



Original research

The effect of exercise repetition on the frequency characteristics of motor output force: Implications for Achilles tendinopathy rehabilitation



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ABSTRACT

Objectives: To investigate the frequency characteristics of the ground reaction force (GRF) recorded throughout the eccentric Achilles tendon rehabilitation programme described by Alfredson.

Design: Controlled laboratory study, longitudinal.

Methods: Nine healthy adult males performed six sets (15 repetitions per set) of eccentric ankle exercise. Ground reaction force was recorded throughout the exercise protocol. For each exercise repetition the frequency power spectrum of the resultant ground reaction force was calculated and normalised to total power. The magnitude of peak relative power within the 8–12 Hz bandwidth and the frequency at which this peak occurred was determined.

Results: The magnitude of peak relative power within the 8–12 Hz bandwidth increased with each successive exercise set and following the 4th set (60 repetitions) of exercise the frequency at which peak relative power occurred shifted from 9 to 10 Hz.

Conclusions: The increase in magnitude and frequency of ground reaction force vibrations with an increasing number of exercise repetitions is likely connected to changes in muscle activation with fatigue and tendon conditioning. This research illustrates the potential for the number of exercise repetitions performed to influence the tendons' mechanical environment, with implications for tendon remodelling and the clinical efficacy of eccentric rehabilitation programmes for Achilles tendinopathy.

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1. Introduction

Eccentric exercise has become the treatment of choice for mid-substance Achilles tendinopathy.¹ However, little is known about the optimal loading parameters required to expedite recovery in tendinopathy.^{1,2} The eccentric rehabilitation programme first described by Alfredson et al.³ for treatment of Achilles tendinopathy has been widely advocated^{4–6} and involves the completion of six sets of eccentric exercise, each comprised of 15 repetitions, twice daily. However, a number of studies that have evaluated the efficacy of eccentric loading in Achilles tendinopathy have used fewer exercise repetitions, particularly within the initial weeks of the rehabilitation programme.^{7–9} While reducing the number of exercise repetitions in order to reduce muscle soreness and aid compliance is common, the impact of this on patient outcome is not

known and yet, has the potential to account for discrepancies in the efficacy of eccentric exercise reported in the literature. For instance, 60% of participants reported being satisfied with **the outcomes of** eccentric exercise protocols which involved the performance of three sets of 15 repetitions twice daily^{7,9} whereas, 82–100% of participants were satisfied with **the outcomes of** eccentric exercise protocols which involved six sets of 15 repetitions twice daily.^{3,10,11}

An in-depth biomechanical comparison of the eccentric ankle exercise described by Alfredson et al.³ and an equivalent concentric exercise, recently demonstrated that, in healthy adults, ground reaction force (GRF) recorded during eccentric exercise was characterised by greater signal power in the 8–12 Hz bandwidth when compared to that recorded during concentric exercise.¹² The authors subsequently suggested that higher magnitude 8–12 Hz vibrations may play a role in the stimulation of tenocytes and, hence, may be associated with the beneficial effect of eccentric but not concentric loading in tendinopathy rehabilitation.¹² Interestingly, research in the field of motor control has shown that the magnitude and frequency of vibrations in the 8–12 Hz

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bandwidth, generated during isometric muscle actions (often referred to as physiological tremor), increase with muscle fatigue.^{13–15} Consequently, the number of eccentric exercise repetitions performed may well influence the magnitude and frequency of 8–12 Hz vibrations generated during eccentric rehabilitation programmes and, in part, account for the varied efficacy of eccentric exercise reported in the literature.

The aim of the current research was, therefore, to investigate the frequency characteristics of the GRF recorded throughout the eccentric Achilles tendon rehabilitation programme described by Alfredson et al.³ It was hypothesised that the magnitude and frequency of peak power within the 8–12 Hz bandwidth would increase with successive exercise sets.

2. Methods

Nine healthy male adults without a medical history of neuromuscular disease, Achilles tendon pain or calf muscle injury participated in the research. The mean ($\pm$ S.E.) age, height and mass of participants were 48.2 ± 3.8 years, 181.6 ± 2.0 cm and 97.3 ± 6.9 kg, respectively. The study received University Human Research Ethics approval and all participants provided written informed consent.

Lower limb kinematics and GRF were recorded while participants performed a widely implemented eccentric exercise protocol used for the therapeutic management of Achilles tendinopathy.³ The protocol involved isolated eccentric loading of the Triceps Surae muscle tendon unit of a single limb. For eccentric loading participants initially stood with their ankle maximally plantarflexed and their forefoot positioned on the edge of a step. Eccentric loading occurred as the heel was lowered below the level of the forefoot to a position of maximal dorsiflexion. No concentric loading followed. Rather, the forefoot of the previously non-weightbearing contralateral limb was placed on the step. All weight was then transferred to this limb which was used to return the body to the start position. The process was repeated 15 times per exercise set **and while the rate of eccentric loading was not specifically controlled, participants were instructed to lower the heel slowly over a period of approximately two seconds.** Consistent with the clinical protocol cited by Alfredson et al.³ three exercise sets were performed with a straight knee and three with the knee slightly flexed. **Participants were provided with a rest period of two minutes between each exercise set.** In order to standardise knee position, participants performed the exercise protocol wearing a post-operative knee brace (Donjoy T-ROM, DJO, LLC, Vista, CA, USA), which effectively immobilised the knee at 0° and 20° of flexion. The exercise protocol was performed without footwear and the allocation of the left or right limb to eccentric exercise was counter balanced across participants.

