The mechanism for efficacy of eccentric loading in Achilles tendon injury; an in vivo study in humans

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Objective. Degenerative disorders of tendons present an enormous clinical challenge. They are extremely common, prone to recur and existing medical and surgical treatments are generally unsatisfactory. Recently eccentric, but not concentric, exercises have been shown to be highly effective in managing tendinopathy of the Achilles (and other) tendons. The mechanism for the efficacy of these exercises is unknown although it has been speculated that forces generated during eccentric loading are of a greater magnitude. Our objective was to determine the mechanism for the beneficial effect of eccentric exercise in Achilles tendinopathy.

Methods. Seven healthy volunteers performed eccentric and concentric loading exercises for the Achilles tendon. Tendon force and length changes were determined using a combination of motion analysis, force plate data and real-time ultrasound.

Results. There was no significant difference in peak tendon force or tendon length change when comparing eccentric with concentric exercises. However, high-frequency oscillations in tendon force occurred in all subjects during eccentric exercises but were rare in concentric exercises (P < 0.0001).

Conclusion. These oscillations provide a mechanism to explain the therapeutic benefit of eccentric loading in Achilles tendinopathy and parallels recent evidence from bone remodelling, where the frequency of the loading cycles is of more significance than the absolute magnitude of the force.

Key words: Tendon, Eccentric exercise, Efficacy.

Introduction

The management of degenerative disorders of tendons is an enormous clinical challenge. Tendon disorders are extremely common, existing medical treatments are generally unsatisfactory and surgical treatments unpredictable [1–3]. Historically it was believed that tendons were fairly inert structures and rest or immobilization was suggested as a treatment. However, over time the negative effects of rest and immobilization have become recognized and there has been a move towards early functional treatment [4, 5]. Until recently there was much support for the use of NSAIDs and local corticosteroid injections [6]. However, it is now appreciated that chronic tendon disorders are predominantly degenerative in nature and anti-inflammatory strategies are largely ineffective [1, 6]. Various suggestions have been made to account for the pain in chronic tendinopathy. Histological assessment of chronic tendinopathy is devoid of inflammatory cells [7]. Microdialysis of the injured Achilles tendon (AT) has confirmed the presence of the neurotransmitter glutamate [8]; substance P [9] has also been implicated in the aetiology of the pain arising from a chronically injured tendon. Why degenerative tendinopathy is only sometimes painful remains unknown.

Recently there has been an increasing interest in the use of eccentric loading in treatment of chronic degenerative disorders of tendon. In an eccentric contraction, the muscle–tendon unit lengths as a load is applied to it. This is in contrast to concentric loading where the muscle–tendon unit shortens (Fig. 1). In 1986, in a prospective study of 200 patients with chronic Achilles tendinopathy, Stanish et al. [4] reported that a once-daily, 6-week eccentric loading programme led to complete relief of pain in 44% and a marked improvement in symptoms in a further 43% of the patients. Unfortunately, the study was weak methodologically (there were no control subjects) and the technique was not widely adopted. More recently, Alfredson confirmed the efficacy of eccentric loading for mid-substance lesions of the AT in prospective randomized trials [10, 11]. Other groups have studied eccentric loading and high success rates (of at least 60% either good or excellent) have also been reported [12–14]. This technique has been successfully extended to the patella and supraspinatus tendons and its use has become widespread, particularly over the last 5 yrs [15–18].

The mechanism for the efficacy of eccentric loading is unknown. Stanish and colleagues [4, 19] proposed that in eccentric loading the tendon is subjected to greater forces than in concentric loading and hence to a greater re-modelling stimulus. Whilst there is evidence from Komi [20] that eccentric contractions can develop greater forces in muscle during dynamic movements, this evidence does not extend to the exercises in the Stanish (or Alfredson) eccentric loading protocol. During sonography of the eccentrically loaded AT, Alfredson observed a temporary compression of the new vessel formation (neovascularization) that often accompanies degenerative Achilles tendinopathy. Although there are some (uncontrolled) data to suggest eccentric loading may lead to a normalization of tendon structure in the long term [21], there is no evidence to suggest that temporary interruption of the blood supply accounts for its efficacy. The optimum exercise ‘dose’ is unknown, both in terms of numbers of repetitions and also the speed of movement; neither is the optimum duration of treatment known. The exercises frequently cause discomfort and, although highly effective for tendinopathy of the body of the Achilles, are more usually ineffective at treating insertional tendon lesions of this tendon [22].

