Postural Control in Achilles Tendinopathy

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Abstract

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Background: Achilles tendinopathy (AT) is a common lower limb overuse pathology that results from excessive or insufficient mechanical loading. AT presents in 1.85 per 1000 of the adult population with up to a 27% recurrence rate. AT disrupts tissue morphology which alters mechanical load regulation and may also affect motor performance. The purpose of this study was to examine the relationship between AT morphology, motor performance, and function. **Methods:** APDM inertial sensors instrumented the modified Balance Error Scoring System (mBESS) and the modified Clinical Test of Sensory Interaction on Balance (CTSIB-M) to measure postural control. To manipulate AT strain, participants were tested unshod on a neutral sham orthosis, a 12 mm forefoot lift, and a 12 mm rearfoot lift. The Victorian Institute of Sport Assessment-Achilles and the Lower Extremity Functional Scale quantified function. A repeated measures ANOVA examined the interaction between variables. **Results:** Twenty-one participants (8 female, 13 male, mean age 35.5, SD 10.8 years) with AT were tested. mBESS postural control was different between involved and uninvolved limbs ($p = .054$), and between forefoot lift and rearfoot lift conditions ($p = .053$). CTSIB-M postural control was not different between participants with AT and control limbs ($p = .534$). Ankle range of motion was very strongly negatively correlated with postural control ($p = .001$). **Conclusion:** This study demonstrated a difference in unilateral postural control between involved and uninvolved limbs and between forefoot lift and rearfoot lift conditions. There was no difference in bilateral postural control between AT and control limbs.

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Dedication

To my parents who taught me that knowledge outweighs the value of any material treasure. Dad, I'll meet you at the gates one day where we'll rejoice in this moment and all the other moments in this life that you missed. JRJ

Acknowledgments

Ashwini Rao, Jacqueline Montes, C. Kevin Wong, Morgan Busko, and Lori Quinn, thank you for all that you have taught me along the way and for all the ways in which you have shepherded me through this journey. I will always remember that scientific inquiry is an enduring process, not a singular event. JRJ

Introduction

Background

Achilles tendon injuries have been recorded in scientific literature since at least 1840 (Docking & Cook, 2019; Puddu et al., 1976; Van Der Vlist et al., 2019). Investigators typically classified these injuries into two main categories: acute traumatic injuries, such as lacerations, and chronic overuse conditions, commonly referred to as tendinitis (Van Der Vlist et al., 2019). In the early 1980s, Stanish et al. pioneered the use of movement rather than rest to treat lower limb tendinitis, a somewhat controversial idea that contradicted the established best practice guidelines of the time (Stanish et al., 1986). Tendon research then idled until Alfredson et al.'s 1998 seminal paper that advocated renaming tendinitis to tendinopathy. Using histochemical analyses, Achilles tendon overuse injuries were demonstrated to lack the biochemical markers that typify inflammation and therefore the *-itis* suffix. Tendinopathy was hence defined as tendon pain and dysfunction (Alfredson et al., 1998; Öhberg et al., 2004). This work marked a significant shift in understanding and terminology for tendon disorders. The term tendinosis was later introduced to describe tendon pathology with tissue composition changes observed through histochemical analyses and diagnostic imaging (Cardoso et al., 2019; Cook & Purdam, 2009). The terminology change from tendinitis to tendinopathy sets the stage for discussing current concepts. Tendon morphology will first be introduced, followed by tendon function with examples drawn from balance, hopping, and gait studies. Next, the impact of tendinopathy on neurophysiology and symptomatology will be investigated. Lastly, the relationship between morphology and function and the extent to which they are modifiable will be unpacked.

Tendon Morphology

Tendon solid state

Healthy tenocytes, or tendon cells, are primarily comprised of type I collagen. Type I collagen best withstands tensile loads, as opposed to type II collagen which best withstands compressive loads.(Cardoso et al., 2019; Cook & Purdam, 2009; Docking & Cook, 2019). Tendons respond adaptively to tensile loads with a mechanical property called stiffness. Healthy tendons adapt to loads applied over time by becoming stiffer, whereas pathological tendons have been demonstrated to be more compliant (Cook & Purdam, 2009; Kulig et al., 2016). Tendinopathy has repeatedly demonstrated signs of collagen type I disorganization and a higher percentage of generic type III collagen, which is not natively good at withstanding tensile or compressive load (Cook & Purdam, 2009; Khan & Scott, 2009). The higher and more sustained the applied load over the time, the stiffer the tendon becomes. Malliaras et al. recently demonstrated that 75% of maximum voluntary contraction applied over an 8 second interval yield the best adaptive mechanical results (Malliaras et al., 2013). Devaprakash et al. (2020) demonstrated that elite middle-distance runners have shorter, stiffer free tendons as compared to age matched controls and Kulig et al. (2016) demonstrated that ballet dancers have thicker cross-sectional areas within their Achilles tendon midportion (Devaprakash et al., 2020; Kulig et al., 2016). These patterns clearly demonstrate that tendon solid state has an influence upon and is influenced by mechanical loading.

Tendon fluid state

Whereas tenocytes are 90% collagen, the collagen fibrils are embedded in a fluid-rich extracellular matrix. The chief biomolecule within the tendon extracellular matrix is called a proteoglycan, which is hydrophilic and serves to aggregate fluid (Abat et al., 2017, 2018; Docking & Cook, 2019). Tendons exposed to excessive or insufficient mechanical load upregulate their extracellular matrix content to reduce stress, given that stress is defined as force divided by surface area (Öhberg et al., 2004; Wang et al., 2013). It is for these reasons that tendinopathic tendons are thicker at rest than their healthy counterparts. It was recently demonstrated that healthy Achilles tendons remain largely isovolumetric when exposed to mechanical loads (Merza et al., 2021). In this way, the load is attenuated between the noncompressible fluid on the one hand and the type I collagen on the other hand. The net result is an even distribution of the force across the entirety of the tendon. Achilles tendinopathy (AT), conversely, responds to loads in a nonuniform manner. As load is applied to the tendon, the fluid extrudes radially and creates maladaptive shear strain rather than adaptive tensile strain. The loss of the fluid from the tendon core further exposes the remaining collagen fibers to excessive mechanical load (Merza et al., 2021).

Tendon Behavior

Tendinopathy is an overuse pathology that results from excessive or insufficient mechanical loading. Running exemplifies excessive lower limb mechanical loading. Runners in fact account for most AT cases, with a 52% incidence rate and a 27% reoccurrence rate (Sancho, Malliaras, et al., 2019; Van Der Vlist et al., 2019). Sedentary individuals exemplify insufficient mechanical loading and acquire AT nearly as frequently as active individuals (Van Der Vlist et al., 2019). This dichotomy between excess and insufficiency underpins why AT remains an unclear disease state. AT pathology affects two distinct portions of the Achilles tendon. Midportion AT impacts the middle of the free tendon typically several centimeters (cm) proximal to its distal attachment on the calcaneus. Midportion AT is more common than insertional AT, which affects the interface between the distal free tendon fibers and their attachment to the calcaneal periosteum. This interface is termed an enthesis organ and is more prone to inflammatory infiltrates than is the free tendon. Insertional AT pathology more closely resembles an adolescent traction apophyseal injury rather than a traditional adult tendon overuse injury. This introduction will focus on midportion AT, except in cases where insertional AT studies provide general mechanistic insights (Cook & Purdam, 2009; Maffulli et al., 2004).

Many publications to date have investigated the influence of AT on function, but few have investigated the influence of AT morphology on function. Most studies have used the Victorian Institute of Sport Assessment Achilles (VISA-A) as an overall surrogate for function (Docking & Cook, 2019; Malliaras et al., 2013; Van Der Vlist et al., 2019). Balance has received the least amount of attention, with only a single published study to date (Scholes et al., 2018). Scholes et al. (2018) investigated the relationship between AT balance and tendon cross sectional area. The authors demonstrated poorer balance as defined by sway area on the involved AT limb compared to the uninvolved control limb. They also found that amongst the involved limbs the thicker AT tendons balanced less well. Hopping and running gait studies have often been published together by the same group. Sancho et al. (2022) demonstrated that runners with AT demonstrate reduced plantar flexor and gluteus medius strength and activation length, but did not investigate tissue morphology (Sancho et al., 2022). In a related recent study, Sancho et al. (2019) showed a poor correlation between AT applied load and pain (Sancho, Morrissey, et al., 2019). Azevedo et al. (2009) and Creaby et al. (2017) published similar studies that sought to characterize the lower limb kinematics of runners with AT and found reduced gluteus medius and maximus electromyogram amplitude and reduced duration of activity (Azevedo et al., 2009; Creaby et al., 2017). These groups, again, failed to appraise frank tendon morphology. Kulig et al. (2011) investigated the hopping kinematics in dancers with AT and found increased lower limb medial rotation during the push-off phase and a higher upper limb adduction impulse during landing dynamics (Kulig et al., 2011). In a separate study, Kulig et al. 2010) demonstrated a correlation between Achilles tendinosis (morphology) and worse mechanical (stiffness) and material (Young's modulus of elasticity) tendon properties (Arya & Kulig, 2010). The authors again did not directly relate AT morphology with function. In summary, many publications have demonstrated that AT effects functional output, but few have accounted for tissue morphology.

Tendon Neurophysiology

Achilles tendinopathy results from excessive or insufficient mechanical loading or persistent neurochemical infiltrates (Cook & Purdam, 2009). An appropriate mechanical load environment compels net adaptive maintenance that serves the tendon and the organism. This maintenance includes organized collagen morphology and appropriate material stiffness (Arya & Kulig, 2010; Farley & Morgenroth, 1999; W. C. Lee et al., 2020). Adjusting the mechanical load environment can reverse maladaptive changes in an impaired tendon (Wang et al., 2013, 2015). How tendons detect and respond to their load environment is complex. An analogy from human motor control theory offers a helpful perspective for understanding this complexity. Motor control theory views the organism as a series of constituent but interrelated parts. The skeletal system represents the plant and the muscles represent the actuators, which act upon the plant. The tendons represent the bridges that connect the plant to the actuators. The plant, the actuators, and the bridges are animated by the controller, the central nervous system, which receives information from the sensors, the proprioceptors. Whereas much AT research has invested in the plant, the actuators, and the bridges, the roles of the sensors and the controllers have been largely disregarded (Kulig et al., 2020).

Neurophysiologists consider muscle spindles to be the third most complex organic system behind only the special senses of vision and hearing. And yet muscle spindles cannot sufficiently manage positional control without coordinate input from the Golgi tendon organ

(Scholes et al., 2018). Spindles sense length and velocity changes in contractile tissue, whereas Golgi tendon organs sense length and force changes in both contractile and tendon tissue. These two systems represent the sensors that gather information from the bridges and inform the controllers Rasske et al. (2017). recently demonstrated further complexity. The authors measured force production in healthy Achilles tendons across a range of different gait velocities and environmental inclines. They found that the triceps surae preserved force output by producing real-time alterations in fascicle length and tension (Rasske et al., 2017). It is well established that AT tendons demonstrate reduced material stiffness, or increased compliance, which introduces a temporal lag in load processing. AT material compliance therefore directly effects all aspects of the motor control plant (Arya & Kulig, 2010; Docking & Cook, 2019).

Achilles tendinopathy undoubtedly impairs neurophysiology. What is uncertain is whether the impairments are casual or consequential to AT. Due to the high incidence and reoccurrence of AT in runners, there have been many published studies that investigate hopping and gait in AT. Most gait studies have involved running, but a few involve ambulatory gait. Rabusin et al. (2019) reviewed ambulatory gait in AT and found some interesting patterns. Walkers with AT typically exhibit reduced triceps surae EMG amplitude, but this can be instantly normalized upon the addition of an orthotic heel lift. The immediacy of the amplitude normalization suggests a neurophysiological impairment, rather than a structural one (Rabusin et al., 2019). Wulf et al. (2016) produced a similar published result, demonstrating that AT force production could be immediately normalized upon the addition of an orthotic heel lift (Wulf et al., 2016). Rabusin et al. (2021) published a follow-up interventional study in which they compared the effect of wearing a 12 millimeter (mm) orthotic heel lift for twelve weeks versus performing heavy eccentric heel raises for twelve weeks in AT. The heel lift group performed better than the heavy eccentric heel raise group when measuring function with the VISA-A and symptomology with the VAS (Rabusin et al., 2021). Alghamdi et al. (2024) recently published similar data but for insertional AT with a 20 mm orthotic heel lift worn for just 2 weeks (Alghamdi et al., 2024). This, once again, calls into question the extent to which AT is governed by neurophysiological processes.

More authors have investigated running gait in AT and demonstrated predominantly neurophysiological results. Azevedo et al. (2009) investigated a range of kinetic and kinematic markers in runners with AT and found reduced gluteus medius and maximus amplitude and offset. The muscles in other words produced less force and for an insufficient time to support efficient running (Azevedo et al., 2009). Creaby et al. (2017) asked similar questions and found reduced rectus femoris and tibialis anterior EMG amplitude in runners with AT (Creaby et al., 2017). Debenham et al. (2016) investigated submaximal hopping in runners with AT compared to healthy controls. The authors found that the AT group landed with stiffer lower limb kinematics as compared to the healthy controls. Stiffness in this context refers not to material tendon stiffness, but rather to the absorption of force during the landing phase of hopping (Debenham et al., 2016). Sancho et al. (2022) demonstrated that runners with AT land from a maximal hop with decreased lower limb kinematic stiffness as compared to healthy controls. It is likely here that the compliant muscle-tendon, the proprioceptors, and the central nervous system were able to cope with the landing forces associated with a submaximal hop but not those associated with a maximal one (Sancho et al., 2022).

