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Research article

Investigating the Effects of Knee Flexion during the Eccentric Heel-Drop Exercise

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Abstract

This study aimed to characterise the biomechanics of the widely practiced eccentric heel-drop exercises used in the management of Achilles tendinosis. Specifically, the aim was to quantify changes in lower limb kinematics, muscle lengths and Achilles tendon force, when performing the exercise with a flexed knee instead of an extended knee. A musculoskeletal modelling approach was used to quantify any differences between these versions of the eccentric heel drop exercises used to treat Achilles tendinosis. 19 healthy volunteers provided a group from which optical motion, forceplate and plantar pressure data were recorded while performing both the extended and flexed knee eccentric heel-drop exercises over a wooden step when barefoot or wearing running shoes. This data was used as inputs into a scaled musculoskeletal model of the lower limb. Range of ankle motion was unaffected by knee flexion. However, knee flexion was found to significantly affect lower limb kinematics, intersegmental loads and triceps muscle lengths. Peak Achilles load was not influenced despite significantly reduced peak ankle plantarflexion moments ($p < 0.001$). The combination of reduced triceps lengths and greater ankle dorsiflexion, coupled with reduced ankle plantarflexion moments were used to provide a basis for previously unexplained observations regarding the effect of knee flexion on the relative loading of the triceps muscles during the eccentric heel drop exercises. This finding questions the role of the flexed knee heel drop exercise when specifically treating Achilles tendinosis.

Key words: Achilles, tendinosis, tendinopathy, rehabilitation.

Introduction

Many conservative and surgical options have been developed and used to treat Achilles tendinopathies (Magnussen et al., 2009). Over time, the eccentric heel-drop exercises proposed by Alfredson et al. (1998) have become the treatment of choice for Achilles tendinosis. These exercises are widely practised, with studies assessing both short and longer term efficacy of the treatment (Kujala et al., 2005; Kingma et al., 2007; Magnussen et al., 2009; van der Plas et al., 2012). Despite a lack of evidence to support the biochemical changes expected with increased tendon loading (Khan and Scott ,2009), improvements in the tendon structure have been reported following eccentric heel-drop exercises (Ohberg et al., 2004). However, while the clinical outcomes are promising, the underlying aetiology of the condition is not known, with abnormal hindfoot kinematics (Donoghue et al., 2008) and altered triceps activation (Wyndow et al., 2010; Wyndow et al., 2013) during running being linked to pathological changes in the Achilles tendon. Furthermore, the biomechanical factors believed to drive the tendon healing process are unclear, with oscillations of Achilles tendon load (Grigg et al., 2013), tendon strengthening and stretching programmes (Kader et al., 2002; Allison and Purdam, 2009) and intra-tendon shearing (Alfredson et al., 1998) all being speculatively linked to tendon healing. This last factor could be considered the target of the commonly adopted heel drop exercises, as the intention of performing the flexed knee exercise is to alter the relative loading between the Gastrocnemius and Soleus muscles, which can result in changes in intra-tendon shear (Hebert-Losier et al., 2009a). Critically however, while previous observations have focussed on the common features of the heel drop exercises, the biomechanical differences between the extended and flexed knee versions of the exercise have been minimally characterised, with functional outcomes, such as pain reduction and functional improvements serving as primary justification of the treatment protocol. Additionally, assessing the biomechanical differences of performing the exercise in shoes is important, as differences between performing the exercise in clinic, generally in shoes, and at home, generally barefoot, may further characterise the mechanics driving the healing process. It is known that differences in EMG activity exist across the triceps during walking (Farris et al., 2013) and running (Wyndow et al., 2013) and as such, it is possible that EMG activation across the triceps differs during the different versions of the heel-drop exercise (Henriksen et al., 2009). Reid et al. (2012) is the only study to investigate the effect of knee flexion on triceps EMG activity during the eccentric heel drop exercise and showed that an extended knee resulted in greater Gastrocnemius activation, with Soleus activation unaffected by knee flexion angle during the exercise. This observation was only partially in line with the mechanical changes proposed by Alfredson et al (1998) where flexion of the knee is expected to shorten the Gastrocnemius, consequently decreasing its activation, necessitating an increase in Soleus muscle activation. However, the reliance on EMG data alone to make clinical inferences is limiting, as it does not quantify any other biomechanical observations which may affect the conclusions drawn regarding the efficacy of the treatment as a whole. As changes in ankle kinematics during the flexed knee exercise have not been previously quantified and can influence triceps surae activation during heel raises (Hebert-Losier et al., 2009b), it is not possible to explain the lack of change in Soleus muscle activation through surface EMG measures alone. Therefore, it is hypothesised that changes in ankle kinematics due to the flexed knee could influence the moment arms of the triceps surae, counteracting any changes in activation caused by shortening the

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Gastrocnemius muscle. The primary aim of this study was to quantify changes in lower limb kinematics, muscle lengths and Achilles tendon force, when performing the exercise with a flexed knee instead of an extended knee. A secondary aim of this study was to quantify any differences in lower limb mechanics when performing the exercises barefoot or in running shoes.