We hypothesize that eccentric loading of the AT results in a fundamentally different physiological loading pattern and stimulus to that seen in concentric loading. We tested this hypothesis by determining tendon length and force during concentric and eccentric exercises in healthy subjects.

Materials and methods

Materials and general procedure

We utilized a method that combines real-time ultrasonography (US) and motion analysis with concurrent force and
EMG recording. This technique has previously been described and successfully used to determine the \textit{in vivo} mechanical properties of the human AT during one-legged hopping [23]. By simultaneously determining AT length and the force acting through the tendon during both concentric and eccentric loading exercises, we directly compared the physiological stimulus with the AT during the two exercises. Additionally, EMG data from the major lower leg muscles were collected on three of the subjects to enable us to study the pattern of muscle activation.

The AT length was defined as the distance between the medial gastrocnemius muscle tendon junction (MTJ) (tendon origin) and the tendon insertion (at the calcaneum). In order to determine the AT length, we needed to establish the position of both these anatomical sites in terms of 3D coordinates over time (i.e. dynamically). By using the Codamotion (CODA) active marker motion analysis system (Charnwood Dynamics, Leicester, UK), the position of the tendon insertion could be tracked. The position of the MTJ was determined by a combination of US and motion analysis. The MTJ was imaged dynamically by a PC-based (US) system (Echoblaster 128, UAB Telemed, Vilnius, Lithuania) and the precise position of the US probe itself was synchronously measured by the CODA system. Electronic synchronization of the two systems then allowed us to determine the position of the MTJ relative to the tendon insertion and hence determine overall tendon length. The 3D ground reaction force was measured using a 600 x 400 mm$^2$ force plate (Bertec Corporation, Columbus, OH, USA). The ankle joint centre was estimated by creating a virtual point relative to markers on medial and lateral malleolus corresponding to an approximation of the centre of rotation of the ankle joint. AT force was calculated by dividing the ankle joint point relative to markers on medial and lateral malleolus.

The exercises should be performed [7]. Subjects were therefore asked to perform the exercises in a controlled moderate speed manner. For each subject, three 10-s data sets were collected for each of the four separate exercises. Some subjects needed to steady themselves by holding onto a chair but they were instructed not to push up on it.

Five individual cycles of data from each of the four exercises described above were randomized and then analysed in order to avoid systemic bias. For each data set it was necessary to determine the position of the MTJ on the video recording (at 50 Hz) of the US trace. From this it was possible to determine the AT length. AT force and ankle angle were also determined in accordance with our previously described method [23].

\textbf{Exercises, data collection and data analysis}

We adopted the ‘Alfredson’ protocol for eccentric loading [10]. The subject stands on the toes of one foot with the heel raised; the subject then lowers the heel in a controlled manner. The exercise is performed over a step to increase the distance that the heel (and hence whole body) may be lowered (Fig. 1). For the concentric exercise, we used the subject starting with the heel below the toes and raised the heel (and hence body) during the exercise. This particular concentric exercise was one of the exercises in the Alfredson concentric comparison group [11]. Concentric and eccentric exercises were both performed with the knee extended and with the knee flexed.

The subjects were shown how to perform the exercises by the lead author (J.D.R.). At the start of the exercise all of the weight would be on the studied leg. At the end of the exercise the subjects would then transfer their weight to the non-study leg, which was used to help get the subject back to the start position. In the Alfredson protocol, there is no mention of the speed at which the exercises should be performed [7]. Subjects were therefore asked to perform the exercises in a controlled moderate speed manner. For each subject, three 10-s data sets were collected for each of the four separate exercises. Some subjects needed to steady themselves by holding onto a chair but they were instructed not to push up on it.

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\textbf{Statistical analysis}

Data for tendon length and peak AT force were tested for normality of distribution by plotting them and performing a Shapiro–Wilks W test showing that both parameters were close to a normal distribution. Residuals were also plotted after the statistical test and the models were observed to be a good fit for the data. Tendon length and peak AT force were then analysed using a general linear model in Statistica AXA 8.0 (Statsoft, Tulsa, OK, USA) with subject and exercise modality as fixed factors. Data are presented with 95% CIs. \textit{P}-values <0.05 were considered statistically significant.