Peripheral versus central impairments

Despite several early papers to the contrary, it appears clear that AT produces or is produced by peripheral rather than central nervous system adaptations. A recent review by Rio et al. (2021) denoted clear upper limb central nervous system adaptations, such as remote site hyperalgesia and positive conditioned pain modulation temperature tests but concluded that the evidence for such central changes in lower limb tendinopathies remains low. The upper limb homunculus occupies a larger cortical surface area than that of the lower limb and the upper limb is involved in more routine interactions with the organism, both which increase the perceived value and frequency of nociceptive input (Rio et al., 2021). Kulig et al. (2020) have demonstrated deficits across a variety of levels of AT neurophysiology. Upon AT loading, increased tendon compliance results in an electromechanical delay, which can be thought of as a problem with feedback from the bridge and the sensors. The delay is then compensated for by increased pre-activation of the tibialis anterior and triceps surae prior to subsequent loading episodes, which is really a supraspinal feedforward response. At the same time, there is increased excitability at the triceps surae alpha motoneuron but decreased EMG amplitude. Lastly, secondary plantar flexors, such as the peroneals, demonstrate increased EMG amplitude (Chang & Kulig, 2015; Kulig et al., 2020). Fernandes et al. (2022) asked similar questions but used transcranial magnetic stimulation to assess supraspinal inhibition in AT. The authors found that indeed there was inhibition present within the primary motor cortex in AT. They additionally showed that the inhibition was related to a reduction in single leg heel raise endurance in the involved but not the uninvolved AT limb. Fernandes et al. (2022) also found reduced excitability at the triceps surae alpha motoneuron, contrary to the findings of Kulig et al. (2015) (Chang & Kulig, 2015; Fernandes et al., 2022). Complex protective neurophysiological adaptations are clearly present in AT.

Tendon symptoms

It remains unclear whether subclinical neurophysiological adaptations cause pain output in AT, or whether pain output in AT drives neurophysiological adaptations. In contrast to many other chronic disease states in which pain may be produced in the absence of loading, AT pain is almost invariably produced coincident with phasic loading. This fact has guided related research. Henrikson et al. (2011) investigated the effect of a nociceptive injection on a healthy Achilles tendon. The authors found that the painful stimulus immediately reduced triceps surae EMG amplitude. The amplitude normalized when the pain subsided (Henriksen et al., 2011). Maquirrian et al. (2014) administered oral anti-inflammatories to individuals with painful AT and found that their function improved in parallel with a reduction of pain (Maquirriain & Kokalj, 2014). Chimenti et al. (2020) administered an anesthetic injection to individuals with painful AT. They demonstrated that when the AT was no longer painful, triceps surae EMG amplitude and heel raise endurance normalized. They did find, however, inappropriately high force output during the heel raise endurance test, indicating some persistent feedback and feedforward motor control impairments despite the abolishment of pain (Chimenti et al., 2020).

Tendon rehabilitation

Since the work of Stanish et al. in the early 1980's, many subsequent groups have used exercise as a means of recovering function in AT (Baxter et al., 2021; Färnqvist et al., 2019; Gheidi et al., 2018; Khan & Scott, 2009; W. C. Lee et al., 2020; Lepley et al., 2020; Revak et al., 2017; Stanish et al., 1986; Wilson et al., 2018). Silbernagel et al. (2020) published a recent review that demonstrated exercise therapy enjoys the highest level of evidence for the restoration of AT function and the reduction of AT symptoms. Best practice guidelines suggest using progressive, heavy, and slow mechanical loadings (Silbernagel et al., 2020). Wang et al. (2013) published basic science guidelines that underpin adaptations to load. The authors demonstrated that a 3% load applied to tissue in a bioreactor over 6 days resulted in pathological changes associated with AT (e.g. increased upregulation of extracellular matrix). This represents insufficient load. A 9% load applied over 6 days also resulted in pathology (e.g. increased upregulation of proinflammatory cytokines consistent with a rupture) (Wang et al., 2013). This represents excessive load. Interestingly, however, a 6% load applied of 6 days rescued the morphological changes created by the other two dichotomies (Wang et al., 2015). Öhberg et al. (2004) initially demonstrated that 12 weeks of eccentric AT loading resulted in the reduction of symptoms and the restoration of tendon cross sectional area, but his work has not been directly replicated (Öhberg et al., 2004). Most studies have demonstrated that whereas progressive, heavy, and slow mechanical loading reduces AT symptoms and increase AT function, a relationship between functional recovery and morphological rescue has not been demonstrated (Docking et al., 2020; Docking & Cook, 2019). In fact, a recent study by Färnqvist et al. (2019) demonstrated that Achilles tendon thickness does not decrease in parallel with the recovery of function (Färnqvist et al., 2019). The recovery of AT function and the reduction of AT symptoms are therefore attainable with exercise therapy, but the extent to which these changes reflect adaptations in morphology remains unclear.

Conclusion

Achilles tendinopathy is a common lower limb overuse pathology that results from excessive or insufficient mechanical loading or persistent neurochemical infiltrates. Both load excess and load insufficiency result in predictable changes in tendon morphology, most notably increased cross-sectional area, disorganized collagen fibril alignment, increased type III collagen, and increased hydrophilic extracellular matrix (Arya & Kulig, 2010; Docking et al., 2015, 2020; Docking & Cook, 2019; Kulig et al., 2016). AT has been correlated with functional impairments in balance, hopping, and running, but few studies have jointly appraised tissue morphology. Exercise therapy can compel the recovery of function and the reduction of symptomatology in AT, but the extent to which it can rescue morphology remains unclear and an important area for future research (Docking et al., 2020; Färnqvist et al., 2019; Kulig et al., 2020). An appropriate mechanical load environment can over time compel adaptive changes that serve the tendon and the organism. This paper incorporated current concepts in neurophysiology to clarify why certain tendons adapt and others maladapt given their environment. Several themes that emerged in AT neurophysiology were temporal inefficiency, motoneuron excitation or inhibition, and pain as a cause or a consequence (Chang & Kulig, 2015; Kulig et al., 2020; Rio, Kidgell, Lorimer Moseley, et al., 2016). Despite several early papers to the contrary, it appears clear that AT is most effected by peripheral rather than central nervous system adaptations (Rio et al., 2021). It is clear that AT provokes functional neurophysiological impairments, but unclear whether the impairments are casual or consequential to AT. Finally, it remains unclear whether subclinical neurophysiological adaptations cause pain output in AT, or whether pain output in AT drives neurophysiological adaptations (Chimenti et al., 2020; Henriksen et al., 2011; Maquirriain & Kokalj, 2014; Rio, Kidgell, Moseley, et al., 2016). Future AT research should consider tendons as a bridge, governed by sensors, controllers, and actuators in the interest of moving the plant.

Chapter 1: Achilles Tendinopathy

1.1 Background

Achilles mid portion tendinopathy (AT) is a common stress instigated disorder that affects sedentary and active individuals alike, presenting in 1.85 per 1000 of the adult population with up to a 27% recurrence rate (Cook & Purdam, 2009; Docking & Cook, 2019; Van Der Vlist et al., 2019). AT impacts runners to the greatest extent, with a 52% lifetime risk (Van Der Vlist et al., 2019). The disorder imposes a significant burden on quality of life and work productivity, costing an estimated $1000 USD per individual per year (Van Der Vlist et al., 2019). The stress instigating AT is typically mechanical, but sometimes biochemical, and is problematic if excessive or insufficient. If excessive, the imposed stress overwhelms the capacity of the Achilles tenocytes to maintain tissue homeostasis and structural maladaptation ensues. If insufficient, the tenocytes are shielded from the minimum stress required to maintain tissue homeostasis and structural maladaptation ensues (Kulig et al., 2020; Wang et al., 2013, 2015; Zhang et al., 2020). AT thus alters tissue morphology, producing neovascularization, indiscriminate collagen alignment, increased extracellular ground substance, and increased alpha motoneuron excitability (Silbernagel et al., 2020; Van Der Vlist et al., 2019). Further, AT demonstrates predictable physiological manifestations, which include reduced plantarflexor torque, tendon stiffness, talocrural joint dorsiflexion, and impaired postural control (Cook & Purdam, 2009; Docking & Cook, 2019; Silbernagel et al., 2020; Van Der Vlist et al., 2019). These impairments curiously only relate to AT symptoms obliquely, with some studies showing a direct relationship, others an indirect one, and yet others no relationship at all (Färnqvist et al., 2019). Nor is it known precisely how maladaptions in AT morphology influence certain constituents of AT motor control, most notably the control of posture (Rio, Kidgell, Lorimer

Moseley, et al., 2016). Note finally that local homeostatic regulation is not unique to tendons, or even to the musculoskeletal system, but rather appears to be a systematic attribute found in complex organisms. Endothelial cells, for instance, display well established mechanosensitive behaviors that surveil laminar blood flow and shear strain rates and adapt accordingly via arteriogenesis, angiogenesis, or both (Haas et al., 2012). Nor is the discrepancy between structural maladaptation and symptom presentation unique to tendons. Sustained turbulent blood flow stimulates decreased vascular compliance, a maladaptive but often symptomatically silent process (Haas et al., 2012).

Achilles tendinopathy diagnoses are dichotomous and rendered clinically using a cluster of physical examination tests. Importantly, insertional AT is etiologically distinct from midportion AT. The former describes a problem at the distal attachment of the Achilles tendon where the interface between tendon and bone is exposed to excessive compressive stress, while the latter, as previously discussed, describes a tensile stress problem along the middle portion of the Achilles tendon (Cook et al., 2016; Cook & Purdam, 2009). For this reason, in the present review AT refers to the mid portion alone. When mid portion Achilles tendon palpation, the painful arc sign, and the Royal London Hospital tests are combined, their overall specificity for detecting AT is 0.833 (Maffulli et al., 2003; Silbernagel et al., 2020). This physical examination cluster is clinically convenient and of low risk and cost. In the absence further tests, however, the diagnosis is tethered to the term tendinopathy. If more detail is warranted, histochemical analysis and diagnostic imaging may be used to further investigate altered tendon morphology. If alterations are discovered, then Achilles tendinosis, rather than tendinopathy, may be diagnosed (Kulig et al., 2020). As aforementioned, tendinotic tissues demonstrate indiscriminate collagen deposition, increased extracellular ground substance, and neovascularization, but no definitive association with a loss of function (Färnqvist et al., 2019; Kulig et al., 2020). In some instances, diagnostic imaging reveals substantial tissue degeneration without associated symptoms, and in others no tissue changes with substantial symptoms. Both scenarios are important to understand, but only the former is likely to progress to a more serious disease state, such as irreversible tissue degeneration or frank rupture. To this end, it is plausible that a sufficiently sensitive test could detect AT cases where tissue changes are present but symptoms are absent. Many AT studies to date have focused on tests of behavior, such as hopping and running, but only a single study has evaluated postural control. Postural control coordinates feedback proprioceptive input and feedforward motor output. The central nervous system governs these inputs and outputs through a variety of specialized mechanoreceptors that may in turn be impaired in AT. An impairment to this system would disrupt the timing between tendon loading and muscle action and introduce a vicious cycle of injury. It is therefore of fundamental importance to clarify the interrelationships between AT morphology and postural control. Once this relationship is established, postural control may be used as an assessment tool to screen for AT and may also represent a clinical surrogate for morphological alterations.

Purpose

In general, it is uncertain if maladaptive features such as reduced plantarflexor torque, tendon stiffness, talocrural joint dorsiflexion, and impaired postural control are causal or consequential to AT. The present narrative review, therefore, aims to summarize current concepts in AT literature with an emphasis on the relationship between structure and function, identify relevant AT literature gaps, and propose future work to address gaps in the AT literature.

1.2 Current concepts

What is known about the Achilles tendon?

The Achilles tendon is an adaptive structure that uses feedforward and feedback control to modify its function in response to movement demands. If certain movement demands persist, then the tendon structural properties are progressively modified. The former modifications are governed by central and peripheral nervous system mechanisms, such as Golgi tendon organs, muscle spindles, and other proprioceptors, and the latter are governed by nervous system mechanisms plus local homeostatic regulation (Docking & Cook, 2019). In general, the Achilles tendon functions in three behavioral modes: energy conservation, power amplification, and power attenuation. A working understanding of these modes creates a framework within which the reader may better survey current tendinopathy research. These modes routinely function in concert with one another but can work in isolation. Energy conservation describes the property of a tendon whereby energy is cyclically transmitted from the body to the tendon and back to the body. Tendons conserve with immense efficiency, retaining approximately 90% of the energy that they absorb. In power amplification tendons transmit force from muscle to tendon to body and in power attenuation from body to tendon to muscle (Roberts & Azizi, 2011) The power amplification and attenuation modes of tendon behavior have historically received more attention in tendinopathy research perhaps for their role in eccentric loading.

What is known about AT?