Methods

Participants

Nineteen healthy individuals were recruited (8 male [mean (SD); age: 28 (3); height: 1.76m (0.10); mass: 73.4kg (12)] and 11 females [age: 29 (6); height: 1.63 (0.05); mass: 58.7kg (10.2)]), with no history of ankle injuries and no lower limb injury in the last 12 months and no clinical symptoms of Achilles Tendinopathies. Individuals were excluded if they had any been diagnosed with Achilles Tendinopathy or had any musculoskeletal or neuromuscular condition of the lower limb. The cohort size was chosen based on previous studies investigating differences in flexed and extended knee eccentric heel drop exercises with optical motion capture (Hebert-Losier et al., 2011b; Grigg et al., 2013),

Description of the exercise and equipment

To best replicate the setup employed at home and in clinic, a wooden step (400mm x 132mm x 132mm) was constructed to replicate a step similar to that that found at home. The step was sanded to provide a smooth and flat surface and the edges were rounded to provide a comfortable radius of curvature to stand on. The step itself was secured over the centre of a forceplate with a ratchet strap (Figure 1).

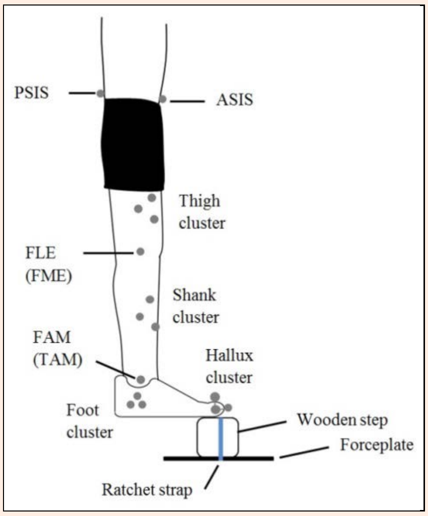

Figure 1. Sketch of the experimental setup and marker set. ASIS/PSIS –anterior/posterior superior iliac spines, FME/FLE – medial/lateral femoral epicondyles, TAM/FAM – medial/lateral malleolus. Marker labels in brackets (TAM and FME) have been omitted for clarity.

Subjects were instructed to perform the eccentric heel-drop exercise following the approach detailed by Alfredson et al. (1998). Briefly, this requires subjects to stand on tip-toe with their ankle in maximal plantarflexion, before lowering themselves in a controlled manner through eccentric loading of the calf to achieve maximum ankle dorsiflexion. Subjects then transfer their weight onto their other leg to concentrically raise their centre of mass before performing the exercise again. This exercise is performed with the knee extended and flexed. Subjects performed a minimum of five cycles using their right leg only and the exercise was considered to have been performed correctly if the subject went through their full range of ankle motion without excessive knee motion during the eccentric portion of the cycle and without the left foot touching the forceplate or wooden step. As knee flexion during the exercise was assessed by eye, if changes in knee flexion were substantial, subjects were asked to perform another cycle of the exercise. This was performed in barefoot and in running shoes (“shod”) and with the knee in extension and flexed to a target angle of 30 degrees (Table 1) (Hebert-Losier et al., 2012). Subjects were given verbal instruction to “maintain a moderate squat” for the knee flexed exercise with the intention that this would provide an achievable position for each subject to reliably return to each time. For the extended knee version of the exercise, subjects were instructed to “keep their knee straight throughout the cycle”. Subjects were given sufficient time to practice the exercise and to be able to perform the exercise without loss of balance and if the knee angle achieved during the knee flexed task was considered too great or too little by visual inspection, subjects were told to flex their knee accordingly.

Table 1. Summary of the four versions of the heel drop exercise assessed.

