, athletes were immediately given a facemask and ushered to the lavatory. While washing their hands, a JYU research affiliate instructed them to not remove the mask until all required data was collected. The treatment table and measurement device were thoroughly disinfected between participants. Timeslots were designed to limit the total number of people in the workspace.

Athletes and JYU staff were forbidden from entering the facility if they showed typical signs of Covid-19 (fever, runny nose, muscle aches, headache, dry cough), or other illness.

5.6 Statistical analysis

SPSS Statistics (version 29.0.1.0 (171), IBM Corp, Armonk, NY)) computed all statistical analysis, with JASP (version 0.18.3. macOS, Amsterdam, Netherlands) illustrating the data. ElastoGUI (version R2021b, MathWorks Inc, Natick, MA, USA) processed young modulus (maximal value, mean and standard deviation), shear modulus (mean and standard deviation), shear wave velocity (mean and standard deviation), surface area, saturation percentage, and void percentage. Baseline descriptive statistics, age and BMI, were reported using mean and standard deviation. Statistical significance was defined as P<0.05. An ANOVA, or analysis or variance, test further evaluated the difference between SWV means. The numbers 1, 2, and 3 correspond to pre1-, pre2-, and post-measure.

6. Results

Twenty subjects were originally selected to volunteer, but correspondent 111 failed to appear at any meetings following the pre2-. Hence, only nineteen datasets were archived.

6.1 Participant demographics

Anthropometric characteristics of all subjects were collected during the group assignment phase and compiled into table 1.

Table 1. Athlete attributes

	Total Sample	Males	Females	Min.-Max.
N	19	12	7	
Mean Age (SD)	34.0 (6.86)	33.67 (5.33)	34.57 (9.40)	26-45
Mean BMI (SD)	24.20 (2.57)	24.64 (2.13)	23.44 (3.23)	21.13-30.40 (6.43)

Although there is a slight favoritism, or bias, toward representation of male endurance athletes, the means of both age and body mass index are quite akin. As expected, the mean BMI lies in a region reserved for active individuals. As for age, it can be inferred that a majority of those selected are on the latter portion of their athletic careers, the moniker of ‘seasoned veterans’ bestowed upon them. Had the participants been older, SWV would change. The logical, yet twisted, explanation to this study’s age demographic can be linked to an extended career's outlook. The longer AT tissue is exposed to strain, the risk of serious injury rises.

6.2 Shear wave velocity (µ, m/s)

During the onboarding process at JYU's Neuromuscular Research Center, the JAMK liaison familiarized themselves with ElastoGUI tracing and SWV collection criteria. Two separate SWV datasets, independent from this thesis, were used as practice. Hopkins tests for reliability were calculated for each, deeming the JAMK affiliate proficient enough to begin quantifying this study's data.

6.2.1 SWV average between sexes

Table 2. SWV average between sexes

Sex	SWV_1_Dist_R (m/s)	SWV_1_Med_R (m/s)	SWV_1_Prox_R (m/s)	SWV_2_Dist_R (m/s)	SWV_2_Med_R (m/s)	SWV_2_Prox_R (m/s)	SWV_3_Dist_R (m/s)	SWV_3_Med_R (m/s)	SWV_3_Prox_R (m/s)
Male	8.87	10.71	11.12	9.08	10.78	11.49	9.47	10.67	11.36
Female	7.81	9.55	10.54	8.81	11.15	11.16	8.84	11.15	12.18

Sex	SWV_1_Dist_L (m/s)	SWV_1_Med_L (m/s)	SWV_1_Prox_L (m/s)	SWV_2_Dist_L (m/s)	SWV_2_Med_L (m/s)	SWV_2_Prox_L (m/s)	SWV_3_Dist_L (m/s)	SWV_3_Med_L (m/s)	SWV_3_Prox_L (m/s)
Male	9.49	10.28	11.63	8.56	10.67	11.56	8.83	10.05	11.75

Female	7.58	9.75	10.85	8.53	9.98	10.90	8.72	10.43	11.86

6.2.2 SWV average between injured & non-injured Achilles

Table 3. SWV average between injured & non-injured Achilles

Status	SWV_1_Dist_R (m/s)	SWV_1_Med_R (m/s)	SWV_1_Prox_R (m/s)	SWV_2_Dist_R (m/s)	SWV_2_Med_R (m/s)	SWV_2_Prox_R (m/s)	SWV_3_Dist_R (m/s)	SWV_3_Med_R (m/s)	SWV_3_Prox_R (m/s)
Injured	8.70	10.39	10.89	8.97	10.91	11.33	9.69	10.88	11.81
Non-injured	8.11	10.10	10.93	8.99	10.92	11.45	8.45	10.79	11.42

Status	SWV_1_Dist_L (m/s)	SWV_1_Med_L (m/s)	SWV_1_Prox_L (m/s)	SWV_2_Dist_L (m/s)	SWV_2_Med_L (m/s)	SWV_2_Prox_L (m/s)	SWV_3_Dist_L (m/s)	SWV_3_Med_L (m/s)	SWV_3_Prox_L (m/s)
Injured	7.97	10.39	11.93	8.50	10.94	11.72	8.17	10.72	11.84
Non-injured	9.26	9.91	11.00	8.57	10.11	11.04	9.15	9.89	11.77

A previous Achilles injury's impact on SWV seems to be inconclusive, as greater values flipflop between injured and non-injured. Previously outlined, the multifaceted approach the body exhibits when repairing itself may lead to over depositing certain microelements. A tissue's natural material can sometimes lead to miscalculations. Emphasis on the prioritization of safety protocols were well heeded, as zero instances of acute Achilles reaggravation were reported.