Although publications recounting tendon disorders may be found as far back as circa 1787, the number of academic papers published over the past 3 decades have risen precipitously (Evans, 1787) Despite this relative publication boom, the precise mechanisms that govern AT pathology and recovery remain unclear. Some patterns have been agreed upon, however, and will now receive attention. First is terminology. The International Scientific Tendinopathy Symposium issued a consensus statement in 2019 that the descriptive term tendinitis should be universally abandoned in favor of tendinopathy, except in cases where a tendon presents with a very recent injury mechanism and evidence of frank inflammation (Scott et al., 2020) That Achilles tendon disorders are most often devoid of inflammatory infiltrates was first registered by Puddu et al. (1976) and then confirmed by Alfredson et al. (1999) (Alfredson et al., 1999; Puddu et al., 1976). Cook et al. (2009) argue that tendinopathies occur along a progressive, but conditionally modifiable, continuum. Tendon disorders begin with reactive tendinopathy, which is theoretically true tendinitis with the presence of inflammatory infiltrates, progress to tendinopathy disrepair, and advance finally to degenerative tendinopathy (Cook & Purdam, 2009). The reversibility of morphological changes decline as the tendon progresses further along this continuum (Cook et al., 2016; Docking & Cook, 2019; Färnqvist et al., 2019). Kulig et al. (2010), as well as a small number of other authors, have argued that tendinosis persists as a more appropriate term with which to describe tendon disorders, which connotes focal tendon thickness and intratendinous disorganization with past or current tendon pain (Arya & Kulig, 2010).

Interventional study focus

The International Scientific Tendinopathy Symposium concurs that AT is a stress instigated disorder, where the stress is persistently either in excess or in dearth (Scott et al., 2020; Silbernagel et al., 2020). On the basis of mechanical stress management, Stanish et al. (1986) were the first authors to recommend an eccentric loading regimen for the treatment of AT, which they termed chronic Achilles tendinitis at the time of publication (Stanish et al., 1986). Recall that the power application and attenuation modes of tendon behavior participate prominently in eccentric muscle actions. Alfredson et al. (1998) later published what is now a seminal work demonstrating the superiority of eccentric loading over conventional rehabilitation modes for the treatment of AT (Alfredson et al., 1998). Following this work, numerous additional tendinopathy groups have published rather heavily in the interventional eccentric loading space, but with only equivocal results. In fact, a recent systematic review concluded that heavy slow eccentric loading programs are not superior to other modes of exercise for the treatment of AT (Murphy et al., 2019). Further, Rabusin et al. (2021) compared a twelve-week eccentric heel raise loading program against wearing a 12 mm in-shoe heel lift for twelve weeks and found the latter to yield superior results when using the VISA-A as an outcome measure (Rabusin et al., 2021).

Performance study focus

Within the International Classification of Functioning, Disability, and Health (ICF) model, only a few studies to date have investigated AT at the body structure and function impairment level. The majority, rather, have tested behaviors such as jumping and running. In a recent systematic review, Sancho et al. (2019) identified a total of 16 studies of satisfactory quality investigating biomechanical changes during jumping or running in AT (Sancho, Malliaras, et al., 2019). Ogbonmwan et al. (2018) completed a similar systematic review filtering for AT publications that tested walking and running, rather than jumping and running, and found a total of 14 studies of satisfactory quality (Ogbonmwan et al., 2018). The results of these systematic reviews stand in contrast to a singular paper by Scholes et al. (2018) that investigated postural control in AT, the only publication known to this author to have done so (Scholes et al., 2018). In summary, AT studies have historically focused on interventional loading programs and behavioral-level assessments.

1.3 Literature gap

Ankle mobility and tendon length gap

Although asymptomatic Achilles tendons may demonstrate latent, but significant, degenerative changes upon diagnostic imaging and remain impervious to mechanical loading, AT is typified by pain that increases with loading and decreases with unloading (Rio, Kidgell, Lorimer Moseley, et al., 2016; Silbernagel et al., 2020). Tendons display unique auxetic material properties, which thicken in a direction perpendicular to an applied tensile load (Gatt et al., 2015). Length therefore imparts load. In a cadaver model study, Costa et al. (2006) demonstrated that the Achilles tendon is the anatomical structure that most directly limits ankle dorsiflexion. In fact, the authors established a linear relationship between Achilles tendon length and ankle dorsiflexion range of motion, making dorsiflexion a clinically useful surrogate for tendon length (Costa et al., 2006). Rabin et al. (2014) demonstrated that reduced ankle dorsiflexion range of motion increases the risk of developing AT in military recruits taking part in intensive physical training (Rabin et al., 2014). Sung & Kim (2018) observed a correlation between decreased plantar flexion range of motion and balance as defined by sway area on a Biodex machine (Sung & Kim, 2018). In the same publication year, Scholes et al. (2015) found impaired unilateral balance in symptomatic AT using a Wii Balance Board (WBB), but did not quantify ankle joint range of motion. The authors did, however, quantify Achilles tendon anteroposterior thickness and found that increased tendon thickness was associated with increased sway amplitude (Scholes et al., 2018). This is the only current study known to this author that has investigated postural control in AT. In following, given that AT develops from inappropriate loads, it is reasonable to consider the modification of tendon length in both the treatment and prevention of AT.

In-shoe heel lift gap

It is a common clinical observation that in-shoe heel lifts reduce pain and improve function in AT, but the mechanisms behind such benefits have not been fully clarified. In their systematic review, Rabusin et al. (2019) summarize that in-shoe heel lifts of 12 to 18 mm decreased gastrocnemius muscle tendon unit length and those of six to nine mm increased medial gastrocnemius electromyography amplitude (Rabusin et al., 2019). Lee et al. (2019) examined custom orthotic inserts and in-shoe heel lifts in runners with AT. Both custom orthoses and heel lifts significantly reduced peak Achilles tendon length and loading rates in runners(K. K. W. Lee et al., 2019). In a recent randomized trial entitled HEALTHY (Heel lifts versus calf muscle eccentric Exercise for AchiLles TendinopatHY), Rabusin et al. (2021) compared a twelve-week eccentric heel raise loading program against wearing a 12 mm in-shoe heel lift for twelve weeks. As aforementioned, despite eccentric loading programs being an established intervention mainstay for AT, the authors found that the 12 mm in-shoe heel lift was more effective at reducing pain and improving function as measured by the VISA-A, but for reasons that were not clarified (Rabusin et al., 2021). These results connote that the immediate modification of tendon length may be more important in the short term than the gradual modification of morphology.

Postural control gap

Postural control coordinates feedforward motor output and feedback proprioceptive input. This coordination is governed by a variety of specialized epithelial mechanoreceptors, the muscle spindle system, and Golgi tendon organs (Proske & Gandevia, 2012; Rio, Kidgell, Lorimer Moseley, et al., 2016). It is unclear if postural control deficits are causal or consequential to AT. Several explanations are plausible. First, it is known that healthy tendon tissue transmits afferent loading data to the central nervous system, but the extent of and accuracy with which tendinotic tissues communicate comparable loading data remains unclear. Various authors have proposed that the tissue regions immediately peripheral to the tendinotic tissue protectively adapt and become materially stiffer. As a direct consequence of this adaption, however, the tendinotic tissue is stress shielded, or mechanically silent as depicted by Cook et al.

(2016) (Cook et al., 2016). In this way, the disordered tissue is deprived of the very mechanical loading required to stimulate a healing response. Further, it has been demonstrated that the agonist muscles associated with tendinopathy increase their resting tensile activity, presumably as a means with which to gather up more afferent loading data in the absence of input from the mechanically silent tendinotic tissue region (Kulig et al., 2020). Second, pain output may alone explain the balance impairments in AT. Chimenti et al. (2020) recently demonstrated that movement pain, motor performance, and pain catastrophizing were normalized with immediate effect after an anesthetic injection was applied to symptomatic chronic AT. Motor performance was here defined as heel raise endurance (Chimenti et al., 2020). If postural control is demonstrated to improve immediately upon the addition of a heel lift, then this may explain, at least in part, why the use of a heel lift was more effective than an eccentric loading program over a 12-week period in the HEALTHY trial (Rabusin et al., 2021). In general, only a few studies have investigated Achilles tendon performance at the level of somatosensory control. The majority, rather, have tested behaviors in AT such as walking, jumping, and running (Devaprakash et al., 2022; Sancho, Malliaras, et al., 2019). This pattern and the aforementioned patterns shape a literature gap for the investigation of basic motor control level mechanisms in AT. Elucidating these mechanisms will have implications for both AT assessment and intervention.

1.4 Discussion

Future concepts potential and conclusions

In summary, midportion AT is a common stress instigated disorder that affects sedentary and active individuals alike, presenting in 1.85 per 1000 of the adult population with up to a 27% recurrence rate (Cook & Purdam, 2009; Docking & Cook, 2019; Van Der Vlist et al., 2019). AT impacts runners to the greatest extent, with a 52% lifetime risk, and imposes a significant burden on quality of life and work productivity, costing an estimated $1000 USD per individual per year (Sleeswijk Visser et al., 2021; Van Der Vlist et al., 2019). While the imposed AT economic burden is not an insignificant cost, its significance multiplies when one considers a 27% recurrence rate. This recurrence rate reflects an only reasonably well understood disease process, which is further exemplified by the pattern that AT affects active and sedentary individuals alike. The former are thought to be mechanically overloaded and the latter underloaded. The disease process ambiguity generates several predictable repercussions. First, active individuals with AT tend to be driven towards higher cost and risk diagnostic tests and interventions, such as magnetic resonance imaging (MRI) and corticosteroid injections. Second, sedentary individuals with AT tend to be discouraged from adopting a more active lifestyle, which perpetuates AT disease and simultaneously encourages metabolic and/or cardiovascular disease. The stress instigating AT is typically mechanical, but sometimes biochemical, and is problematic if excessive or insufficient. If excessive, the imposed stress overwhelms the capacity of the Achilles tenocytes to maintain tissue homeostasis and structural maladaptation ensues. If insufficient, the tenocytes are shielded from the minimum stress required to maintain tissue homeostasis and structural maladaptation ensues (Kulig et al., 2020). AT thus alters tissue morphology, producing neovascularization, indiscriminate collagen alignment, increased extracellular ground substance, and increased alpha motoneuron excitability. Further, AT demonstrates predictable physiological manifestations, which include reduced plantarflexor torque, tendon stiffness, talocrural joint dorsiflexion, and impaired postural control (Cook & Purdam, 2009; Docking & Cook, 2019; Kulig et al., 2020; Silbernagel et al., 2020; Van Der Vlist et al., 2019). These impairments curiously only relate to AT symptoms obliquely, with some studies showing a direct relationship, others an indirect one, and yet others no relationship at all (Färnqvist et al., 2019). Nor is it known precisely how maladaptions in AT morphology influence certain constituents of AT motor control, most notably the control of posture (Rio, Kidgell, Lorimer Moseley, et al., 2016). AT studies have historically focused on interventional loading programs and behavioral-level assessments. This pattern shapes a literature gap for the investigation of basic motor control level mechanisms in AT. Elucidating these mechanisms will have implications for both AT assessment and intervention.

Chapter 2: Postural Control in Achilles Tendinopathy: Preliminary Study

2.1 Background

Achilles tendinopathy (AT) is a common lower limb overuse pathology that results from excessive or insufficient mechanical loading. AT presents in 1.85 per 1000 of the adult population with up to a 27% recurrence rate (Van Der Vlist et al., 2019). AT disrupts tissue morphology which alters mechanical load input and output and may also affect motor performance. A growing body of evidence has failed to demonstrate a direct relationship between changes in AT structure and function. For instance, a pathologically thickened Achilles tendon will not necessarily function more poorly than a healthy Achilles tendon and may in fact function better (Docking & Cook, 2019). Several trends may help explain this ambiguity. First, the functional measures that characterize Achilles tendon function, such as heel raise endurance, hopping, and running, are agnostic to the underlying tendon morphology. They define function well but cannot detect structural abnormalities. Second, the adaptive changes that govern an organism's response to injury seek foremost to preserve function. In a muscle tendon unit injury, such as AT, these adaptations make it difficult to parse the extent to which increased muscle function is concealing tendon dysfunction or vice versa. More sensitive measures to define tendon function and more accessible measures to detect tendon structure are therefore required.

In-shoe heel lifts reduce pain and improve function in AT, but for mechanisms not fully established. In-shoe heel lifts are understood to slacken Achilles tendon length and thereby reduce strain. Rabusin et al. (2019) systematically reviewed orthoses and concluded that in-shoe heel lifts of 12 to 18 mm decreased gastrocnemius muscle tendon unit length but also increased medial gastrocnemius electromyography amplitude (Rabusin et al., 2019). In an ensuing randomized controlled trial entitled HEALTHY (Heel lifts versus calf muscle eccentric Exercise for AchiLles TendinopatHY), Rabusin et al. (2021) compared a twelve-week eccentric heel raise loading program against wearing a 12 millimeter (mm) in-shoe heel lift for twelve weeks. Despite reasonable evidence supporting eccentric loading programs as a primary intervention for AT, the authors found that the 12 mm in-shoe heel lift intervention was more effective at reducing pain as measured by the visual analog scale and improving function as measured by the Victorian Institute of Sport Assessment Achilles (VISA-A) (Rabusin et al., 2021). Lee et al. (2019) examined in-shoe heel lifts in runners with AT and determined that they significantly reduced peak Achilles tendon length and loading rates during running (K. K. W. Lee et al., 2019). These results all connote that the immediate modification of tendon length may be at least as important in the short term as the gradual modification of morphology in the long term.