Abbreviation	Description of the leg position
“bare_ext”	Barefoot with the knee extended
“bare_flex”	Barefoot with the knee flexed
“shoe_ext”	In shoes with the knee extended
“shoe_flex”	In shoes with the knee flexed

Data collection and pre-processing

Optical motion (MX-series, Vicon Motion Systems, Oxford, UK) and forceplate (9628BA, Kistler, Winterthur, Switzerland) data were collected for all conditions and used as inputs to the musculoskeletal model (described below) for barefoot conditions. The vertical coordinate of the centre of pressure (CoP) in this coordinate system was set to the height of the wooden step (measured to be 132mm). For shod conditions, the use of an in-shoe plantar pressure measurement system (Pedar-X, Novel GmbH, Munich, Germany) was used to provide the CoP data for the musculoskeletal model for the shod condition. An in-shoe plantar pressure system was used for shod conditions, as this was considered to give a more accurate CoP value of loading under the foot, as the forceplate CoP in this setup may have resulted in projection errors due to the 132mm distance between the measurement and plantar surfaces. However, for completeness, the CoP values from the forceplate and plantar pressure insoles were compared post-hoc and no differences in CoP displacement or mean positions were found during the shod exercises (data not presented).

Optical motion and plantar pressure data were recorded at 100Hz and forceplate data was recorded at

1000Hz. Data were recorded continuously while the subjects performed repeated cycles of the exercise and only the portion of each cycle corresponding to a lowering of the heel was considered for processing. This was defined from the onset of a continuous decrease in lateral malleolar marker height until the first subsequent increase in malleolar height (Hebert-Losier et al., 2012; Grigg et al., 2013). The mean of the five trials was used to represent the subject's biomechanics during each version of the exercise. A cohort-average across all 19 subjects was then used for subsequent statistical analysis.

Lower limb musculoskeletal model

A unilateral model of the lower limb defined by optical markers placed on the pelvis and leg (Figure 1) was scaled according to body weight and height and implemented in Matlab (The Mathworks Inc), Additionally, the following foot landmarks were digitised relative to the clusters on the shoe using a calibration wand with a pointed tip and an RMS error of the digitised point less than 2mm: the Achilles insertion on the calcaneus, the first metatarsal head and base, the fifth metatarsal head and base and the tip of the second phalanx. This data was used to calculate the angles and inter-segmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics (Winter, 2009). Body segment parameters were defined for the leg using truncated cones with segment mass and radii of gyration defined by Diaz et al. (2006) and using a solid ellipsoid for the feet according to Challis et al. (2012). The hip and knee joints were modelled with three rotational degrees of freedom (DoF), the ankle as a saddle joint with two rotational DoF and the MTP as a hinge with one DoF (Weinert-Aplin, 2014). The muscle origins, insertions, via points and PCSA data from literature (Klein Horsman et al. 2007) were scaled according to segment length and implemented in the model to determine muscle forces for the 12 muscles (represented by 39 muscle elements) crossing the ankle joint using static optimisation of a summed muscle stress cubed cost function with maximum muscle bounds defined by a muscle's physiological cross-sectional area (PCSA) and a specific tension of 37.7N/cm (Haxton 1944). Whole muscle lengths were calculated from the scaled musculotendon unit (MTU) geometry data using only the muscle portion of the MTU lengths and are presented as muscle lengths normalised to the length calculated in a static standing position. Muscle activation is presented as a fraction of peak instantaneous muscle force to its maximum permitted force, as defined above (Rasmussen et al. 2001). For shod trials, external ground reaction force (GRF) and centre of pressure (CoP) data were spatially aligned with the plantar pressure data according to Fradet et al. (2009) and Saraswat et al. (2010).

Statistical analyses

Statistical analysis of the results was performed in Matlab 2010b using the Statistical Analysis Toolbox (The Mathworks Inc,). All data was checked for normality using a Kolmogorov-Smirnov test and unless otherwise stated, statistical comparisons consisted of a 2-way ANOVA (flexed knee vs. extended knee and shod vs. barefoot); the level of significance set at $p < 0.05$ for main effects and if significant, a Bonferonni correction was applied.

Results

A summary of the changes in lower limb mechanics during the eccentric heel-drop exercises due to knee flexion when barefoot or in running shoes are quantitatively summarized in Table 2.

Table 2. Summary of the biomechanical changes due to knee flexion for barefoot and in-shoe versions of the exercise.