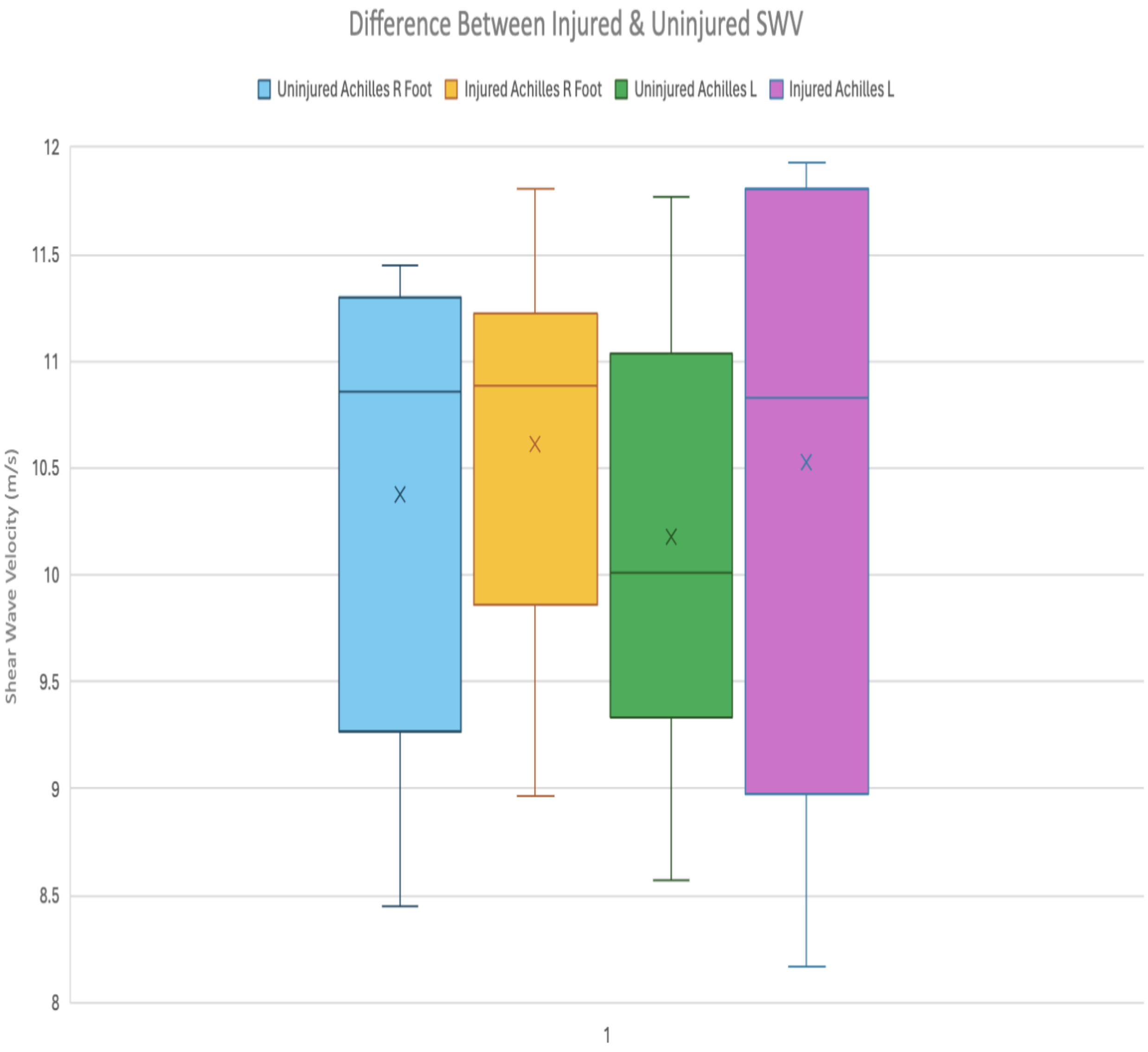


Figure 8. Difference between injured & uninjured SWV

The range, IQR, and median are displayed above, with little to no consistency. No concrete answer can be extrapolated from previous injury history.