The purpose of this preliminary study was to examine the relationship between AT morphology, motor performance and function. Aim one will examine the relationship between AT morphology and postural control. Postural control is the process by which the central nervous system coordinates sensory information from the visual, vestibular, and somatosensory subsystems with the motor output necessary to maintain a controlled, upright posture and is easily measured. Achilles tendon length was hypothesized to correlate with postural control as defined here by jerk (m^2/s^5) and sway area (m^2/s^4); as tendon strain decreases postural control will improve. Jerk is the derivative of acceleration and describes the smoothness of postural corrections from the center of mass. Sway area is the area of an ellipse covering 95% of sway acceleration in both the sagittal and the coronal plane (Horak, 1987). Aim two established the relationship between postural control and AT function as defined by the Lower Extremity Functional Scale (LEFS) and the VISA-A. It is currently unknown whether poor postural control is associated with poor function in AT. If such a relationship were established, then postural control could be used as a leading indicator for AT morphology and a lagging indicator for the retention of AT function. Postural control was hypothesized to correlate positively with function; good postural control will be associated with higher LEFS and VISA-A scores.

2.2 Methods

Study population

The study approved by Columbia University Irving Medical Center Institutional Review Board (Protocol #AAAU0117). Participants aged 18 years or greater, with Achilles tendon symptoms present in one or both lower limb(s) for a minimum of two months, who reported having pain rated at least 3 out of 10 on a numerical rating scale, and who were able to walk household distances without an assistive device were included in the study. Participants with previous Achilles tendon surgery in the involved lower limb, previous Achilles tendon rupture in the involved lower limb, chronic ankle instability in the involved lower limb, and the presence of competing ankle diagnoses, such as osteoarthritis, insertional AT, inflammatory arthritis, or impingement syndrome, were excluded from the study. Recruitment fliers were posted in the Columbia University Program in Physical Therapy department, Columbia Doctors sites, and running club sites.

Self-reported tests

Data collection occurred at the Columbia University Program in Physical Therapy PACE laboratory or at the Orthology Physical Therapy Union Square clinic. The participants provided informed consent forms and self-reported outcome measures, which included the LEFS and the VISA-A. The LEFS is a 20-question survey that quantifies lower extremity dysfunction over a range of functional tasks with a Likert scale that ranges from 0-to-80, with higher scores indicating better performance. The LEFS is included in the American Physical Therapy Association outcomes registry. The VISA-A is an eight-item self-administered questionnaire used to evaluate symptoms specific to AT and their effect on physical activity. It can be used to determine clinical severity and provide a guideline for treatment and for monitoring the effects of treatment (Robinson et al., 2001). These outcome measures facilitated the objectives of aim two.

Clinician-administered tests

The investigators performed a series of tests to characterize AT dysfunction. Three clinical tests were performed to confirm or refute the diagnosis of midportion AT: direct tendon palpation, the painful arc test, and the Royal London Hospital test. When combined, the overall sensitivity of these tests for detecting midportion AT is .586 and the overall specificity .833 (Maffulli et al., 2003; Silbernagel et al., 2020). Direct tendon palpation confirmed tenderness two to six cm proximal to the retrocalcaneus. Once the painful tendon portion was identified, the ankle was passively plantar- and dorsiflexed. The painful portion of the tendon was expected to move with the passive motion and differentiates tendinopathy from paratenonitis. The ankle was then actively dorsiflexed, which placed the tendon and paratenon under tension thereby reducing tendon palpation tenderness. Passive plantar flexion, dorsiflexion, eversion, and inversion range of motion were assessed using a standard goniometer. The heel raise endurance test as described by Rabusin et al. (2021) was performed as a measure of plantar flexor strength (Rabusin et al., 2021). Foot posture was described using the Foot Posture Index (FPI-6), which is a foot posture assessment tool consisting of six items. The assessment was conducted as described by Redmond et al. (2006). High positive aggregate values reflect a pronated foot posture, neutral values reflect a neutral foot posture, and high aggregate negative values reflect a supinated foot posture. The FPI-6 is a valid and reliable test (Redmond et al., 2006).

Performance-based tests

Performance-based tests were used to quantify static postural control. The modified Balance Error Scoring System (mBESS) was chosen to measure static postural stability in three different positions, double limb stance with on hips and feet together, single limb stance on the involved and uninvolved leg with hands on hips, and tandem stance with the uninvolved foot behind the involved foot in heel-to-toe fashion and vice versa. The mBESS was instrumented with APDM technologies research grade wearable sensors. For each of the instrumented performance-based tests, three different custom orthotic devices were used to manipulate tendon strain (length). A 12 mm rearfoot lift was used to increase tendon length, a 12 mm toe lift to decrease tendon length, and neutral sham lift to preserve resting length. The order of experimental condition was randomized. All three lifts were manufactured from identical ethylene-vinyl acetate (EVA) to control somatosensory input. Ankle joint range of motion (degrees (deg)) and Achilles tendon length (cm) relate to each other with a 12:1 ratio, respectively (Costa et al., 2006).

The Optogait was chosen to evaluate jump height in AT to understand performance limitations within limbs and between participants. The Optogait is a noninvasive system for spatiotemporal measurement which uses a transmitting and a receiving light-emitting diode (LED) bar. Each bar contains 96 LEDS that communicate with the same number of LEDs on the opposite bar. The system detects interruptions in communication between the pair of bars and calculates duration and position. Spatiotemporal parameters are measured with an accuracy of 1 thousandth of a second and a resolution of 1.041 cm. The test involved a single limb jump for height starting from an upright position within the Optogait bars with hands on hips and with counter movement. The test then proceeds as follows: rest hands on hips (to measure leg performance instead of arm performance), stand straight up for one to two seconds, jump as high as possible, land with normal flexion and stand still in neutral position for one to two seconds, and repeat on the opposite limb. Flight time, height reached from center of gravity, and power were measured.

The instrumented tests facilitated the objectives of aim one. The equipment needed to complete these tests included the APDM wearable sensors, which are commercially available and have been extensively tested for reliability and accuracy in a number of populations, the custom orthotic EVA devices which included a 12 mm rearfoot lift, 12 mm forefoot lift, and neutral sham lift, and the Optogait system.

Data Analysis

All data were assessed for normality in SPSS using the Shapiro-Wilk test and visually using a Quantile-Quantile scatterplot. To detect effect size of .3, with an alpha level of .05, and a power of .8, 21 participants with AT were required. The study was powered to detect differences that were smaller than those previously reported by Scholes et al. (2018) (Scholes et al., 2018). For aim one, a 3x2 repeated measures Analysis of Variance (ANOVA) within-subjects design was used to analyze the data. The three levels were the neutral orthotic condition (neutral tendon strain), the rearfoot lift orthotic condition (decreased tendon strain), and the forefoot lift orthotic condition (increased tendon strain). The two levels were the presence of absence of AT between limbs. For aim two, Spearman's correlation was used to assess the relationship between sway area and jerk, and the LEFS and VISA-A scores.

Outcomes

The primary outcome measure was postural control as delineated by sway area (m^2/s^4) and jerk (m^2/s^5). The secondary outcomes measures were LEFS and VISA-A scores.

2.3 Results

Participants

Thirteen participants (4 female, 9 male, mean age 33.46, SD 7.66 years) with clinically diagnosed midportion AT were tested (Table 1). No participant failed to complete the study protocol.

Table 1: AT participant demographics.

Demographics	
Age	Mean = 33.46 [23-47]
Sex	*n* = 4 females; *n* = 9 males

Primary outcome measures

A statistically significant difference was demonstrated in sway area between involved and uninvolved limbs (*p* = .044) (Fig. 1). A difference was demonstrated in jerk between involved and uninvolved limbs which approached but did not reach statistical significance (*p* = .073) (Fig. 2). Neither sway area (*p* = .100) nor jerk (*p* = .639) was different between the sham, rearfoot lift, or forefoot lift conditions (Fig.1, Fig. 2).

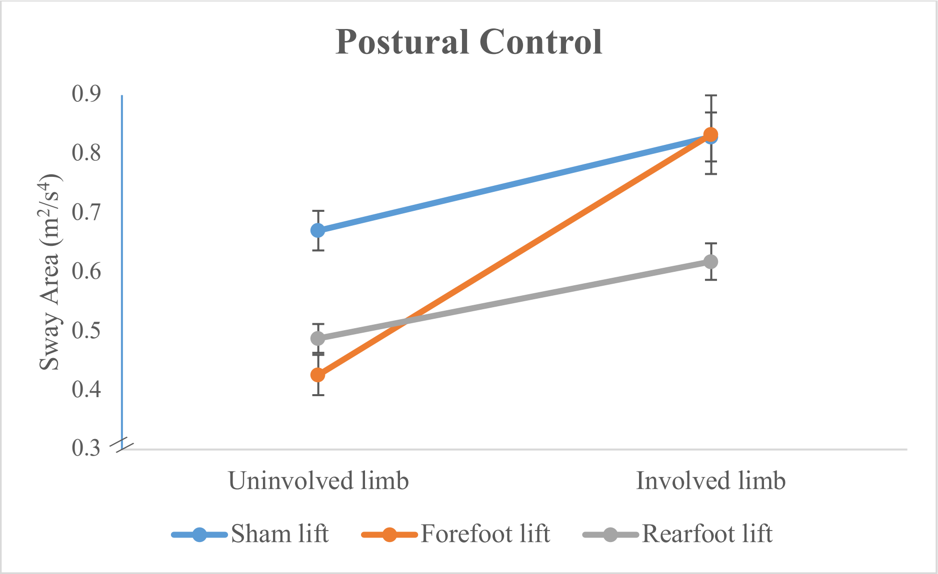

Figure 1: A statistically significant difference in sway area between involved and uninvolved limbs (p = .044). Sway area was not statistically different between sham, forefoot lift, or rearfoot lift conditions (p = .100).

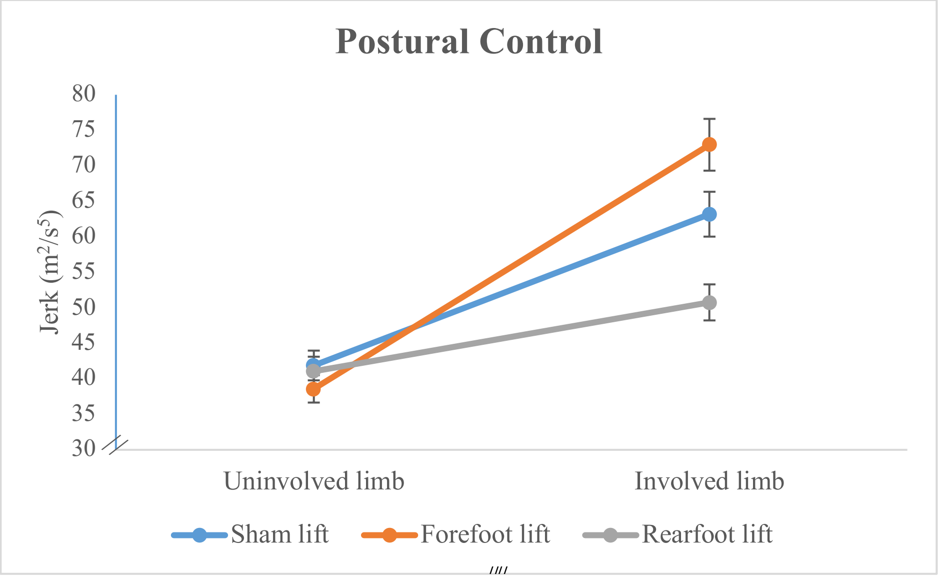

Figure 2: An equivocal difference in jerk between involved and uninvolved limbs (p = .073). Jerk was not statistically different between sham, forefoot lift, or rearfoot lift conditions (p = .639).

Secondary outcome measures

The LEFS scores ranged from 50 to 78 with a mean of 66.4 and standard deviation of 8.7. The VISA-A scores ranged from 54 to 98 with a mean of 70.9 and standard deviation of 13.5.

Functional outcome measure scores were not related to sway area or jerk. Involved limb FPI-6 scores ranged from 10 to -8 with a mean of 5.8 and standard deviation of 5.2. Uninvolved limb FPI-6 scores ranged from 11 to -10 with a mean of 5.3 and standard deviation of 6.1. Involved limb heel raise endurance scores ranged from 4 to 20 with a mean of 12.9 and standard deviation of 4.9. Uninvolved limb heel raise endurance scores ranged from 14 to 25 with a mean of 21.8 and standard deviation of 3.5. Involved limb jump height (cm) ranged from 1.5 to 14.7 with a mean of 9.9 and standard deviation of 4.6. Uninvolved limb jump height ranged from 2 to 14.9 to with a mean of 10.9 and standard deviation of 3.9. Finally, a statistically significant correlation was not found between functional outcome measure scores and postural control (Table 3).

Table 2: Secondary outcomes data (mean (SD)) of participants.

Outcome variables	Involved limb	Uninvolved limb
LEFS	66.4 (1.5)	N/A
VISA-A	70.9 (13.5)	N/A
HRE	12.9 (4.9)	21.8 (3.5)
FPI-6	5.8 (5.2)	5.3 (6.1)
Jump Height (cm)	9.9 (4.6)	10.9 (3.9)

Table 3: Spearman's correlation of secondary outcomes with postural control data.

Spearman's correlation		VISA-A	LEFS	HRE	Jump height
Sway area	rho	.533	.508	.326	-.055
p < 0.05	Sig. (2-tail)	.091	.111	.327	.873
Jerk	rho	.569	.499	.234	.064
p < 0.05	Sig. (2-tail)	.067	.118	.488	.853

Adverse events

There were no serious adverse events. The most common adverse events were pain and fatigue in the involved triceps surae, the secondary plantar flexors, and the Achilles tendon midportion. No falls occurred during the postural control protocol.

