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ABSTRACT

Objective: To investigate the acute effects of isolated eccentric and concentric calf muscle exercise on Achilles tendon sagittal thickness.
Design: Within-subject, counterbalanced, mixed design.
Setting: Institutional.
Participants: 11 healthy, recreationally active male adults.
Interventions: Participants performed an exercise protocol, which involved isolated eccentric loading of the Achilles tendon of a single limb and isolated concentric loading of the contralateral, both with the addition of 20% bodyweight.
Main outcome measurements: Sagittal sonograms were acquired prior to, immediately following and 3, 6, 12 and 24 h after exercise. Tendon thickness was measured 2 cm proximal to the superior aspect of the calcaneus.
Results: Both loading conditions resulted in an immediate decrease in normalised Achilles tendon thickness. Eccentric loading induced a significantly greater decrease than concentric loading despite a similar impulse (-0.21 vs -0.05, $p<0.05$). Post-exercise, eccentrically loaded tendons recovered exponentially, with a recovery time constant of 2.5 h. The same exponential function did not adequately model changes in tendon thickness resulting from concentric loading. Even so, recovery pathways subsequent to the 3 h time point were comparable. Regardless of the exercise protocol, full tendon thickness recovery was not observed until 24 h.
Conclusions: Eccentric loading invokes a greater reduction in Achilles tendon thickness immediately after exercise but appears to recover fully in a similar time frame to concentric loading.

Achilles tendinopathy is a common musculoskeletal disorder in physically active and sedentary individuals alike.[1 2] Although reported to occur in men and women of all ages, Achilles tendinopathy is most prevalent in men aged 35–45 years, and in sports involving stretch-shortening cycle activities such as running and jumping.[1 3] Initially characterised by insidious pain and stiffness at the onset of tendon-loading activities, the condition may progress to have a substantial negative effect on health and well-being.[1]

As the pathophysiology of tendinopathy is inadequately understood,[4] Achilles tendinopathy has proven difficult to treat, as evidenced by the myriad of treatment regimes that are employed clinically.[1 3 5] Eccentric exercise as a rehabilitation technique for Achilles tendinopathy is one of the few treatment regimes with an evidence base demonstrating positive results.[5] Initially eccentric exercise was shown to be highly effective, with more than 80% of patients satisfied with treatment outcomes.[6–10] Subsequent studies, however, have reported treatment success rates closer to 60%.[11–13] Despite some disparity in reported treatment success rates, eccentric exercise remains a popular conservative Achilles tendinopathy treatment technique.[3 5 14]

The apparent efficacy of eccentric exercise compared with other treatments is currently difficult to evaluate given the inconsistencies in eccentric exercise protocols; variations in exercise compliance within and between studies; the use of control groups confounded by other treatments; along with differences in outcome measures and follow-up time frames.[1 3 14] Interestingly, strengthening exercises involving other forms of muscle action such as concentric activation have been shown to be less effective in the treatment of tendinopathy.[3 8 15] At present the mechanisms underpinning the beneficial effects of eccentric exercise, as opposed to the application of tendon stress via other forms of muscle action, are unclear. Quantitative assessment of the acute Achilles tendon response to eccentric and concentric exercise may provide a more objective and reliable measure of tendon response to different therapeutic regimes. The advent of high-resolution ultrasonography within clinical settings affords the opportunity to evaluate the effect of such therapeutic approaches by quantifying changes in tendon morphology.

The purpose of this research was to investigate the acute effects of isolated eccentric and concentric calf muscle exercise, on the sonographically determined Achilles tendon sagittal thickness.

METHODS

Participants

A convenience sample of 11 healthy, recreationally active male adults (mean age 25.9 (SD 4.9) years, body mass 74.2 (11.8) kg and height 177.9 (6.5) cm) were recruited from university staff and students. Volunteers with a history of Achilles tendon pain, musculoskeletal injury of either limb or osseous enlargement of the posterolateral aspect of the calcaneus, the Haglund's deformity, were excluded from participating in the study. The study received University Human Research Ethics approval.