6.3 SWV average between volume & interval group

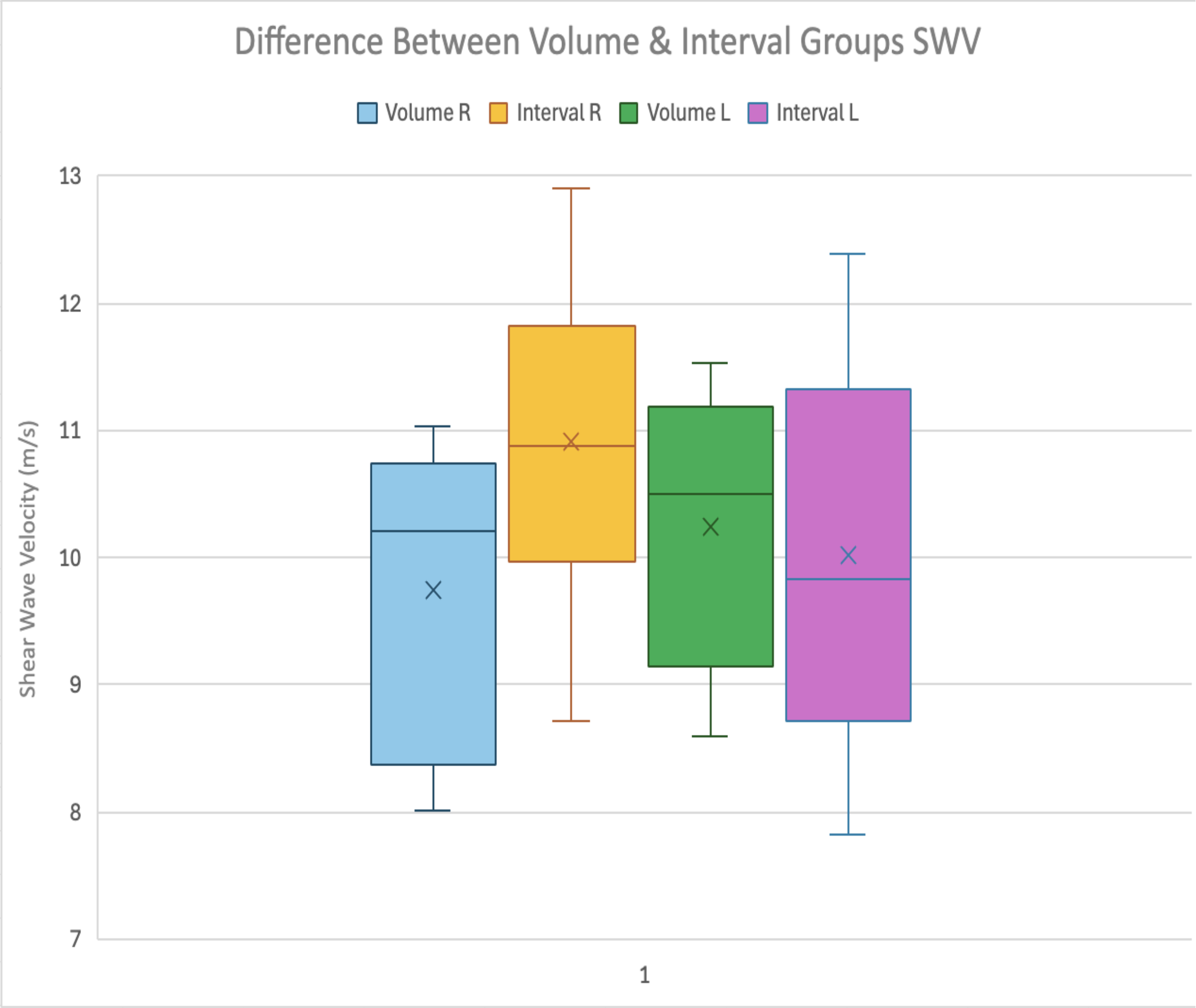


Figure 9. Difference between volume & interval groups SWV

Table 4. Difference between volume & interval groups SWV

Subject	SWV_1_Dist_L (m/s)	SWV_1_Med_L (m/s)	SWV_1_Prox_L (m/s)	SWV_2_Dist_L (m/s)	SWV_2_Med_L (m/s)	SWV_2_Prox_L (m/s)	SWV_3_Dist_L (m/s)	SWV_3_Med_L (m/s)	SWV_3_Prox_L (m/s)
V R	8.28	10.12	10.94	8.46	10.38	11.03	8.01	9.90	10.55

INT R	8.71	10.37	10.88	9.56	11.51	11.75	10.59	11.90	12.90
V L	9.65	10.49	11.53	8.64	10.94	11.10	8.60	10.03	11.27
INT L	7.83	9.63	11.14	8.44	9.84	11.52	8.90	10.37	12.38

When comparing each volume and corresponding interval data set in the right foot, 88% of stiffness measurement rise. With a p-value of 0.007, there is a significant correlation between volume and interval group shear wave velocity in the right foot ($p<0.05$). A hypothesis could be made that the left interval group should mimic that of the right. Oddly, this trend is not as clear with only 44% of SWV's increasing.

7. Discussion

The primary objective of this study was to quantify whether exercise intensity can affect Achilles tendon stiffness. Shear wave elastography was utilized to examine Achilles tendon stiffness in endurance athletes. Sex and age were linked to affecting measured outcomes. Alfuraih et al. (2019) state, overall resting muscle SWV gradually decreases with age. The relationship between age and musculature surrounding the AT is further investigated by Pang et al. (2021), showing atrophy of the gastrocnemius directly changes lower-limb muscle stiffness. Hormones can play an integral role in this comparison due to testosterone's effect on cross-sectional area and overall FFM, fat free mass. Although this parameter is not the primary focus, it offers additional insight on Achilles composition. According to Chino & Takahashi (2016), men tend to have greater passive ankle joint stiffness in neutral anatomic position and 20° dorsiflexion. The data quantified in ElastoGUI corroborates this publishing, with males having higher stiffness in 72.22% of all SWV samples.

Surprisingly, lower limb injury history was not correlated to impacting stiffness. After an initial drop post-injury, stiffness increases to eventually match or even exceed that of the uninjured tendon (Agres et al., 2015; Karamanidis & Epro, 2020). AT stiffness was lower in the injured limb 3–12 months after surgical treatment (Chen et al., 2013; Geremia et al., 2015; McNair et al., 2013). These changes in tendon stiffness have functional consequences via their effects on the muscle's force-length and force-velocity relationships (Khair et al., 2022).

Achilles tendon stiffness is challenging to generalize as two individuals injured under artificially identical circumstances will heal differently. If a serious injury such as an AT rupture transpires, the tendon often repairs itself into an elongated version of its predecessor. Gastrocnemius cross-sectional area undergoes atrophy to accommodate. Khair et al. (2022) observe that a difference in MG CSA between limbs was associated with a greater inter-limb dissimilarity in normalized AT stiffness, as changes in MG structure directly reflect muscle force production capacity. Young’s modulus of tendon stiffness, along with force transfer following mechanical loading, based on potential energy storage capacity and force output.

Navigating return to sport criteria must involve a multidisciplinary approach. An elongated AT can predispose an athlete to eccentrically-induced muscle damage or strain as the tendon cannot work as efficiently to dissipate energy nor reduce the negative power done by surrounding musculature (Roberts & Azizi, 2010). In some respects, modern science still cannot understand the body’s modus operandi to healing. Each step has been finetuned over centuries, continuously working to protect uninjured and ailed tissues alike from future trauma. Focusing on tendon elongation, lower maximal elongation coupled with an increase in tendon length greatly reduces tendon strain, which has been speculated to be important for reducing the risk of tendon injury (Karamanidis & Epro, 2020) and fatigue damage (Wren et al., 2003).