2.4 Discussion

Primary outcome measures

The first aim of this preliminary study was to explain the relationship between AT morphology (length) and postural control. A difference in static postural control was found between involved and uninvolved limbs with midportion AT. More specifically, a statistically significant difference was demonstrated in sway area between the involved and uninvolved limbs ($p = .044$). This finding corresponds with the only previous study to date that investigated postural control in AT. Scholes et al. (2018) demonstrated a statistically significant difference in center of pressure (COP) path length between involved and uninvolved limbs during unilateral eyes closed stance using a Wii Balance Board (WBB). Unlike the ADPM wearable biosensors, the WBB generates composite data only and does not resolve COP path length into sagittal and coronal planes (Scholes et al., 2018). This preliminary study also demonstrated a difference in jerk between involved and uninvolved limbs which approached but did not achieve statistical significance ($p = .073$). Sway area is powered to the fourth and jerk is powered to the fifth, which may explain why statistical significance was achieved with the former but not the latter. To the author's knowledge no previous study has investigated jerk in AT. Neither sway area ($p = .100$) nor jerk ($p = .639$) was significantly different between the sham, rearfoot lift, or forefoot lift conditions. Although no statistical differences were seen across conditions, graphical trends clearly supported the hypothesis and may require a larger sample size to resolve. Recall that the a priori determined sample size to detect an effect size of 0.3, with an alpha level of .05, and a power of 0.8, was 21 participants. In the involved limb, sway area and jerk were comparable between the sham and forefoot lift conditions but lower in the rearfoot lift condition. The sham condition assessed postural control with the Achilles tendon in its native strain environment, which presumably had been sufficiently high to promote maladaptations in the involved limb, and the toe lift condition introduced even greater strain. The rearfoot lift condition conversely reduced tendon strain. Tendinopathy impairs mechanoreception which may explain why increased tendon strain worsened sway area and jerk and decreased tendon strain improved sway area and jerk. The increase in sway area and jerk from uninvolved to involved limbs was greater for the toe lift condition than in the rearfoot lift condition.

Secondary outcome measures

Functional outcome measure scores were not related to sway area or jerk. The LEFS scores ranged from 50 to 78 with a mean of 66.4 and a standard deviation of 8.7. These values were consistent with a minimum to moderate functional limitation and the standard deviation was below the minimally important clinical difference for the LEFS of nine points. The VISA-A scores ranged from 54 to 98 with a mean of 70.6 and standard deviation of 13. These values were consistent with mild to moderate AT and the standard deviation was above the minimally important clinical difference for the VISA-A of seven points. In general, the participants reported mild dysfunction which may explain why their scores were not related to sway area or jerk.

Foot posture was characterized using the FPI-6. Involved limb FPI-6 scores ranged from 10 to -8 with a mean of 5.8 and standard deviation of 5.2. This mean value was consistent with a normal foot posture. Five feet demonstrated a pronated posture, and 1 foot demonstrated a supinated posture. Uninvolved limb FPI-6 scores ranged from 11 to -10 with a mean of 5.3 and standard deviation of 6.1. This mean value was consistent with a normal foot posture. Five feet demonstrated a pronated posture, and two feet demonstrated a supinated posture. These data suggested that the participants' FPI-6 scores were not different between involved and uninvolved limbs and agree with previous publications that have delivered equivocal evidence that foot posture relates to AT. The heel raise endurance test is a valid and reliable method of discerning lower limb strength in AT. Involved limb heel raise endurance scores ranged from 4 to 20 with a mean of 12.9 and standard deviation of 5. Uninvolved limb heel raise endurance scores ranged from 14 to 25 with a mean of 21.8 and standard deviation of 3.5. Uninvolved limb heel raise endurance was significantly greater than involved limb heel raise endurance, but again did not relate to postural control. Jump height was not different between involved and uninvolved limbs. Involved limb jump height (cm) ranged from 1.5 to 14.7 with a mean of 9.9 and standard deviation of 4.6. Uninvolved limb jump height ranged from 2 to 14.9 to with a mean of 10.9 and standard deviation of 3.9. Involved limbs have previously been shown to exhibit reduced stiffness but no difference in height during jumping compared to uninvolved limbs (Corrigan et al., 2022; Sancho, Malliaras, et al., 2019). The muscle-tendon unit in AT may preserve general performance in tasks such as jumping despite the presence of specific demonstrable impairments. These similarities in function may also be explained by the mild dysfunction reported by the participants.

Limitations

This preliminary study had several limitations. First, the a priori determined sample size to detect an effect size of 0.3, with an alpha level of .05, and a power of 0.8, was 21 participants. Notwithstanding, the first 13 participants attested to the feasibility of the methodology and analysis, and the results showed that the research questions are suitable for further examination. Second, midportion AT was diagnosed as present or absent using a reliable cluster of clinical tests, but diagnostic imaging was not used to characterize the morphological changes present in AT positive cases. For reference, Scholes et al. (2018) previously demonstrated that increased Achilles tendon thickness was associated with increased COP path length during a unilateral eyes-open task on both the involved and the involved limbs (Scholes et al., 2018). Third, the EVA orthoses manipulated tendon strain up or down with an estimated 12:1 range of motion (deg) to length (cm) ratio, but true length change was unknown. Finally, previous publications have reviewed the benefits of in-shoe heel lifts, but this preliminary study tested participants unshod.

Conclusion

In conclusion, this preliminary study demonstrated a difference in postural control between involved and uninvolved limbs with midportion AT. Thirteen participants were tested. A statistically significant difference was shown in the sway area between the involved and uninvolved limbs (p = .044), whereas the difference in jerk between involved and uninvolved limbs approached but did not reach statistical significance (p = .073). Functional outcome measures were not related to postural control. Although no differences were seen across conditions, graphical trends clearly supported the hypothesis and may require a larger sample size to resolve. The mBESS protocol includes a unilateral stance condition which made it suitable for manipulating tendon strain and measuring interlimb differences in postural control. The mBESS tests solely with eyes closed and does not manipulate proprioception which made it unsuitable for understanding sensory interaction. The addition of the instrumented CTSIB-M would further appraise motor control mechanisms in AT by testing the interrelation of the visual, vestibular, and somatosensory systems in AT.

Chapter 3: Postural Control in Achilles Tendinopathy

3.1 Background

Achilles tendinopathy (AT) is a common lower limb overuse pathology that results from excessive or insufficient mechanical loading. AT presents in 1.85 per 1000 of the adult population with up to a 27% recurrence rate (Silbernagel et al., 2020; Van Der Vlist et al., 2019). AT disrupts tissue morphology which may alter Golgi tendon organ (GTO) function and proprioception, impairing mechanical load input detection and output production. It is unclear how AT effects motor performance and postural control. In fact, recent evidence has demonstrated an indeterminate relationship between AT structure and function. For instance, a pathologically thickened Achilles tendon will not necessarily function more poorly than a healthy Achilles tendon and may in fact function better (Docking & Cook, 2019). Several trends may help explain this uncertainty. The common testing protocols that characterize AT function, such as heel raise endurance, hopping, and running, are agnostic to tendon morphology. They define function well but cannot detect structural abnormalities. The adaptive changes that govern an organism's response to injury seek foremost to preserve function. In muscle-tendon unit pathophysiology, these adaptations make it difficult determine whether increased muscle function is concealing tendon dysfunction or vice versa. Further, alterations in Achilles tendon morphology have been observed bilaterally in persons with unilateral AT (Docking et al., 2015; Rabello et al., 2020). Maladaptive changes in the contralateral tendon may be mediated by central or systemic mechanisms, though this remains unclear (Andersson et al., 2011; Rio et al., 2021). More sensitive measures to define lower limb tendon function and more accessible measures to detect tendon structure are therefore required. Postural control is highly sensitive and easily measured with commercially available inertial sensors. It is defined as the process by which the central nervous system coordinates sensory information from the visual, vestibular, and somatosensory subsystems with the motor output necessary to maintain a controlled, upright posture (Horak, 1987). When quantified with validated tests such as the modified Balance Error Scoring System (mBESS) and the Clinical Test of Sensory Interaction on Balance (CTSIB-M), postural control may explain the complex interaction between AT morphology and function.

In-shoe heel lifts reduce pain and improve function in AT and noninvasively manipulate tendon length. In-shoe heel lifts are understood to slacken Achilles tendon length and thereby reduce strain (Costa et al., 2006). Rabusin et al. (2019) systematically reviewed orthoses and concluded that in-shoe heel lifts of 12 to 18 millimeters (mm) decreased gastrocnemius muscle tendon unit length but also increased medial gastrocnemius electromyography amplitude (Rabusin et al., 2019). In an ensuing randomized controlled trial entitled HEALTHY (Heel lifts versus calf muscle eccentric Exercise for AchiLles TendinopatHY), Rabusin et al. (2021) compared a twelve-week eccentric heel raise loading program against wearing a 12 mm in-shoe heel lift for twelve weeks. Despite reasonable evidence supporting eccentric loading programs as a primary intervention for AT, the authors found that the 12 mm in-shoe heel lift intervention was more effective at reducing pain as measured by the visual analog scale and improving function as measured by the Victorian Institute of Sport Assessment Achilles (VISA-A) (K. K. W. Lee et al., 2019; Rabusin et al., 2021). Lee et al. (2019) examined in-shoe heel lifts in runners with AT and determined that they significantly reduced peak Achilles tendon length and loading rates during running (K. K. W. Lee et al., 2019). These results all connote that the immediate modification of tendon length may be at least as important in the short term as the gradual modification of morphology in the long term.

A preliminary investigation conducted by the author demonstrated the feasibility of the methodology and analysis, and the findings indicated that the research questions warrant further exploration. Using the instrumented mBESS, a difference in postural control between involved and uninvolved limbs with midportion AT was demonstrated. Achilles tendon strain was manipulated using orthotic devices, a forefoot lift increased strain, while a rearfoot lift reduced it. These were referenced against a neutral sham lift which did not alter strain. The rearfoot lift condition improved postural control in the involved limb which supported the hypothesis. While the instrumented mBESS precisely quantifies balance errors, it cannot clarify which neuromotor mechanisms generate the errors. AT reduces tendon stiffness, or resistance to strain and elongation, which introduces a lag between muscle activation and measurable force production (Chang & Kulig, 2015). Further, the triceps surae demonstrates increased alpha motor neuron excitability, intracortical inhibition, and diminished electromyography amplitude (Chang & Kulig, 2015; Fernandes et al., 2022; Rio, Kidgell, Lorimer Moseley, et al., 2016). These multilevel adaptations necessitate clarification. The instrumented CTSIB-M appraises the interaction of the visual, vestibular, and somatosensory systems and helps clarify postural control mechanisms in AT.

The purpose of this study was to examine the relationship between morphology, motor performance and function in 21 participants with midportion AT. All participants were tested with the mBESS and half of the participants were tested with the mBESS and the CTSIB-M. A sample size of 21 was expected to yield statistical significance. The CTSIB-M clarified the interaction of the visual, vestibular, and somatosensory systems in AT. The mBESS and CTSIB-M combined group created an embedded preliminary study within the full-scale study. Aim one established the relationship between AT morphology and postural control data from the mBESS.

Postural control was defined as jerk (m^2/s^5) and sway area (m^2/s^4). Jerk is the derivative of acceleration and describes the smoothness of movement corrections from the center of mass. Sway area describes the area of an ellipse covering 95% of sway acceleration in the sagittal and coronal planes (Horak, 1987). It was hypothesized that as tendon strain decreases postural control will improve. Aim two established the relationship between AT somatosensation and postural control data from the CTSIB-M. The CTSIB-M data are gathered bilaterally and manipulate visual, vestibular, and proprioceptive input, which makes it unique to the mBESS. This is important for several reasons. The structural integrity of the Achilles tendon is decreased bilaterally in persons with unilateral AT compared to healthy controls (Docking et al., 2015; Rabello et al., 2020). Persons with AT demonstrate greater triceps surae intracortical inhibition than healthy controls (Fernandes et al., 2022). It was therefore hypothesized that as somatosensory input decreases postural control will decrease proportionally more in AT compared to healthy norms. The link between poor postural control and impaired function in AT is currently unknown, but if established, postural control could serve as a leading indicator for AT morphology and a lagging indicator for maintaining AT function. Aim three established the relationship between postural control and AT function as defined by the Lower Extremity Functional Scale (LEFS) and the VISA-A. Postural control was hypothesized to correlate positively with function, where good postural control is associated with higher LEFS and VISA-A scores.

3.2 Methods

Study population

The study was approved by Columbia University Irving Medical Center Institutional Review Board (Protocol #AAAU0117) and Teachers College Institutional Review Board

(Protocol #25-181). Participants aged 18 years or greater, with Achilles tendon symptoms present in one or both lower limb(s) for a minimum of two months, who report having pain rated at least three out of 10 on a numerical rating scale, and who can walk household distances without an assistive device were included in the study. Participants with previous Achilles tendon surgery in the involved lower limb, previous Achilles tendon rupture in the involved lower limb, chronic ankle instability in the involved lower limb, and the presence of competing ankle diagnoses, such as osteoarthritis, insertional AT, inflammatory arthritis, or impingement syndrome, were excluded from the study. Recruitment fliers were posted in the Columbia University Program in Physical Therapy department, Columbia Doctors sites, and running club sites.