The orientations of lower limb segments were recorded by an eleven camera motion analysis system sampling at 200 Hz (Vicon, Oxford Metrics Group, Oxford, England). The PlugInGait (SCAR) model within Vicon Nexus (version 1.4.116, Vicon, Oxford Metrics Group, Oxford, England) was used to model the lower body as seven rigid segments (pelvis, right and left upper leg, lower leg and foot segments).¹⁶ The model required the attachment of 15 passive markers ($\varnothing$ 14 mm) to the participant. Markers were attached bilaterally to the dorsum of the second metatarsal head, lateral malleolus, posterior superior calcaneus, mid-tibia, lateral femoral condyle, mid-thigh and anterior superior iliac spine. A marker was also positioned on the midpoint of the sacrum.

A force plate (OR6-6200 Advance Mechanical Technology Inc., Watertown, MA, USA) sampling at 1000 Hz was used to record GRF during the eccentric exercise protocol. To allow maximal ankle joint dorsiflexion, a solid wooden step (90 mm high) was mounted at the middle of the force plate. The step was confined entirely within the

borders of the force plate and ensured that the body was centred over the plate. It was assumed that no deformation of the wooden step occurred during exercise performance. GRF and kinematic data were synchronised by the Vicon Nexus system.

All marker displacements and joint kinematics were calculated by Vicon Nexus. Kinematic and GRF data were segmented using MATLAB software (version R2008a, The MathWorks Inc., Natick, MA, USA). Vertical displacement of the second metatarsal head and calcaneus was used to isolate the 15 repetitions in each set of eccentric exercise. Maximum and minimum sagittal joint angles and joint range of motion (ROM) were calculated for the knee and ankle joints. The average angular velocity of the ankle joint was also determined.

The resultant GRF (GRFres) was calculated **by taking the Euclidean norm of the three dimensional force vectors**, that is $GRFres = \sqrt{Fx^2 + Fy^2 + Fz^2}$, where Fx represents the GRF in the x (anterior posterior) direction and likewise for Fy (medial lateral) and Fz (vertical). Following removal of the mean offset (body-weight), the GRFres was high-pass filtered, with a 0.5 Hz cut-off frequency, in order to remove the trend associated with whole body movement. For all exercise repetitions 99% of the spectral energy was below 15.5 Hz. Consequently, the residual content above 20 Hz was removed by low-pass filtering. Low- and high-pass filtering was conducted using linear-phase finite impulse response (FIR) filters with even-order, symmetric filter coefficients (Type I). Filtered data were then down-sampled from 1000 Hz to 100 Hz, zero-padded to 4096 sample points and Fourier transformed to calculate the magnitude power spectrum. Given the potential for differences in total power of the magnitude spectrum between exercise repetitions, each magnitude spectrum was normalised to total power. Normalisation ensured that all spectra had a total energy value of unity and allowed quantification and comparison of the relative power contained within specified bandwidths of each magnitude spectrum. The relative spectral power was then summed over non-overlapping 1 Hz windows within the range 0.5–15.5 Hz.

The Statistical Package for the Social Sciences (version 17, SPSS Inc, Chicago, IL USA) was used for all statistical procedures. General linear models were employed to evaluate the effects of exercise set (1, 2, 3, 4, 5 or 6) on kinematic variables, the relative power within each frequency window and the peak relative power in the frequency range 8–12 Hz. Within each model, exercise set and participant were treated as random effects. The underlying assumption of normality of the residual variance was met in all cases. Significant main effects were investigated using custom hypothesis tests within the models, while significant interactions were investigated using pair-wise comparisons and 95% confidence intervals. Estimated marginal means and standard errors (SE) calculated by the linear mixed models are presented in the text.

3. Results

Sagittal knee and ankle joint angles are illustrated in Fig. 1. Peak knee flexion and extension angles were not significantly different between exercise sets 1, 2 and 3. The knee brace successfully ensured that knee flexion was significantly greater, approximately 18°, in exercise sets 4–6 compared to sets 1–3 ($P < 0.05$). The knee did, however, gradually extend over the final three sets ($\approx 8^\circ$) and as such, peak flexion and extension angles were significantly lower in set 6 compared to set 4 ($P < 0.05$, Fig. 1). Nevertheless, there was no statistically significant difference in knee joint ROM between any of the exercise sets.

There were no statistically significant differences in peak ankle dorsiflexion, peak ankle plantarflexion or ankle joint ROM between any of the exercise sets (Fig. 1). Similarly, the average angular velocity of the ankle joint did not vary significantly across the six exercise

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