One study limitation is the relationship between ultrasound imaging and applied pressure. Excessive pressure may influence fascicle orientation, length, and pennation angle. Khair et al. (2022) estimate a ~6% error in elastography mean value. Modeling a viscoelastic material as linear elastic tends to overestimate the SW propagation velocity (Naganuma & Ishida, 2022).

A peculiar case of mismanagement of data archiving is evident in athlete 135, the shear wave elastography presented as zero in the second proximal imaging of the left foot. This is due to the raw data reading ‘data missing’. The zero-value acting as a place holder to create illustrations using JASP, this data point was always omitted when calculating group-specific SWV averages and standard deviations.

A final oversight in this study was the non-uniformity in measurement collection. Participants were asked upon arrival if they had exercised that day, with responses ranging from moderate walking to ten-kilometer bike rides. Some opted to walk from their homes to the testing facility. As Rosengarten and colleagues summarized, recreational activities effectively change Achilles tendon structure. Exercise within two days before measurement was found to affect Achilles tendon non-uniformity, mean anterior tendon displacement, and Achilles tendon shear wave velocity at the proximal measurement location (Sukanen et al., 2024). Minimal physical activity should have been prescribed on the day of testing.

Omitting human error, shear wave elastography can be deemed an excellent tool in reliability and ease of use. The findings of this study should be open to interpretation though, not canon. A previous study has shown that tendon structure can be altered up to 72 hours after exercise when assessed with ultrasound tissue characterisation (Rosengarten et al. 2015). Being a viscoelastic organ, tendon stiffness has been found to decrease for a short period after exercise (Grigg et al. 2009; Fahlström and Alfredson 2010). Rarely do academic studies have perfect comparisons, as Pękala et al. (2017) suggest Achilles tendon discrepancies are normal given anatomical variability. Thus, this study and its findings are merited.

8. Conclusion

The repercussions of an Achilles tendon injury are very serious, as it can prematurely end an upcoming phenom’s, or proven veteran's, career in an instant. Those lucky enough to return to the field often experience a downgrade from pre-injury performance capacity or fading of play minutes. Compounding this hurdle is an internal battle with the psyche, trying to suppress fears of reinjury while striving for competitive competence. As humanity progresses, continued research along with undiscovered rehabilitation, surgical, and prevention techniques can abate the negative prognosis of AT lesion.

In the realm of workout intensity variability, neither high- or low-intensity training epitomized a definitive significant difference in Achilles tendon stiffness. Persons with tendon injuries need to be patient, since tendon healing progresses from inflammatory phase in the first week to proliferative phase lasting up to 6 weeks, while remodeling can take months or years (Benage et al., 2022). Ensuring sufficient recovery alongside performance and objective markers may provide the most valid and actionable assessment of current readiness to train (Nuutilla et al., 2022).

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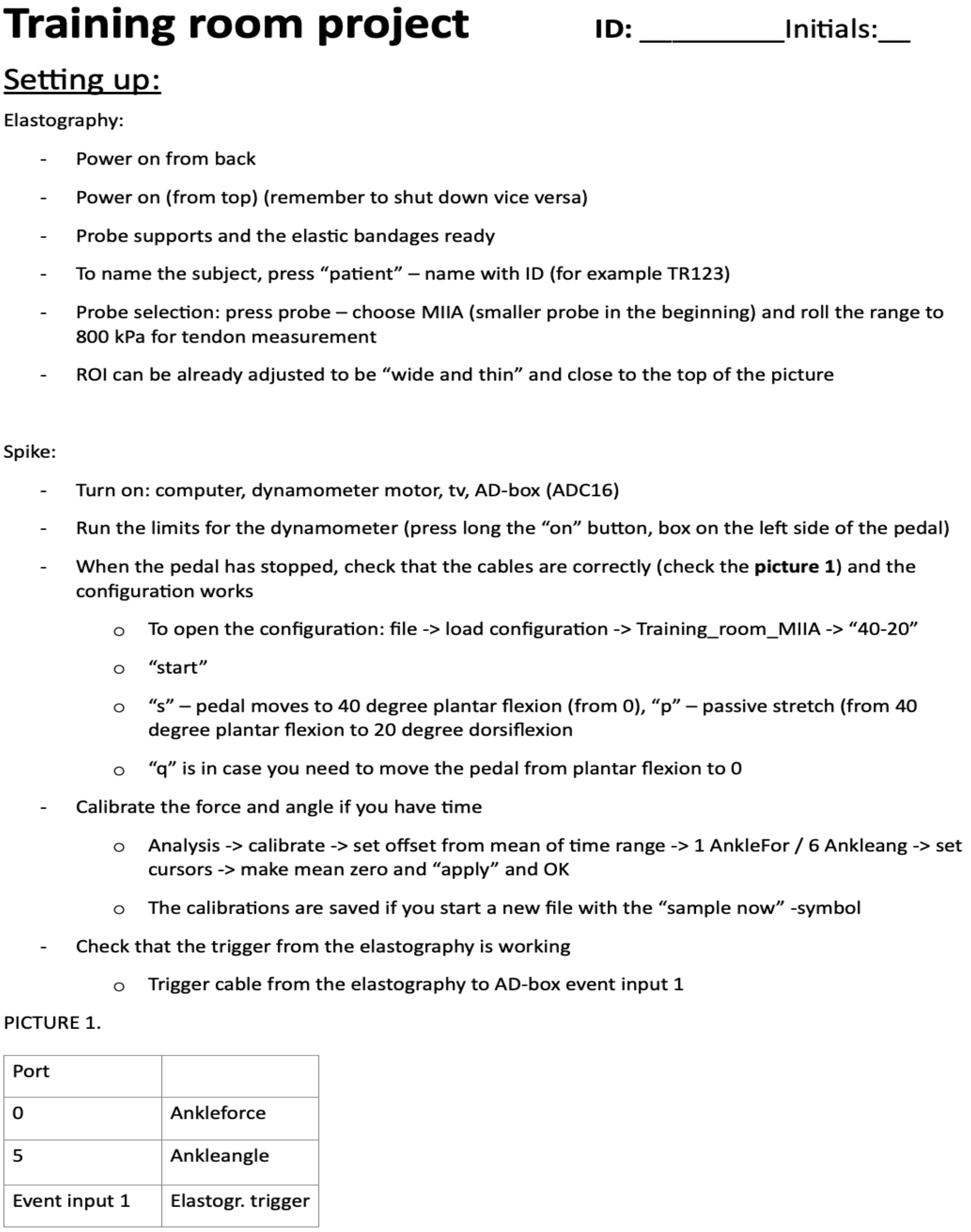
Appendices