Self-reported tests

Data collection occurred at the Columbia University Program in Physical Therapy PACE laboratory and at the Orthology Physical Therapy Union Square clinic. The participants provided written informed consent forms and completed self-reported outcome measures, which included the LEFS and the VISA-A. The LEFS is a 20-question survey that quantifies lower extremity dysfunction over a range of functional tasks with a Likert scale that ranges from 0-to-80, with higher scores indicating better performance. The LEFS is included in the American Physical Therapy Association outcomes registry. The VISA-A is an eight-item self-administered questionnaire used to evaluate symptoms specific to AT and their effect on physical activity. It can be used to determine clinical severity and provide a guideline for treatment and for monitoring the effects of treatment (Robinson et al., 2001). These outcome measures facilitated the objectives of aim two.

Clinician-administered tests

The investigators performed a series of tests to characterize AT dysfunction. Three clinical tests were performed to confirm or refute the diagnosis of midportion AT, direct tendon palpation, the painful arc test, and the Royal London Hospital test. When combined, the overall sensitivity of these tests for detecting midportion AT is 0.586 and the overall specificity 0.833 (Maffulli et al., 2003; Silbernagel et al., 2020). Direct tendon palpation confirmed tenderness two to six centimeters (cm) proximal to the retrocalcaneus. Once the painful tendon portion was identified, the ankle was passively plantarflexed and dorsiflexed. The painful portion of the tendon moved with the passive motion and differentiated tendinopathy from paratenonitis. The ankle was then actively dorsiflexed, which placed the tendon and paratenon under tension thereby reducing tendon palpation tenderness. Passive plantar flexion, dorsiflexion, eversion, and inversion range of motion were assessed in degrees (deg) using a standard goniometer. The heel raise endurance test as described by Rabusin et al. (2021) was performed as a measure of plantar flexor strength (Rabusin et al., 2021). Foot posture was described using the Foot Posture Index (FPI-6), which is a foot posture assessment tool consisting of six items. The assessment was conducted as described by Redmond et al. (2006). High positive aggregate values reflect a pronated foot posture, neutral values reflect a neutral foot posture, and high aggregate negative values reflect a supinated foot posture. The FPI-6 is a valid and reliable test (Redmond et al., 2006).

Performance-based tests

Performance-based tests quantified static postural control. The mBESS measured static postural stability in double limb stance with hips and feet together, single limb stance on the uninvolved and involved leg with hands on hips, and tandem stance with the uninvolved foot behind the involved foot in heel-to-toe fashion and vice versa. The mBESS was instrumented with research grade wearable APDM sensors. For each of the mBESS components, custom orthotic devices manipulated tendon strain (length). A 12 mm rearfoot lift was used to increase tendon strain, a 12 mm forefoot lift to decrease tendon strain, and neutral sham lift to preserve in situ strain. The order of experimental condition was randomized. All three lifts were manufactured from identical ethylene-vinyl acetate (EVA) to control somatosensory input. The Achilles tendon lengthens by approximately one cm for every 12° of imposed ankle dorsiflexion (Costa et al., 2006). The instrumented CTSIB-M was used to examine somatosensory and visual contributions to postural control. The CTSIB-M measures postural sway, visual dependence, proprioceptive dependence, and vestibular loss, and consists of four positions: eyes open firm surface, eyes closed firm surface, eyes open foam surface, and eyes closed foam surface.

The Optogait evaluated jump height in AT to explain performance limitations within limbs and between participants. The Optogait is a noninvasive system for spatiotemporal measurement which uses a transmitting and a receiving light-emitting diode (LED) bar. Each bar contains 96 LEDS that communicate with the same number of LEDs on the opposite bar. The system detects interruptions in communication between the pair of bars and calculates duration and position. Spatiotemporal parameters are measured with an accuracy of one-thousandth of a second and a resolution of 1.041 cm. The test involved a single limb jump for height starting from an upright position within the Optogait bars with hands on hips and with counter movement. The test then proceeded with the following directives: rest hands on hips (to measure leg performance instead of arm performance), stand straight up for one to two seconds, jump as high as possible, land with normal flexion and stand still in neutral position for one to two seconds, and repeat on the opposite limb. Flight time, height reached from center of gravity, and power were measured.

The instrumented tests facilitated the objectives of Aim one. The equipment needed to complete these tests included the APDM wearable sensors, which are commercially available and have been extensively tested for reliability and accuracy in a number of populations, the custom orthotic EVA devices which included a 12 mm rearfoot lift, 12 mm forefoot lift, and neutral sham lift, the Optogait system, and an Airex pad for the CSTIB-M protocol.

Data Analysis

All data were assessed in SPSS for normality using the Shapiro-Wilk test and visually using a Quantile-Quantile (QQ) plot. The Friedman Analysis of Variance (ANOVA) was used for nonparametric data. To detect effect size of 0.3, with an alpha level of .05, and a power of 0.8, 21 participants with AT were required. Outliers in the participant data were assessed through box and whisker plot visual inspection and by calculating the interquartile range in the sham condition (IQR) (Smiti, 2020). The study was powered to detect differences that were smaller than those previously reported by Scholes et al. (2018) (Scholes et al., 2018). For aim one, a 3x2 repeated measures ANOVA within-subjects design was used to analyze the data from the single limb stance mBESS that were normally distributed. The three ANOVA levels were the neutral sham orthotic condition (neutral tendon strain), the rearfoot lift orthotic condition (decreased tendon strain), and the forefoot lift orthotic condition (increased tendon strain). The two ANOVA levels were the presence or absence of AT between limbs. For aim two, postural control was compared between participants with AT and age-matched reference norms from the composite CTSIB-M score (Purcell et al., 2019; Voss et al., 2021). Established precedents were followed to compare participant data to reference data (Baldwin et al., 2015; Kendall et al., 1999). To detect within-subjects differences, a 4x2 repeated measures ANOVA was used. The CTSIB-M conditions, eyes open-firm surface (EOFi), eyes closed-firm surface (ECFi), eyes open-foam surface (EOFo), and eyes closed-foam surface (ECFo), were the within-subjects factors. The AT group and the healthy norms group were the between-subjects factors. For aim three, Spearman's correlation was used to assess the relationship between sway area and jerk, LEFS and VISA-A scores, and other secondary outcome measures.

Outcomes

The primary outcome measure was postural control as delineated by sway area (m^2/s^4) and jerk (m^2/s^5). The secondary outcomes measures were LEFS, VISA-A, HRE, and jump height scores.

3.3 Results

Twenty-one participants who met the inclusion criteria were enrolled. No participants withdrew from the study, but five were unable to complete the jump height assessment due to symptom severity. Two statistical outliers were identified during data analysis through box plot visual inspection (Fig. 1, Fig. 2) and the IQR test and removed from the data set. Both outliers were from the aim one involved limb sham lift condition.

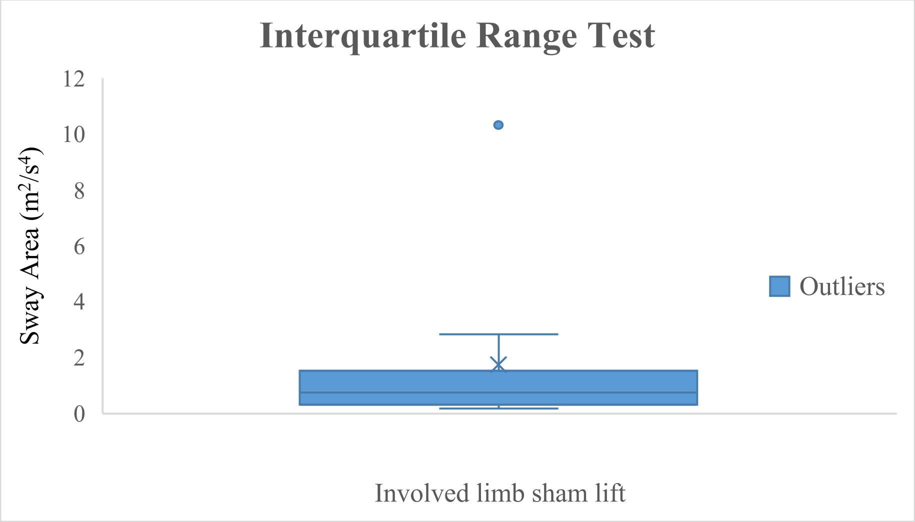

Figure 1: Interquartile range test box and whisker plot for involved limb sham lift condition sway area (median [IQR]: .758 [1.167]). Outliers above the IQR upper boundary (3.212): 10.329, 10.393.

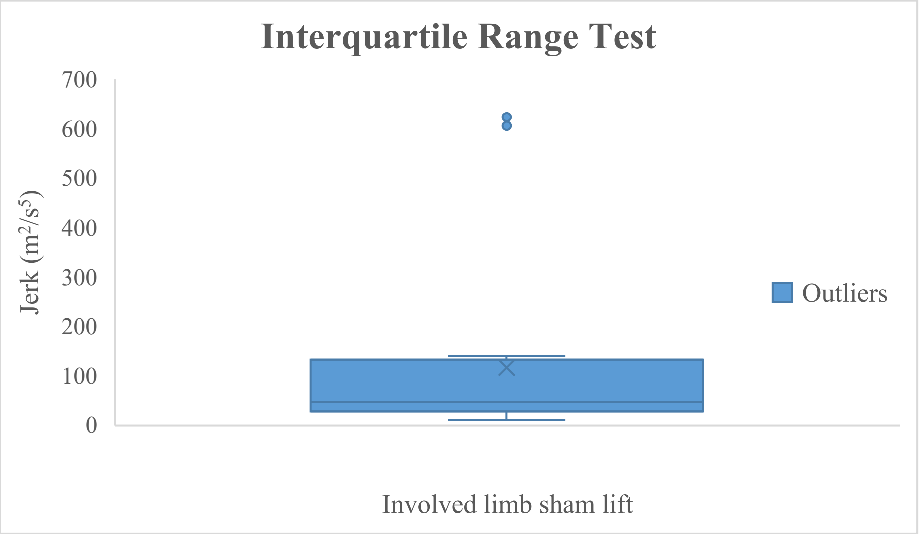

Figure 2: Interquartile range test box and whisker plot for involved limb sham lift condition jerk (median [IQR]: 47.699 [107.664]). Outliers above the IQR upper boundary (296.08): 606.257, 624.151.

Nineteen participants (7 female, 12 male, mean age 36.3, SD 11.5 years) were therefore included in the study. No participants were sedentary. Fifteen participants were moderate-to-extremely active in long-distance running and four participants were moderate-to-vigorously active in other modes of physical activity such as interval and resistance training (Table 1). Shapiro-Wilk test of normality and QQ scatterplot visual inspection demonstrated that some of the aim one data were nonparametric, and some were normally distributed (p >.05), including primary outcome measures sway area (p = .191) and jerk (p = .631). A Friedman test was run to determine if there were differences in postural control between involved and uninvolved limbs across sham lift, forefoot lift, and heel lift conditions. Sway area decreased from the sham lift (*Mdn* = .734) to the forefoot lift (*Mdn* = .628), to the heel lift condition (*Mdn* = .478), but the differences were not statistically significant, $\chi^2(2) = 7.421$, $p = .191$. Jerk decreased from the sham lift (*Mdn* = 45.681) to the rearfoot lift condition (*Mdn* = 33.977), and increased to the forefoot lift condition (*Mdn* = 46.158), but the differences were not statistically significant, $\chi^2(2) = 3.451$, $p = .631$. There were no departures from normality for aim two and three data.

Table 1: Descriptive data of participants (*n* = 19).

Participant	Sex	Age (years)	Height (cm)	Physical Activity (mode)
1	Male	38	185	Extreme (running)
2	Male	31	165	Moderate (running)
3	Male	24	170	Vigorous (interval)
4	Female	47	154	Moderate (interval)
5	Female	40	149	Moderate (running)
6	Male	41	175	Vigorous (running)
7	Male	41	175	Moderate (running)
8	Male	24	172	Moderate (running)
9	Male	31	172	Moderate (running)
10	Female	31	162	Extreme (running)
11	Female	28	167	Vigorous (running)
12	Male	23	181	Vigorous (running)
13	Male	34	178	Moderate (running)
14	Male	69	180	Moderate (resistance)
15	Female	30	166	Vigorous (running)
16	Female	27	167	Moderate (running)
17	Male	38	177	Vigorous (running)
18	Male	32	175	Vigorous (running)
19	Female	56	170	Moderate (interval)

Primary outcome measures

The first aim of this study was to explain the relationship between AT morphology (strain) and postural control. A difference in sway area that approached statistical significance was determined between involved and uninvolved limbs with midportion AT (95% CI [-.004, .373], *p* = .054). A graphical trend was demonstrated between the sham, forefoot, and rearfoot lift conditions, but not an unequivocal difference (*p* = .241) (Fig. 3). The rearfoot lift condition demonstrated the lowest sway area, followed by the sham lift and forefoot lift conditions. A difference in jerk was not determined between involved and uninvolved limbs with midportion AT (95% CI [-10.864, 28.157], *p* = .364). Like sway area, a graphical trend in jerk was demonstrated between the sham, forefoot, and rearfoot lift conditions, but not an unequivocal difference (*p* = .225) (Fig. 4). The rearfoot lift condition demonstrated the lowest jerk, followed by the sham lift and forefoot lift conditions. Although ANOVA remains moderately robust to departures from normality, the Wilcoxon signed-rank test, which is specially intended for nonparametric data, was used to further analyze differences between conditions. There was an equivocal median decrease in impaired limb jerk (12.181) from the forefoot lift (46.158) to the rearfoot lift condition (33.977), $z = -1.932$, $p = .053$. There was no significant median decrease in impaired limb sway area (.149) from the forefoot lift (.627) to the rearfoot lift condition (.477), $z = -1.087$, $p = .277$.