		Barefoot			Shod		
		Extended Knee	**Flexed Knee**	***P*-value**	**Extended Knee**	**Flexed Knee**	***P*-value**
Kinematic outputs [Degrees]	**Mean hip adduction angle**	4.2 (4.0)	5.7 (4.5)	-	5.5 (3.2)	6.5 (3.3)	-
	Mean hip flexion angle	9.6 (6.7)	28.5 (8.3)	NC	8.2 (7.0)	27.3 (7.5)	NC
	Mean change in hip flexion angle	.5 (3.1)	-3.8 (4.9)	-	1.3 (3.8)	-2.8 (5.3)	-
	Mean knee adduction angle	12.1 (3.1)	10.1 (5.1)	-	11.4 (2.3)	9.2 (4.6)	-
	Mean knee flexion angle	-8.7 (7.5)	-35.3 (7.7)	NC	-7.2 (6.5)	-33.9 (6.4)	NC
	Mean change in knee flexion angle	2.6 (4.5)	9.1 (8.5)	<.001	-.2 (5.8)	6.4 (8.3)	.004
	Mean ankle inversion ROM	11.2 (4.0)	11.5 (5.9)	-	9.9 (3.8)	9.4 (4.4)	-
	Mean ankle angle at start	-17.7 (4.5)	-11.0 (5.9)	<.001	17.5 (7.3)	-10.4 (7.2)	<.001
	Mean ankle angle at end	23.5 (6.3)	27.5 (7.3)	.001	25.4 (6.2)	30.5 (4.6)	<.001
	Mean ankle flexion ROM	41.2 (7.4)	38.5 (7.6)	-	42.8 (7.8)	40.8 (6.7)	-
Inter-segmental moments [Nm/ (BW*ht)]	**Peak hip extension moment**	.28 (.06)	.35 (.11)	<.001	.25 (.08)	.32 (.11)	<.001
	Peak hip adduction moment	.28 (.06)	.35 (.12)	.001	.24 (.09)	.33 (.12)	<.001
	Peak knee extension moment	.13 (.05)	-.04 (.08)	<.001	.10 (.06)	-.07 (.07)	<.001
	Peak knee adduction moment	.13 (.05)	-.04 (.08)	<.001	.10 (.06)	-.07 (.07)	<.001
	Peak ankle plantar-flexion moment	-.75 (.04)	-.72 (.04)	<.001	-.76 (.09)	-.71 (.08)	<.001
	Peak ankle inversion moment	.09 (.07)	.10 (.07)	-	.05 (.05)	.05 (.04)	-
Force [BW]	**Peak Achilles tendon force**	3.02 (.50)	2.86 (.48)	-	2.76 (.50)	2.51 (.43)	-
Muscle activation [% F_{max}]	**Soleus**	.20 (.06)	.19 (.06)	-	.18 (.05)	.16 (.04)	-
	Gastrocnemius	.21 (.07)	.17 (.07)	-	.19 (.06)	.17 (.05)	-

Note: "start" and "end" refer to the start and end of the exercise, which is determined by peak ankle plantar-flexion and dorsi-flexion respectively and *P*-values correspond to differences due to knee flexion. NC – Not Compared.

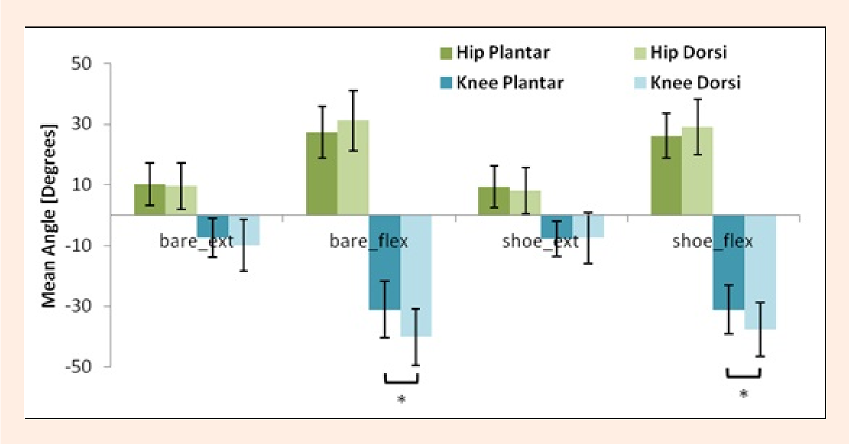

Figure 3. Comparison of mean hip and knee flexion angles for each heel-drop exercise. "Plantar" and "Dorsi" refer to when the ankle was at peak plantarflexion (start of the cycle) and peak dorsiflexion (end of the cycle) respectively. Positive values correspond to adduction and hip flexion and knee extension. * denotes statistically significant differences. For definitions of each exercise, the reader is directed to Table 1.