Appendix 1. Guidelines for operating the computer during data collection for custom dynamometer



Training room project ID: _________Initials:__

Setting up:

Elastography:

- Power on from back
- Power on (from top) (remember to shut down vice versa)
- Probe supports and the elastic bandages ready
- To name the subject, press "patient" – name with ID (for example TR123)
- Probe selection: press probe – choose MIIA (smaller probe in the beginning) and roll the range to 800 kPa for tendon measurement
- ROI can be already adjusted to be "wide and thin" and close to the top of the picture

Spike:

- Turn on: computer, dynamometer motor, tv, AD-box (ADC16)
- Run the limits for the dynamometer (press long the "on" button, box on the left side of the pedal)
- When the pedal has stopped, check that the cables are correctly (check the **picture 1**) and the configuration works
    - To open the configuration: file -> load configuration -> Training_room_MIIA -> "40-20"
    - "start"
    - "s" – pedal moves to 40 degree plantar flexion (from 0), "p" – passive stretch (from 40 degree plantar flexion to 20 degree dorsiflexion
    - "q" is in case you need to move the pedal from plantar flexion to 0
- Calibrate the force and angle if you have time
    - Analysis -> calibrate -> set offset from mean of time range -> 1 AnkleFor / 6 Ankleang -> set cursors -> make mean zero and "apply" and OK
    - The calibrations are saved if you start a new file with the "sample now" -symbol
- Check that the trigger from the elastography is working
    - Trigger cable from the elastography to AD-box event input 1

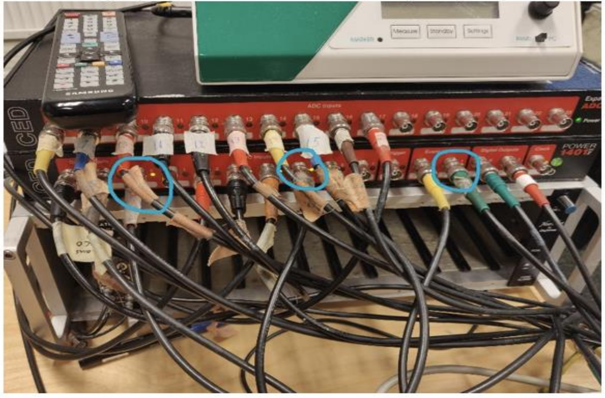
PICTURE 1.

Port	
0	Ankleforce
5	Ankleangle
Event input 1	Elastogr. trigger

Training room project

ID: __________Initials:__

Monitoring Injury and Illness in Athletes (MIIA)



Other stuff:

- "Table" ready for the tendon measurements (pillow, padding for the shin, cover paper to keep it cleaner
- Post-it notes on the sides of the "table" with the ID on it (for the pictures)
- Dynamometer: smaller bench and small white board (on the left side of the pedal) instead of the brown one
- Measurement tape
- PAPER (a lot)
- "Data log" ready (in the folder, print if needed)

Setting up:

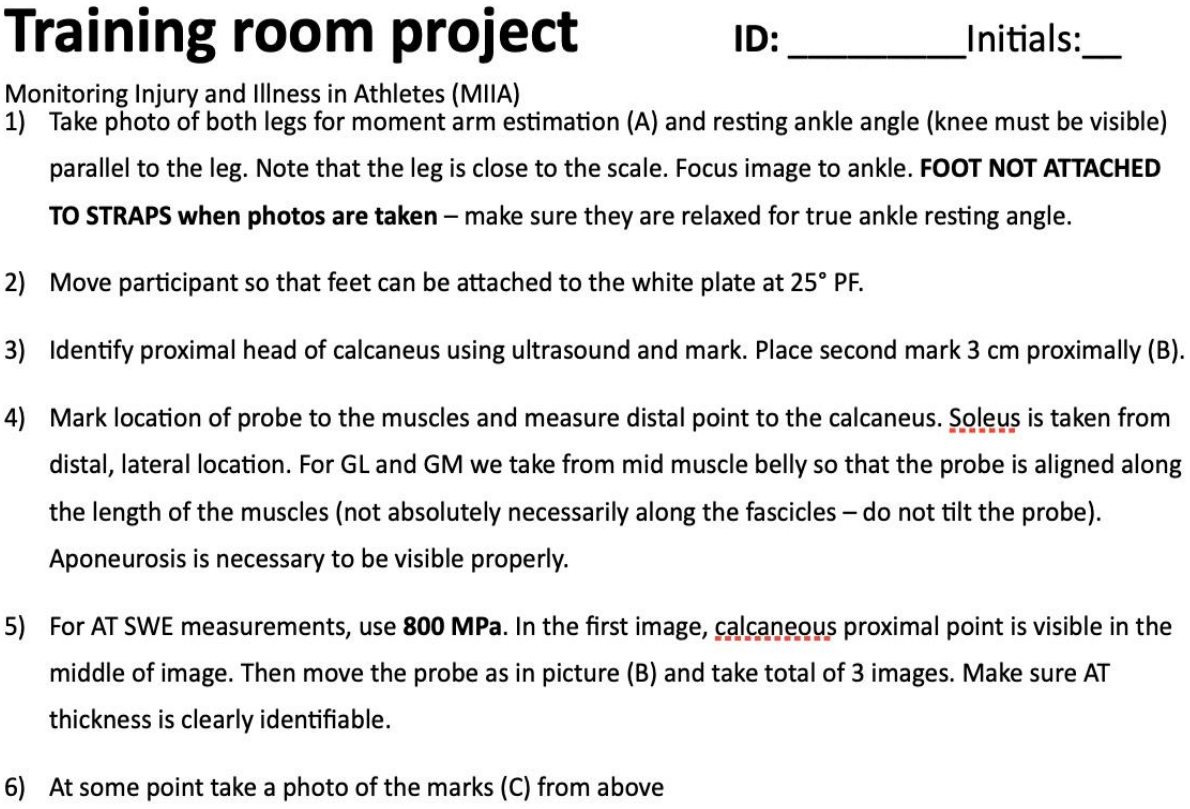
1) Use MIIA presets in SWE (penetrate, opacity 100%, no persistence, 5/9 smoothing elasticity)
2) AT is measured with **800 MPa**, passive muscle with **600 MPa (adjust if needed** during measurements!)
3) B-mode gain should be adjusted fairly bright.
4) SWE image should be on top and B-mode image in the bottom of the screen (optimal for analysis).
5) Wide probe for LG and MG, Smaller probe for SOL and AT
6) SPIKE folder: Training room.