\textbf{Fig. 1.} Eccentric and concentric loading of the Achilles tendon. (A) Image showing the starting position for eccentric loading. The Achilles tendon lengthens as the heel is lowered below the level of the forefoot (B). Concentric loading involves shortening of the Achilles tendon and is the reverse procedure. Figure reproduced from Ref. [1].

\textbf{Research subjects}

Seven adult participants (average age range 19–41 yrs) gave written consent to take part in the study, which was approved by the hospital ethics committee. There were four male and three female participants. This male:female ratio was similar to that used in the original Alfredson study [10]. In none of the participants was there a past history of AT disorder. The subjects' weight and height were recorded.
Results

During heel lowering the AT length increased through the movement and during heel rise AT length decreased, which we attributed to the dynamics of the movement being different (see Discussion). The length changes were not significantly different when comparing concentric and eccentric exercises ($P = 0.23$). During concentric movement tendon length decreased on average by 14.9 mm (95% CI $\pm 1.9$ mm), and during eccentric movement tendon length increased by 13.6 mm on average (95% CI $\pm 1.6$ mm).

Peak AT forces during both eccentric and concentric exercises showed minimal (non-significant) intra-subject variability (Fig. 2). There was a much more marked variation in calculated peak AT force between subjects, however, and there was a linear relationship between maximum tendon force and body mass for both eccentric and concentric loading ($R^2 = 0.59$ and 0.49, respectively).

The pattern of loading/unloading of the tendon was different between concentric and eccentric loading. In Fig. 3, the typical relationship of derived AT force and AT length over time for two subjects during concentric and eccentric movement is shown. As expected, for the concentric exercises peak force occurs at the start of the exercise (raising the heel and accelerating the body upwards against gravity), and for eccentric exercises peak force occurs at the end of the exercise (decelerating the centre of mass at the end of the movement thus overcoming gravity and momentum). In essence, AT force rises through the course of an eccentric loading movement and falls during a concentric loading movement.

In eccentric exercises, there was a very smooth force trace. However, the eccentric movement pattern consistently demonstrated a sinusoidal waveform appearance with frequent ‘inversions’ of the force trace. Indeed, over all eccentric observations there were, on average, two force inversions per cycle (1.94 inversions per cycle, 95% CI $\pm 0.54$). For concentric loading force inversions were uncommon and occurred less than once every two cycles (0.47 inversions per cycle, 95% CI $\pm 0.28$). Furthermore, when the inversions did occur in concentric movements they tended to occur early in the cycle and not during the main part of the exercise, and hence not during rapid tendon shortening or lengthening.

Whilst the individual number of inflexions per trial was not a normally distributed or continuous variable, the average number of inflexions per subject (across all the trials) passed tests for normality of distribution and a $t$-test was performed on these figures. This difference was highly significant ($P = 0.00004$). The analysis was repeated using a Kolmogorov–Smirnov non-parametric test and a high level of significance shown. Typical plots of each of two representative subjects are presented (Fig. 3), as are data on number of inversions for all subjects (Fig. 4).

In three subjects, EMG data were simultaneously collected from the gastrocnemius and from tibialis anterior as the main representative of the antagonist muscle group. The data showed similar values for root mean square (RMS) signal for gastrocnemius activation for both concentric and eccentric loading. Tibialis anterior tended to have higher RMS values both at the start of concentric loading and at the end of eccentric loading, suggesting that this muscle may have a role in the initiation of concentric loading and the termination of eccentric loading.

Discussion

Eccentric loading regimes have been shown in clinical trials to offer promise for mid-substance tendon lesions, particularly of the AT. This is the first article to examine the mechanism by which eccentric loading is effective.

Our data show that at the start of concentric movement the calf muscles are activated, the AT length decreases and the subject accelerates upwards and then slows to a halt. The peak derived AT force occurs at the beginning of the exercise when the subject is accelerating against gravity. In the eccentric movement, the subject starts to drop ‘under control’. The movement is controlled (resisted) by lengthening of the activated calf muscle and by stretching of the AT. The maximal derived AT force occurs at the end of the eccentric movement when maximum force is required to decelerate the subject against gravity.

Our results show that peak tendon forces in eccentric loading are of the same magnitude as those seen in concentric loading. This means that tendon force magnitude, as originally suggested by Stanish et al. [4], alone cannot be responsible for the therapeutic benefit seen in eccentric loading. Furthermore, the data on AT length change, confirming that both concentric and eccentric exercises have the same magnitude of length change and are also supportive of the force being the same for both exercises.