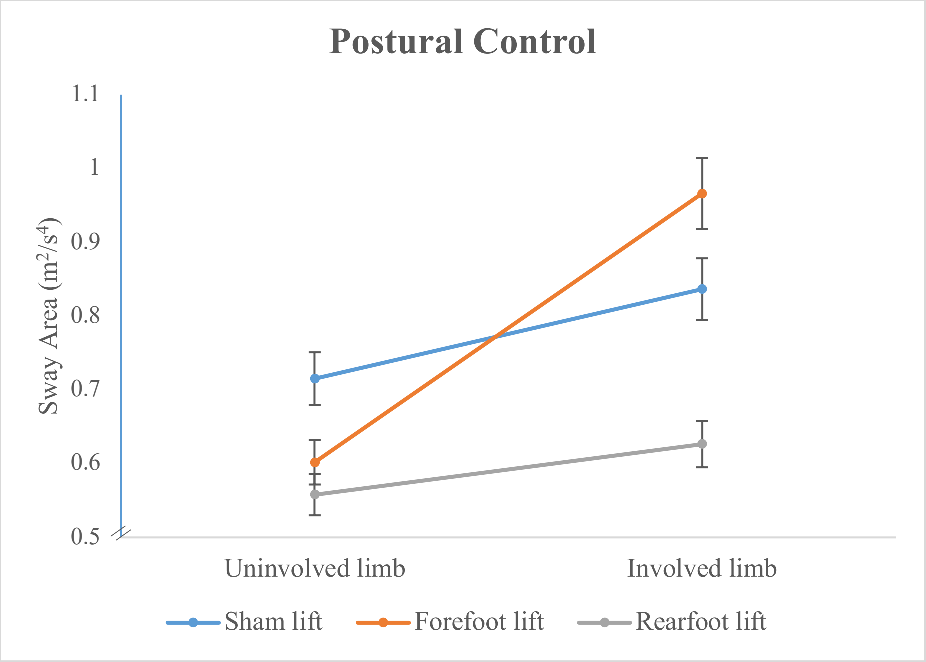

Figure 3: An equivocal difference in sway area between involved and uninvolved limbs (95% CI [-.004, .373], *p* = .054). Sway area was not statistically different between sham, forefoot lift, or rearfoot lift conditions (*p* = .241).

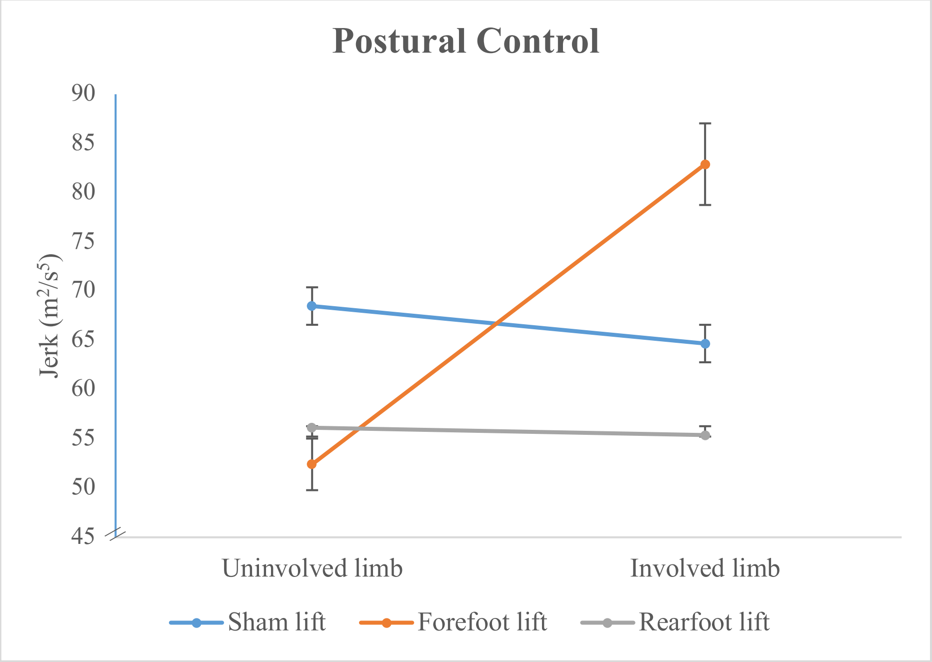

Figure 4: An equivocal difference in jerk between involved and uninvolved limbs (95% CI [-10.864, 28.157], *p* = .364). Jerk was not statistically different between sham, forefoot lift, or rearfoot lift conditions (*p* = .225).

The second aim of this study was to establish the relationship between AT and postural control using the CTSIB-M. Eight participants were tested and compared to published age-matched normative data. A statistically significant difference in sway area was found between CTSIB-M conditions in AT and control limbs ($p < .001$), apart from between EOFi and ECFi ($p = .229$). No difference in sway area was found between AT and control limbs ($p = .534$) (Fig. 5). A statistically significant difference was also found in jerk between CTSIB-M conditions in AT and control limbs ($p = .002$), apart from between EOFi and ECFi ($p = .320$). No difference in jerk was found between AT and control limbs ($p = .443$) (Fig. 6) (*Mobility Lab Whitepaper*, n.d.).

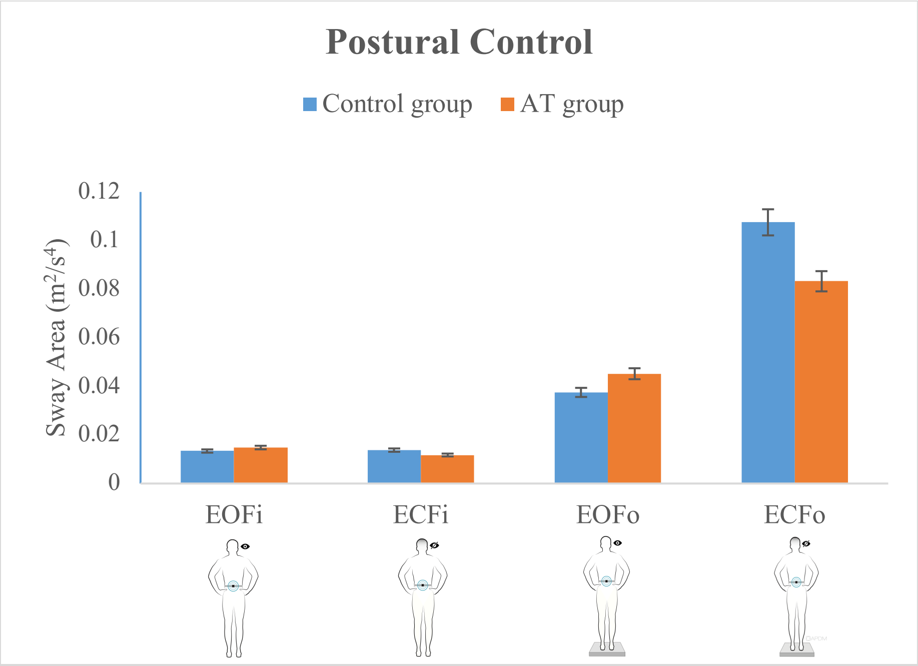

Figure 5: A statistically significant difference in sway area between CTSIB-M conditions in AT and control limbs (*p* < .001). No statistical difference in sway area between AT and control limbs (*p* = .534).

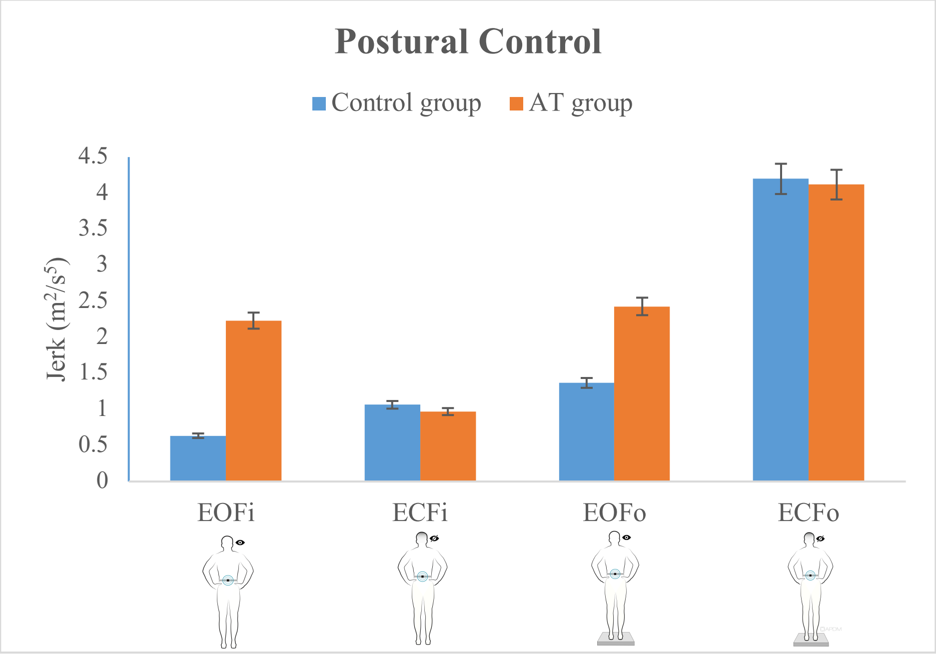

Figure 6: A statistically significant difference in jerk between CTSIB-M conditions in AT and control limbs (*p* = .002). No statistical difference in jerk between AT and control limbs (*p* = .443).

Secondary outcome measures

The third aim examined the relationship between postural control and AT function as defined by the LEFS and the VISA-A. Data from clinician administered tests were also analyzed within the third aim (Table 2). A very strong negative correlation was observed between involved limb dorsiflexion range of motion and sway area ($r_s(18) = -.711$, $p = .001$) and jerk ($r_s(18) = -.727$, $p = .001$). A strong negative correlation was observed between involved limb plantarflexion range of motion and sway area ($r_s(18) = -.615$, $p = .007$) and jerk ($r_s(18) = -.539$, $p = .021$). A medium negative correlation was observed between involved limb KTW (cm) score and sway area ($r_s(18) = -.490$, $p = .039$) but not jerk ($r_s(18) = -.036$, $p = .134$) (Table 3). The LEFS scores ranged from 42 to 78 with a mean of 61.4 and standard deviation of 11.2. The VISA-A scores ranged from 39 to 98 with a mean of 67.4 and standard deviation of 15.6. Neither the LEFS ($r_s(18) = .168$, $p = .504$) nor the VISA-A ($r_s(18) = .102$, $p = .686$) were related to sway area. The LEFS ($r_s(18) = .118$, $p = .641$) and the VISA-A ($r_s(18) = .048$, $p = .851$) were not correlated with jerk. Involved limb heel raise endurance scores ranged from 2 to 23 with a mean of 13.5 and standard deviation of 5.6. Uninvolved limb heel raise endurance scores ranged from 14 to 25 with a mean of 21.8 and standard deviation of 3.1. Involved limb heel raise repetitions were significantly lower than uninvolved limb repetitions ($p = .0001$, CI 95% [5.217, 11.382]), but unrelated to sway area ($r_s(18) = -.154$, $p = .542$) or jerk ($r_s(18) = -.277$, $p = .266$). Involved limb jump height ranged from 1.5 to 14.2 with a mean of 9.4 and standard deviation of 3.9. Uninvolved limb jump height ranged from 2 to 14.9 with a mean of 10 and standard deviation of 3.9. Involved and uninvolved limb jump heights were not different ($p = .688$, CI 95% [-2.537, 3.777]) and unrelated to sway area ($r_s(13) = .240$, $p = .409$) or jerk ($r_s(13) = .354$, $p = .215$). Involved limb FPI-6 scores ranged from -8 to 10 with a mean of 4.7 and standard deviation of

5.1. Uninvolved limb FPI-6 scores ranged from -10 to 11 with a mean of 4 and standard deviation of 5.3. FPI-6 scores were unrelated to sway area ($r_s(18) = -.286$, $p = .251$) and jerk ($r_s(18) = -.313$, $p = .207$) (Table 2, Table 3).

Table 2: Secondary outcomes data (mean (SD)) of participants.

Outcome variables	Involved limb	Uninvolved limb
LEFS	61.4 (11.2)	N/A
VISA-A	67.4 (15.6)	N/A
Heel Raise Endurance	13.5 (5.6)	21.8 (3.1)
Jump Height (cm)	9.4 (3.9)	10 (3.9)
Foot Posture Index	4.7 (5.1)	4 (5.4)
Dorsiflexion (deg)	3.6 (5.7)	6.2 (5.9)
Plantarflexion (deg)	39.9 (6.2)	40.3 (5.3)
Knee-to-Wall test (cm)	6.6 (3.5)	7.6 (3.9)

Table 3: Spearman's correlation of secondary outcomes with postural control data.

Spearman's correlation		DF ROM	PF ROM	KTW	LEFS	VISA-A
Sway area	rho	-.711	-.615	-.490	.168	.102
$p < 0.05$	Sig. (2-tail)	.001	.007	.039	.504	.686
Jerk	rho	-.727	-.539	-.036	.118	.048
$p < 0.05$	Sig. (2-tail)	.001	.021	.134	.641	.851

Adverse events

There were no serious adverse events. The most common adverse events were mild pain and fatigue in the involved triceps surae, secondary plantar flexors, and Achilles tendon midportion. No falls occurred during the postural control protocols.