Appendix 2. Measurement protocol, theoretical

Dynamometer measurements:

1) Place foot to the pedal but do not tighten the straps. Adjust bench and mark down bench position.
2) Explain the movement of the pedal. Straps loosely tightened. Explain to use the stop switch if needed. (In case we see that 20 deg dorsiflexion is close to limit, then run another script -> 10 or 15 degree as maximum)
3) If the stretch is fine (and force is not over c. 15 Nm), tighten the straps.
4) Place smaller probe onto AT. Make sure that AT is visible and fairly bright. USE 10-2 probe with B-mode (adjust RESOLUTION and FrameRate so that we **have Frame rate ~60 Hz)** so that its internal shear can be analyzed using speckle tracking. (Here we are not interested in SWE images but they need to be visible in order to have the trigger.) Instruct participant to increase force level gradually (ramp) to 50 Nm level where you have placed a horizontal line and down. Let the subject practice first.
5) Do passive SOL measurements with smaller probe at 600 MPa.
    a. Measurement process: In spike, use Button **S** to move pedal from 90 to 40 deg plantarflexion. Then press Freeze once and wait for 3 seconds. Then press Freeze to start recording in ultrasound machine and press **P** button in signal. Then press Freeze and Save Clip.
6) Measure LG and MG in random order with the **bigger probe**. For muscle SWE measurements use **600 MPa** as maximal. If saturation to dark red is seen in some subjects, then adjust.
    a. (adjust the scale of each muscle to be as precise in order to observe weak changes in stiffness (Le Sant et al. 2017 JAnat: GM : 128 kPa, GL : 67,1 kPa, SOL : 10,2 kPa))
7) Same measurements to the other leg (**remember** to measure the bench position for both legs)
8) When all the measurements are done “End exam” – the session is saved and you can start a new subject (patient)

Appendix 3. Measurement protocol, practical



Training room project

ID: _________Initials:__

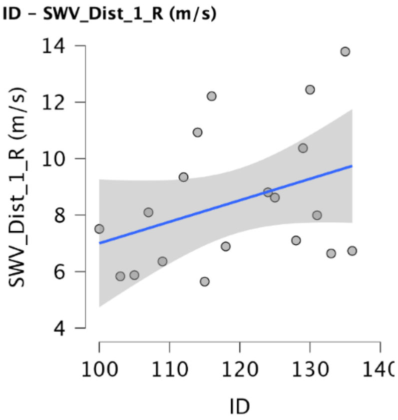
Monitoring Injury and Illness in Athletes (MIIA)

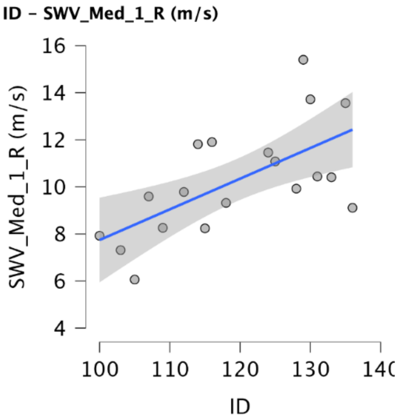
1) Take photo of both legs for moment arm estimation (A) and resting ankle angle (knee must be visible) parallel to the leg. Note that the leg is close to the scale. Focus image to ankle. **FOOT NOT ATTACHED TO STRAPS when photos are taken** – make sure they are relaxed for true ankle resting angle.
2) Move participant so that feet can be attached to the white plate at 25° PF.
3) Identify proximal head of calcaneus using ultrasound and mark. Place second mark 3 cm proximally (B).
4) Mark location of probe to the muscles and measure distal point to the calcaneus. Soleus is taken from distal, lateral location. For GL and GM we take from mid muscle belly so that the probe is aligned along the length of the muscles (not absolutely necessarily along the fascicles – do not tilt the probe). Aponeurosis is necessary to be visible properly.
5) For AT SWE measurements, use **800 MPa**. In the first image, calcaneous proximal point is visible in the middle of image. Then move the probe as in picture (B) and take total of 3 images. Make sure AT thickness is clearly identifiable.
6) At some point take a photo of the marks (C) from above