Procedure

Participants were requested to refrain from physical activity above that required to perform

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necessary daily activities, both 24 h prior to and during the study. Participants were also asked not to consume alcohol or non-steroidal anti-inflammatory drugs throughout the duration of the study period. Testing began at approximately 8:00 am, at which time the Achilles tendon of both limbs underwent initial sonographic examination. Each limb was subsequently assigned to perform either a concentric or eccentric exercise protocol using a counterbalanced design. Limb dominance was not assessed. Immediately on completion of the exercise protocol, Achilles tendons were re-examined and additional sonographic images were acquired over the next 24 h at 3, 6, 12 and 24 h post-exercise.

Exercise protocol

The exercise protocol was based upon a widely implemented therapeutic programme for Achilles tendinopathy in which the calf muscle of the affected limb is eccentrically loaded.[10] The protocol involved isolated eccentric loading of the tendon of a single limb, while the contralateral tendon experienced isolated concentric loading. Participants were required to stand with the forefoot of the eccentric limb positioned on the edge of a step, with their ankle maximally plantarflexed and with their bodyweight centred on the eccentric limb. Eccentric loading occurred as the participant lowered the heel below the level of the forefoot to a position of maximal dorsiflexion. No concentric loading followed; rather, the forefoot of the contralateral limb was placed on the edge of the step in maximal dorsiflexion and all weight transferred from the eccentric limb. The participant then performed a concentric muscle action, moving the ankle from a position of maximal dorsiflexion to maximal plantarflexion. The process, which consisted of one eccentric and one concentric muscle action, was repeated 15 times per set. Three exercise sets were performed with a straight knee and three sets were performed with the knee slightly flexed. Participants were afforded 1 minute rest between sets. The duration of loading of each limb during the exercise protocol was recorded via timing switches incorporated within the foot supports. The footswitch data also provided an active visual feedback system that encouraged participants to undertake eccentric and concentric muscle actions over an equal duration of 2 seconds. All eccentric and concentric exercises were performed with an additional 20% bodyweight added via a weighted backpack.

Sonographic imaging

Ultrasonography was performed with a linear-array transducer at a frequency of 8 MHz (LOGIQ BookXP, GE Healthcare, Wauwatosa, WI, USA) by a single operator experienced in musculoskeletal imaging. Sagittal images of the Achilles tendon were collected with the aid of an acoustic stand-off pad while the participant was positioned prone, with the ankle passively dorsiflexed to approximately 90° by the operator.[16] Images encompassed the superior aspect of the calcaneus and approximately 3 cm of the distal Achilles tendon. Ten replicate images were collected for analysis at each time interval (pre and 0, 3, 6, 12, 24 h post-exercise).

Image analysis

Images were exported in DICOM format and analysed using MATLAB software (version 7.2.0.232 R2006a, The MathWorks Inc., Natick, MA, USA). Semi-automated measures of tendon thickness were made for each image, at a standard reference point, 2 cm proximal to the superior aspect of the calcaneus. A grey-scale profile at each measurement site was used to aid the identification of the superficial and deep tendon borders. Tendon thickness was calculated with a measurement resolution of 0.1 mm. To avoid potential examiner bias, the order of image analysis (limb and time point) was randomised and measures were blinded until replicate digitisation completion. Repeated measures reliability, represented by the root mean square error of the linear mixed model residual variance, was $\pm$0.3 mm. Statistical analysis was performed on mean tendon thickness values derived from replicate image digitisation. To normalise for pre-existing differences in tendon thickness, measures of sagittal thickness were expressed as a ratio of the pre-exercise value.

Statistical analysis

The Statistical Package for the Social Sciences (version 15, SPSS Inc, Chicago, IL USA) was used for all statistical procedures. Since outcome variables were normally distributed, mean values and standard deviations were calculated and are presented in the text. Differences between eccentric and concentric loading durations and the pre-exercise raw sagittal tendon thickness values were assessed using paired t tests. Differences in normalised sagittal tendon thickness between exercise protocols (concentric and eccentric) at each time point (0, 3, 6, 12, 24 h post-exercise) were evaluated using a linear mixed model. In each case, the participant was treated as a random effect, while time and exercise protocol were treated as fixed effects. As a significant interaction between time and exercise protocol was present, confidence intervals were utilised to compare the tendon thickness at each time point. Recovery in Achilles tendon thickness over the study period was modelled using an exponential function ($f(t) = a^*(1-\exp(-t/T1))+c$) derived from the Kelvin–Voigt model of viscoelasticity.[17] The model was constrained by requiring that both constants a and c be positive. The ability of this function to fit the data was determined by calculation of the root mean square error and r^2 statistic. The tendon thickness recovery time constant was determined by the T1 coefficient.