If the efficacy of eccentric loading cannot be explained by the magnitude of force, then what is responsible? Intriguingly, we observed a pattern of sinusoidal loading and unloading in eccentric loading. The fluctuations in force probably reflect the difficulty in controlling a dynamic movement with a lengthening muscle, similar to the experience that it is easier to lift a heavy weight under precise control than to lower the same weight. We propose that these fluctuations in force may provide an important stimulus for the re-modelling of tendon. Certainly in the remodelling of bone it is known that bone responds to high frequency loading and appropriate mechanical signals can lead to a dramatic increase in bone density [24]. These force fluctuations provide a possible explanation for the therapeutic benefit seen. Whilst the number of inflexions appears to represent a small change in the mechanical environment of the tendon, the fluctuation in the force and length in the muscle tendon unit will be much greater that that observed externally due to the mechanical low pass filtering effects of the inertia of the foot and limb. It is likely that additional higher frequency oscillations also exist in the muscle tendon unit, which are not apparent in the external forces. Our data were collected in healthy subjects and it is possible that in injured patients the eccentric control is impaired thus leading to even more pronounced force fluctuations than those demonstrated in the healthy subjects.

During the ageing process tendinous tissue becomes more compliant [25]. Resistance exercises can mitigate this reduction in tendon stiffness and may therefore reduce tendon stress and risk of injury possibly enabling the tissue to operate closer to the

![Fig. 2. Maximum (peak) AT force (N/S) during concentric and eccentric loading. There was no significant difference in the maximum AT force between concentric and eccentric exercises. Vertical bars are 95% CIs.](http://rheumatology.oxfordjournals.org/)

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optimum region of the length–tension relationship [26]. Eccentric loading exercises may be particularly effective in increasing tendon stiffness.

A potential criticism of our method is that our data were collected using inverse dynamics rather than from direct measurements, such as those from a directly implanted transducer around the AT [27] and does not take into account the contribution from the antagonist muscle group (tibialis anterior in particular). However, we do not believe that this invalidates our conclusions. Our method is less invasive and has been shown to be reliable in previous studies [23]. Furthermore, the antagonist muscles are small in comparison with the gastrocnemius and soleus complex. And, as they oppose the calf muscles in both concentric and eccentric movements, their effect will at least in part cancel out.

Our technique of ‘tracking’ the Achilles MTJ frame by frame initially suggests that during eccentric loading the tendon is operating at a shorter range than during concentric loading. Since the tendon is never unloaded, we cannot discriminate between whether the shape of the MTJ is different during either a concentric or eccentric contraction and it is possible (or probable) that a different point of interest of the MTJ is tracked in each of the two exercises. An alternative, or contributory, explanation is that the tendon is longer throughout eccentric loading cycle than during concentric loading cycle.

The speed of the eccentric movement, and its relationship to force fluctuations, is of particular interest and worthy of further research. It may be that a protocol with faster eccentric movements (such as a protocol with a progressive increase in the speed of the eccentric exercises) will lead to greater force fluctuations and hence a greater re-modelling stimulus. This is the first article to examine why eccentric loading is successful as a therapeutic intervention for mid-substance lesions of the AT. We suggest that the pattern of tendon loading, with its force fluctuations, rather than the magnitude of the force, is responsible for the therapeutic benefit seen. This parallels evidence from bone remodelling. The challenge now is to improve eccentric loading protocols, and hence outcome, for tendinopathy. Greater understanding of the tendon loading pattern should lead to improved rehabilitation protocols.

![Graph showing force characteristics for eccentric and concentric loading of the AT.](http://rheumatology.oxfordjournals.org/)

**FIG. 3.** Force characteristics for eccentric and concentric loading of the AT. In eccentric loading the AT is subject to repeated unloading and loading in a sinusoidal-type pattern. In concentric loading, this additional loading and unloading is largely absent. Typical examples are shown for one female (subject 1) and one male (subject 2). Eccentric loading is shown in the top two graphs and concentric loading in the bottom two graphs.

**FIG. 4.** Mean number of inflexions per cycle for each subject/activity. No error bars due to low number of potential values. Inflexions of the AT force pattern occurred much more frequently during eccentric loading of the AT rather than during concentric loading for all subjects ($P < 0.0001$).
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References