A)
B)
C)
Scale is here
TR43
TR43

Appendix 4. SWV of all athletes, right foot & left foot

Right foot


ID – SWV_Dist_1_R (m/s)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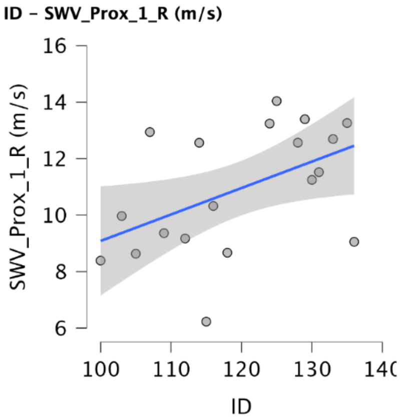
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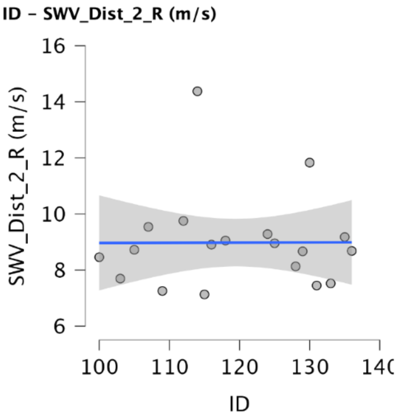
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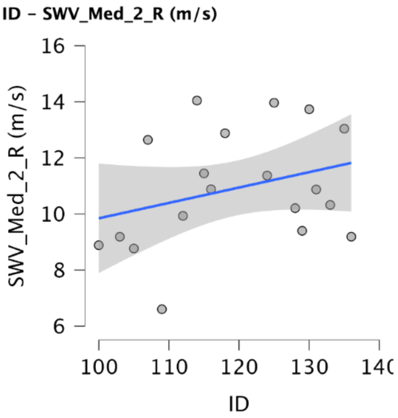
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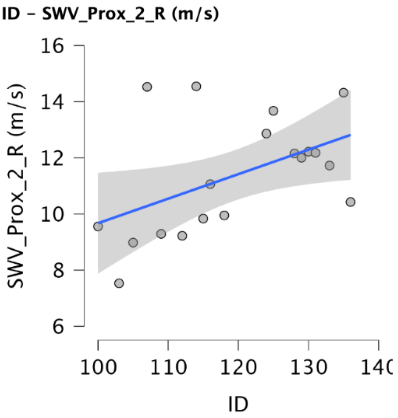
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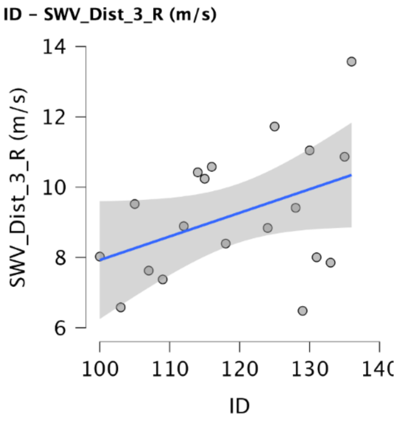
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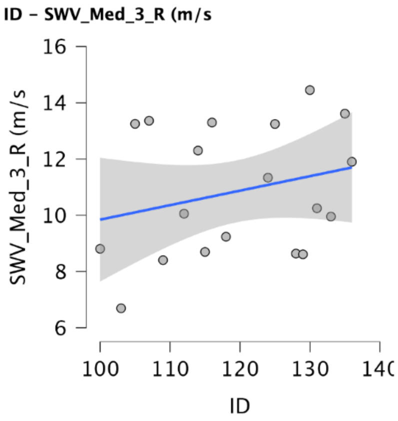
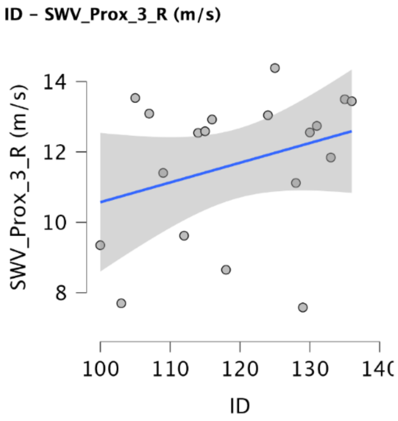

ID – SWV_Med_3_R (m/s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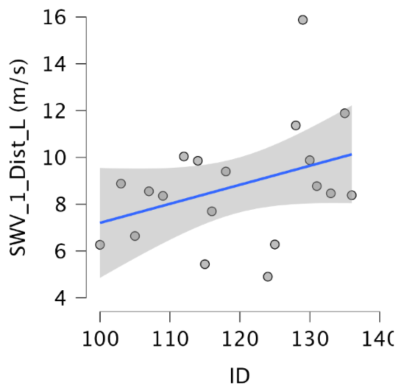
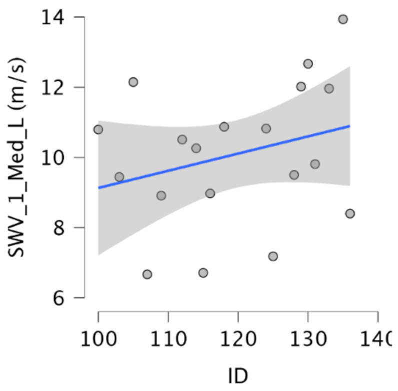
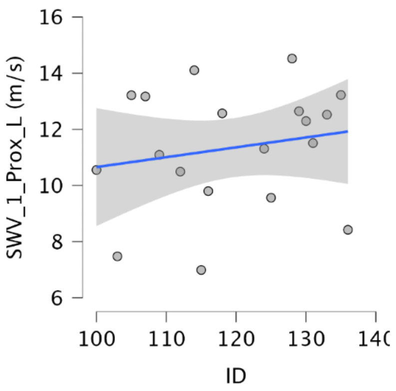
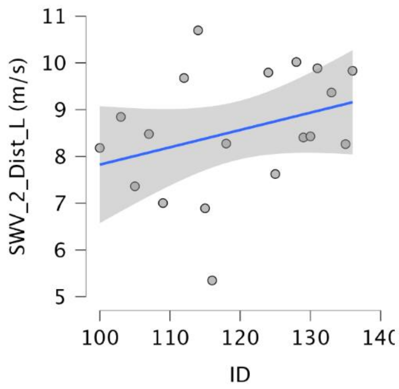
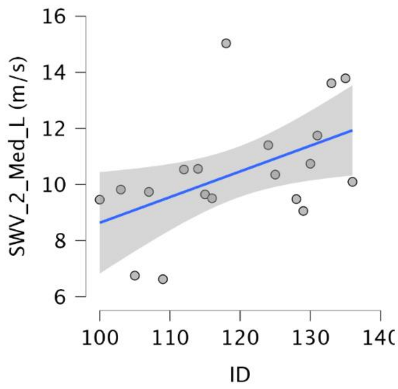
Left foot