3.4 Discussion

Primary outcome measures

The first aim of this study was to explain the relationship between AT morphology (strain) and postural control. The a priori hypothesis proposed that postural control would improve with decreased strain and worsen with increased strain. A difference that approached statistical significance in sway area (95% CI [-.004, .373], *p* = .054) and an equivocal difference in jerk (95% CI [-10.864, 28.157], *p* = .364) was seen between involved and uninvolved limbs with midportion AT. Sway area is powered to the fourth and jerk is powered to the fifth, which may explain their differences in statistical significance. To the author's knowledge no previous study has investigated jerk in AT. These findings correspond with the only previous study to date that investigated postural control in AT. Scholes et al. (2018) demonstrated a statistically significant difference in center of pressure (COP) path length between involved and uninvolved limbs during unilateral eyes closed stance using a Wii Balance Board (WBB). The WBB generates simple translatory data only and does not resolve COP path length from sagittal and coronal planes (Scholes et al., 2018). Conversely, the APDM inertial sensors used in this study detect complex motions, such as jerk, and resolve them into composite data. This increased complexity may explain the differences in reported significance between Scholes et al. (2018) and the current study.

A clear graphical trend was seen between the sham, forefoot, and rearfoot lift conditions, but not a statistically significant difference (*p* = .241) (Fig. 3). The rearfoot lift condition demonstrated the lowest sway area, followed by the sham lift and forefoot lift conditions. Similar to sway area, an obvious graphical difference in jerk was seen between the sham, forefoot, and rearfoot lift conditions, but not a statistically significant difference (*p* = .225) (Fig. 4). The rearfoot lift condition demonstrated the lowest jerk, followed by the sham lift and forefoot lift conditions. The largest differences in postural control were seen between the involved limb forefoot lift and the involved limb rearfoot lift conditions. The results of the Wilcoxon signed-rank test, which is specially intended for nonparametric data, corroborate some the differences between the forefoot lift and rearfoot lift conditions (*z* = -1.932, *p* = .053). The standard error in sway area decreased from .242 m^2/s^4 with the forefoot lift to .097 m^2/s^4 with the rearfoot lift, a 59.92% change. Likewise, the standard error in jerk decreased from 20.005 m^2/s^5 with the forefoot lift to 10.829 m^2/s^5 with the rearfoot lift, an 84.7% change. The rearfoot lift thus evidently stabilized postural control relative to the forefoot lift condition. This makes mechanistic sense. Recall that the sham lift condition maintains intrinsic AT strain, the forefoot lift increases strain, and the rearfoot lift decreases strain. AT disrupts tissue morphology, disorganizing collagen and reducing stiffness, which directly impairs tenocyte mechanosensitivity and creates a neuromotor lag between mechanical load input and force output. Golgi tendon organ and muscle spindle function are almost certainly also compromised (Arya & Kulig, 2010; Chang & Kulig, 2015). Cook et al. (2016) have even described tendinopathic tissue as “mechanically silent” (Cook et al., 2016). It is therefore plausible that the increased forefoot lift strain challenges the impaired neuromotor feedback loop and provokes postural control errors. The rearfoot lift conversely alleviates strain on the feedback loop and moderates postural control errors. This may explain why increased tendon strain worsened postural control and decreased tendon strain improved it.

The second aim investigated the relationship between AT and postural control data from the CTSIB-M. A statistically significant difference in sway area ($p < .001$) and jerk ($p = .002$) was found between CTSIB-M conditions in AT and controls. This finding validates that the CTSIB-M conditions were appropriately discriminatory in the AT population, apart from between EOFi and ECFi for both sway area ($p = .229$) and jerk ($p = .320$). Eyes open-foam surface and ECFo were statistically different from EOFi and ECFi ($p < .001$), and from each other ($p < .001$). The AT participants therefore appear able to maintain baseline postural control in the absence of visual information, but not in the absence of visual information with somatosensory interference. No difference in sway area (*p* = .534) or jerk (*p* = .443) was found between AT and control limbs across any condition (Fig. 5, Fig. 6). Recall that the structural integrity of the Achilles tendon is often impaired bilaterally in persons with unilateral AT compared to healthy controls (Docking et al., 2015; Rabello et al., 2020). These findings align with previous publications that have contested the presence of central processing mechanisms in the pathogenesis of lower limb tendinopathies (Rio et al., 2021; Rio, Kidgell, Lorimer Moseley, et al., 2016).

Secondary outcome measures

The third aim examined the relationship between postural control and AT function. Data from clinician administered tests were also analyzed within the third aim (Table 2). A very strong negative correlation was observed between involved limb dorsiflexion range of motion and sway area ($r_s(18) = -.711$, $p = .001$) and jerk ($r_s(18) = -.727$, $p = .001$). A strong negative correlation was also observed between involved limb plantarflexion range of motion and sway area ($r_s(18) = -.615$, $p = .007$) and jerk ($r_s(18) = -.539$, $p = .021$). These data indicate that as dorsiflexion or plantarflexion range of motion decrease in AT, postural control worsens. It is unclear if this mechanism is causal or consequential to AT. Joint hypermobility is often associated with aberrant motions, but it appears joint hypomobility may also introduce aberrance. This is perhaps due to the direct relationship between Achilles tendon length and ankle dorsiflexion, and triceps surae force production and ankle plantarflexion. A medium negative correlation was observed between involved limb KTW (cm) score and sway area ($r_s(18) = -.490$, $p = .039$), which simply further supports the inverted relationship between ankle dorsiflexion and postural control (Table 3).

The LEFS scores ranged from 42 to 78 with a mean of 61.4 and standard deviation of 11.2. These values were consistent with a minimum to moderate functional limitation, but the standard deviation was above the minimally important clinical difference for the LEFS of nine points. The VISA-A scores ranged from 39 to 98 with a mean of 67.4 and standard deviation of 15.6. These values were consistent with mild to moderate AT and the standard deviation was above the minimally important clinical difference for the VISA-A of seven points. Neither the LEFS (r_s(18) = .168, p = .504) nor the VISA-A (r_s(18) = .102, p = .686) were related to sway area. The LEFS (r_s(18) = .118, p = .641) and the VISA-A (r_s(18) = .048, p = .851) were not correlated with jerk. The participants in general reported mild dysfunction which may explain why their scores were not correlated to sway area or jerk.

The heel raise endurance test is a valid and reliable method of discerning lower limb strength in AT (Silbernagel et al., 2020). Involved limb heel raise endurance scores ranged from 2 to 23 with a mean of 13.5 and standard deviation of 5.6. Uninvolved limb heel raise endurance scores ranged from 14 to 25 with a mean of 21.8 and standard deviation of 3.1. Involved limb heel raise repetitions were significantly lower than uninvolved limb repetitions (p = .0001, CI 95% [5.217, 11.382]), but unrelated to sway area (r_s(18) = -.154, p = .542) or jerk (r_s(18) = -.277, p = .266). Involved limb jump height ranged from 1.5 to 14.2 with a mean of 9.4 and standard deviation of 3.9. Uninvolved limb jump height ranged from 2 to 14.9 with a mean of 10 and standard deviation of 3.9. Involved and uninvolved limb jump heights were equivocal (p = 688, CI 95% [-2.537, 3.777]) and unrelated to sway area (r_s(13) = .240, p = .409) or jerk (r_s(13) = .354, p = .215). Involved limbs have previously been shown to exhibit reduced stiffness but no difference in height during jumping compared to uninvolved limbs (Corrigan et al., 2022; Sancho, Malliaras, et al., 2019). The neuromotor system in AT appears able to preserve performance in tasks such as jumping and running despite the presence of demonstrable impairments. These similarities in function may also be explained by the mild dysfunction reported by the participants.

Foot posture was characterized using the FPI-6. The total score ranges from -12 to +12, with negative scores indicating a supinated foot posture and positive scores indicating a pronated foot posture. A score that approaches zero represents a neutral alignment (Redmond et al., 2006). Involved limb FPI-6 scores ranged from -8 to 10 with a mean of 4.7 and standard deviation of 5.1. This range contained four highly pronated, six pronated, seven normal, and two highly supinated feet. The mean value was consistent with a normal foot posture. Uninvolved limb FPI-6 scores ranged from -10 to 11 with a mean of 4 and standard deviation of 5.4. This range contained two highly pronated, seven pronated, seven normal, two supinated, and one highly supinated foot (Table 4).

Table 4: Participant Foot Posture Index (FPI-6) scores.

Foot Posture Index score category	Involved limb	Uninvolved limb
Highly pronated: +10 to +12	$n = 4$	$n = 2$
Pronated: +6 to +9	$n = 6$	$n = 7$
Normal: 0 to +5	$n = 7$	$n = 7$
Supinated: -4 to -1	$n = 0$	$n = 2$
High supinated: -12 to -5	$n = 2$	$n = 1$

This mean value is consistent with a normal foot posture. FPI-6 scores were not correlated with sway area ($r_S(18) = -.286$, $p = .251$) or jerk ($r_S(18) = -.313$, $p = .207$) (Table 2, Table 3). Similar to previously published literature, FPI-6 scores were equivocal between involved and uninvolved limbs (Van Der Vlist et al., 2019). Risk factors for AT appear to become more important when they occur in clusters. A highly pronated foot, for instance, may incidentally increase Achilles tendon torsional strain but not be predictive of AT in the absence of excessive net loading.

Limitations

This study may have potential limitations. First, midportion AT was diagnosed as present or absent using a reliable cluster of clinical tests, but diagnostic imaging was not used to detail the morphological changes present in AT positive cases. For reference, Scholes et al. (2018) previously demonstrated that increased Achilles tendon thickness was associated with increased COP path length during a unilateral eyes-open task on both the involved and the involved limbs (Scholes et al., 2018). Second, the EVA orthoses may manipulate tendon strain with a calculated 12:1 range of motion (deg) to length (cm) ratio, but true length change was unknown. Previous publications have reviewed the benefits of in-shoe rearfoot lifts, but this study tested participants unshod. This may theoretically have led to more unchecked coronal plane motion, particularly in the highly pronated and pronated foot posture groups. Third, whereas the AT sample used in this study was heterogenous with respect to age and sex, it was homogenous with respect to activity level. Most participants were highly active recreational athletes who reported only mild dysfunction. Lastly, to the author's knowledge no study has used the CTSIB-M to characterize AT postural control, making direct comparisons to previous literature not possible.

Conclusion

In this study, participants with AT demonstrated equivocal bilateral postural control compared to age-matched control limbs during each condition from the CTSIB-M. Unilateral postural control from the mBESS was worse in involved limbs with AT but not statistically different from uninvolved limbs. The largest difference in postural control was observed between involved limbs with a forefoot lift versus a rearfoot lift. The forefoot lift increased postural control variability and the rearfoot lift decreased it. Participants with AT demonstrated a very strong negative correlation between ankle joint range of motion and postural control. The LEFS, VISA-A, HRE, FPI-6, and jump height were not correlated with postural control. The results of this study were not all statistically significant and should be interpreted as such, but it would be prudent for clinicians to consider evaluating postural control and rearfoot-to-forefoot drop in AT.

Conclusion

In conclusion, this study demonstrated some important differences in postural control between involved and uninvolved limbs with midportion AT and demonstrated some ways in which they are they not different. Postural control was defined by sway area and jerk. An equivocal difference in postural control was observed between involved and uninvolved limbs, where involved limbs exhibited reduced postural control. The structural integrity of the Achilles tendon is often compromised bilaterally in AT, potentially contributing to this ambiguous finding (Docking et al., 2015; Rabello et al., 2020). Postural control does appear to respond immediately to strain manipulation in AT, which is a novel finding of this study. An obvious graphical difference in postural control was demonstrated between the orthotic lift conditions, but not a statistically significant difference. The rearfoot lift demonstrated the lowest sway area and jerk, followed by the sham lift, and then the forefoot lift condition. The largest difference in postural control was seen between the involved limb forefoot lift and the involved limb rearfoot lift conditions. The rearfoot lift reduced postural control variability by 72.31% on average from the forefoot lift condition. AT disrupts tissue morphology which directly impairs tenocyte mechanosensitivity and creates a neuromotor lag between mechanical load input and force output. The forefoot lift appears to exacerbate postural control variability while the rearfoot lift curbs it. Taken together, these trends may explain why in-shoe heel lifts were recently demonstrated to be more effective than eccentric exercise in reducing pain and improving function at 12 weeks in adults with midportion AT (Rabusin et al., 2021). Bilateral postural control tested with the CTSIB-M was not different between AT and age-matched control limbs. CTSIB-M conditions EOFo and ECFo demonstrated more discriminatory capacity than conditions EOFi and ECFi, suggesting that visual interference alone is insufficient to meaningfully unsettle postural control in midportion AT. The AT and the age-matched control groups performed the most poorly during the fourth test condition, which challenged both visual and somatosensory input. A very strong negative correlation was found between ankle range of motion and postural control, a novel finding of this study. The reportedly mild dysfunction and high-performance capacity of the participants in this study probably obscured measurable correlations between functional outcomes and postural control. The results of this study were not all statistically significant and should be interpreted as such, but it would still be prudent for clinicians to consider evaluating postural control and rearfoot-to-forefoot footwear offset in midportion AT.

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