RESULTS

The mean exercise set loading duration was not significantly different between eccentric (43.5 (SD 6.9) s) and concentric (42.5 (5.3) s) exercise protocols ($p>0.05$) and consequently the total loading impulses were deemed equivalent. Allowing for 1 minute rest between sets, the total exercise intervention was completed in less than 15 minutes.

The mean Achilles tendon sagittal thickness measured prior to exercise was not significantly different ($p>0.05$) for tendons assigned to the concentric and eccentric exercise protocols (table 1). Calf muscle exercise produced an immediate post-exercise decline in normalised tendon thickness 2 cm proximal to the calcaneal insertion ($p<0.05$). The eccentric exercise protocol resulted in a four-fold greater decrease in tendon thickness (−0.21 (0.06)) immediately post-exercise when compared with the concentric exercise protocol (−0.05 (0.05)) (fig 1). Although the magnitude of this initial response varied between participants, an identical pattern was observed across all participants. The thickness of tendons exposed to the two exercise protocols did not differ significantly at subsequent time points and tendons did not return to pre-exercise values until 24 h (fig 1).

The recovery of Achilles tendon thickness following eccentric exercise was adequately fit (root mean square error 0.02, r^2 0.96)

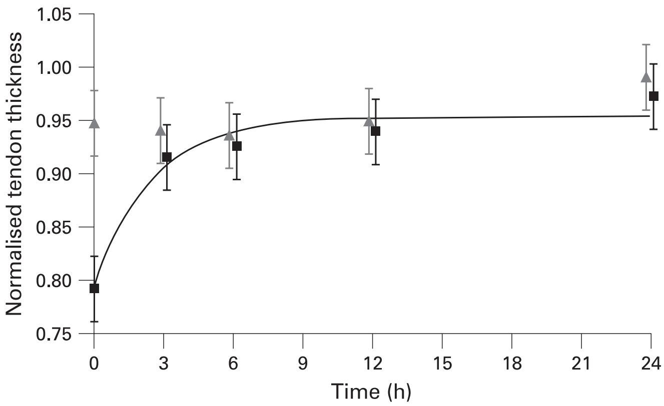

Figure 1 Mean Achilles tendon sagittal thickness normalised for pre-exercise values following eccentric (■) and concentric (▲) calf muscle exercise. Error bars represent 95% confidence intervals. Exponential fit representative of the eccentric recovery time course (—). For clarity, data points have been shifted either side of the specified time points at which they were observed.

by the exponential function $f(t) = a^*(1-\exp(-t/T1))+c$, where $a = 0.26$, $c = 0.79$ and $T1 = 2.50$ (fig 1). The time constant for tendon thickness recovery following eccentric exercise was 2.5 h, which is representative of a 63% recovery in tendon thickness. Since the model fit is primarily determined by the initial post-exercise response magnitude and, as shown in fig 1, the concentric data did not change significantly over the recovery period, the exponential function was not applied to the concentric data.

DISCUSSION

Eccentric loading of the Achilles tendon is a widely implemented rehabilitation technique for Achilles tendinopathy and is suggested to be more effective than techniques that do not directly stress the tendon.[14] Although mechanical loading is known to be crucial for tendon remodelling,[18] mechanisms underlying a beneficial effect of eccentric, as opposed to concentric, loading are unclear. The current investigation is the first to demonstrate that eccentric and concentric loadings invoke different Achilles tendon thickness responses, with eccentric loading producing a substantially greater reduction in tendon thickness immediately post-exercise when compared with the concentric loading condition.