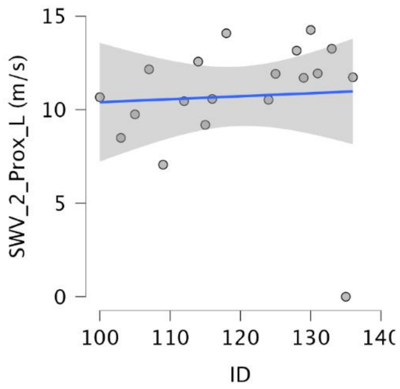

ID - SWV_1_Dist_L (m/s)

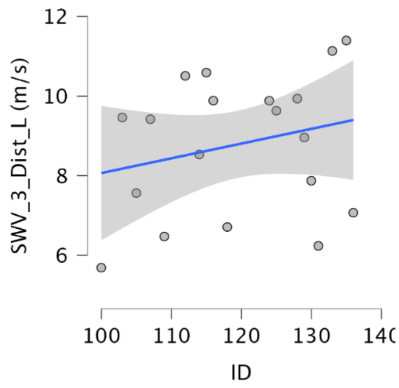

ID - SWV_1_Med_L (m/s)

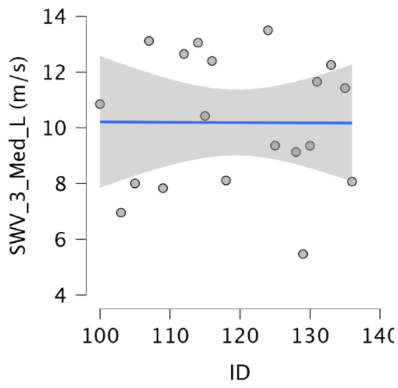

ID - SWV_1_Prox_L (m/s)

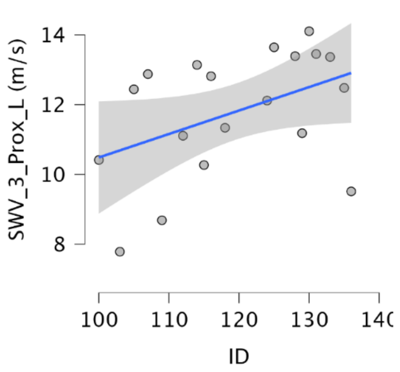

ID - SWV_2_Dist_L (m/s)


ID - SWV_2_Med_L (m/s)


ID - SWV_2_Prox_L (m/s)


ID - SWV_3_Dist_L (m/s)


ID - SWV_3_Med_L (m/s)


ID - SWV_3_Prox_L (m/s)

Appendix 5. Data collection dates

Outlined prior, three different instances were allotted to gather individual shear wave velocities from both a resting and seated position.

ID	Pre 1	Days Past	Pre 2	Days Past	Post
100	10.9.2020, klo 13:15	8	18.9.2020, klo 14:30	25	13.10.2020
103	3.9.2020, klo 7:15	19	22.9.2020, klo 15:30	24	16.10.2020
105	9.9.2020, klo 16:00	7	16.9.2020, klo 16:15	28	14.10.2020
107	10.9.2020, klo 12:30	12	22.9.2020, klo 12:15	24	16.10.2020
109	7.9.2020, klo 9:00	8	15.9.2020, klo 9:00	30	15.10.2020
112	14.10.2020	7	21.10.2020	20	10.11.2020

114	18.9.2020, klo 7:00	12	30.9.2020	30	30.10.2020
115	20.9.2020, klo 10:00	10	30.9.2020	27	27.10.2020
116	28.9.2020	7	5.10.2020	29	3.11.2020
118	20.9.2020, klo 10:45	10	30.9.2020	26	26.10.2020
124	16.10.2020, klo 17:00	4	20.10.2020	23	12.11.2020
125	16.10.2020	4	20.10.2020	23	12.11.2020
128	15.10.2020	6	21.10.2020	21	11.11.2020, klo 16:00
129	5.10.2020	10	15.10.2020	25	9.11.2020
130	18.9.2020, klo 9:15	20	8.10.2020	19	27.10.2020

131	5.10.2020	8	13.10.2020	28	10.11.2020
133	1.10.2020	7	8.10.2020, klo 13:00	33	10.11.2020
135	13.10.2020	8	21.10.2020	21	11.11.2020
136	8.10.2020	13	21.10.2020	19	9.11.2020

Roughly 90% of athletes had their preliminary and follow-up meeting in two weeks' time, as initially outlined in the methods as pre1- and pre2-measurements. Two candidates' punctuality must be scrutinized when availability for an academic study is hindered, or delayed, by nearly three weeks.

Variability between pre2- and post- is examined too. With a minimum-maximum difference of ten days, minimum being twenty and maximum thirty days, an opaque veil casts a shadow of concern on the intervention's efficacy to treating torn Achilles tendons. Twenty-seven days was tracked as the lowest total days for data recovery, whereas the most elongated case took forty-three days. Data uniformity is slightly blemished.