In the current investigation, concentric and eccentric exercise at nominally equivalent stress and duration caused Achilles tendon thickness to decline by approximately 5 and 20%, respectively. The observed decrease in Achilles tendon thickness following both concentric and eccentric exercise is consistent with previous in vivo research, in which a heel raise exercise combining both eccentric and concentric muscle actions was shown to decrease the sonographically determined Achilles tendon thickness by approximately 15%.[19] Similarly, in vitro models have shown cyclic loading to exude water from the tendon, resulting in decreased tendon dimensions[20–22] and movement of water from the tendon core to the peritendinous space.[23 24] This extravasation of water has been attributed to crimp straightening and collagen realignment and stretching, producing lateral compressive forces between fibrils and a reduction in the interfibrillar space, giving rise to a positive hydrostatic pressure and thus fluid movement out of the tendon.[20 25]

These findings are in contrast to those of Shalabi *et al*,[26] in which sagittal plane magnetic resonance imaging (MRI)-based measures of Achilles tendon volume and intratendinous signal were reported to increase immediately following eccentric and concentric exercise in individuals with mid-portion tendinopathy. While methodological differences between the studies prevail, it is possible that tendinopathy may mediate the acute response of tendon to exercise, such that it responds in the opposite manner to normal healthy tendon. Further research is required to ascertain whether this is the case.

Differences in eccentric and concentric muscle activation patterns may be responsible for the differential effect on tendon thickness observed between exercise protocols. Eccentric muscle actions are characterised by the ability to generate greater muscle forces for a lower level of electromyographic activity, inferring that the number of motor units required to generate a specific force during lengthening is less than the number required during shortening.[27 28] Activation of fewer motor units would result in a less uniform stress distribution within the tendon, greater shear stress concentrations within the matrix and higher localised collagen strain,[29] which, in turn, would enhance collagen straightening, potentially leading to greater mobilisation of water from the tendon.[20 25]

Tendon strain, fluid flow and associated fluid-induced shear stress are known to be important for stimulation of tendon remodelling[30–32] and the provision of nutrition.[33] It is tempting to speculate that eccentric exercise may generate greater strain and fluid flow within tendon, as evidenced by a greater thickness change, and may as a consequence provide insight into why eccentric exercise is a more effective treatment strategy than concentric exercise.

Consistent with the principles of viscoelastic theory,[17] tendons loaded via eccentric muscle actions recovered exponentially upon unloading, with 63% of tendon thickness recovered in approximately 2.5 h. The response to concentric loading could not be adequately modelled using the Kelvin–Voigt exponential function due to the relatively small initial response. The large discrepancy between initial tendon thickness response to eccentric and concentric exercise dictates the different patterns of recovery or change observed over the first 3 h. Beyond the 3 h time point, however, the thickness of tendons loaded via different exercise protocols did not differ significantly and, in both cases, full tendon thickness recovery was not achieved until 24 h post-exercise. Thus, subsequent to the first 3 h, the recovery of tendons loaded via different exercise protocols would appear to follow essentially the same pathway.

This study has a number of important limitations. Tendon thickness was measured at one specific site (2 cm proximal to the superior aspect of the calcaneus) and, due to variations in tendon structure along the length, the findings may not be generalised to other sites within the tendon. While participants

Table 1 Mean (standard deviation) sagittal thickness (mm) of Achilles tendons allocated to eccentric or concentric exercise protocols

Time	Pre	Immediate	3 h	6 h	12 h	24 h
Eccentric (n = 11)	4.4 (0.3)	3.5 (0.2)*	4.1 (0.3)	4.1 (0.3)	4.2 (0.3)	4.3 (0.4)
Concentric (n = 11)	4.5 (0.4)	4.3 (0.5)	4.2 (0.5)	4.2 (0.4)	4.3 (0.3)	4.5 (0.4)

*denotes statistically significant difference between exercise protocols.

were requested to refrain from physical activity beyond that required to perform essential daily activities, incidental activity during the recovery period may have influenced tendon thickness recovery. Future studies should, therefore, endeavour to either account for or restrict incidental activity. Moreover, these findings are applicable to healthy tendons only. Although it is expected that tendinopathic tendons would respond to eccentric and concentric exercise in a similar manner, this is currently unknown and requires further investigation.

Nonetheless, the findings of the current study demonstrate that, despite a similar loading impulse, eccentric exercise results in a greater reduction in Achilles tendon thickness than concentric exercise. Further research is required to ascertain whether the observed changes reflect fluid movement within tendon and are beneficial in tendon remodelling.

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