Kinematic changes

The ankle started in significantly greater plantarflexion during the extended knee exercise compared to the flexed knee exercise (Figure 2, left). At maximum dorsiflexion, the ankle remained more plantarflexed during the flexed knee exercise regardless of shoe condition (Figure 2, right).

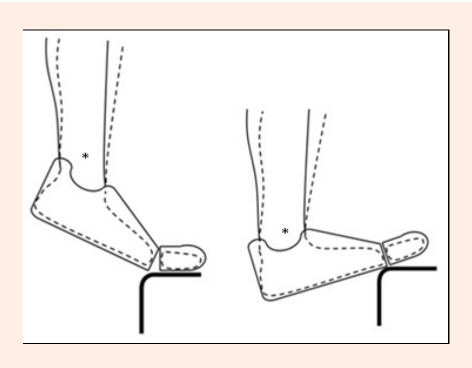

Figure 2. Illustration of the changes in ankle kinematics during the straight knee (solid line) and flexed knee (dashed line) heel drop exercise. * denotes a significant change in joint angle.

For the extended knee exercise, hip and knee flexion angles were maintained regardless of shoe condition (Figure 3). For the flexed knee exercise, hip angle was maintained, but knee flexion was significantly different between the start and end of the exercise (Figure 3, $p < 0.001$ and $p = 0.004$ when barefoot and shod respectively).

Inter-segmental moment changes

No differences in ankle inversion moment were observed due to knee flexion (Table 2). However, peak ankle flexion moment was significantly reduced with knee flexion. Changes in the relative moments between the hip and knee were observed, with greater hip extension and adduction moments and reduced knee extension and adduction moments when performing the flexed knee exercise.

No changes in peak Achilles tendon force were observed due to knee flexion (Table 2).

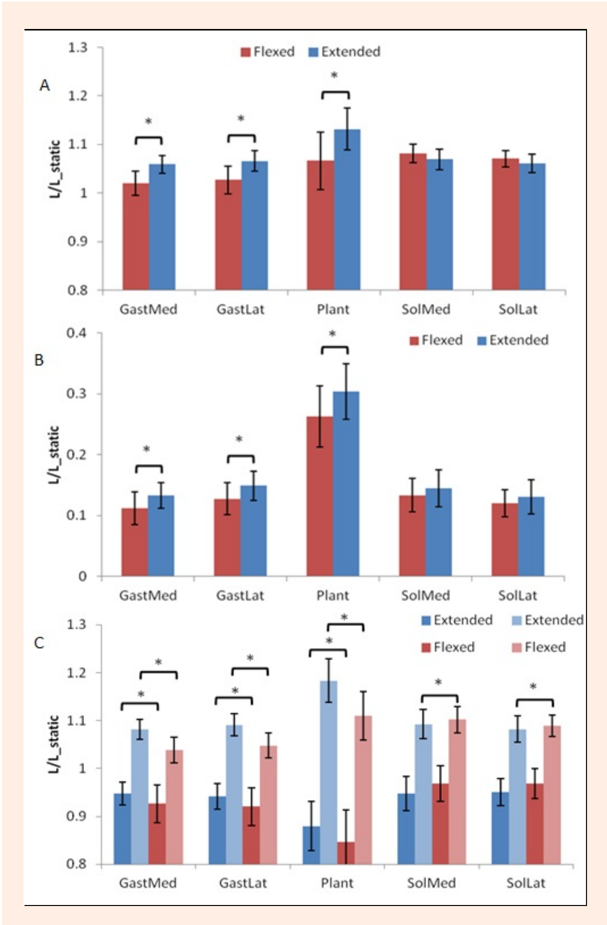

Figure 4. A) Relative triceps muscle lengths at peak Achilles tendon force for each exercise; B) Change in triceps length during each exercise; C) Maximum and minimum triceps lengths for each exercise. * denotes a statistically significant difference. GastMed/GastLat – Medial/Lateral heads of Gastrocnemius, SolMed/SolLat – Medial/Lateral portions of Soleus, Plant – Plantaris

Triceps muscle lengths

At peak Achilles force, whole muscle length of the medial and lateral heads of Gastrocnemius and Plantaris were found to be significantly reduced during the flexed knee exercise (Figure 4A). Interestingly, a decrease in biarticular muscle length *change* was observed during the flexed knee exercise only when barefoot, with no differences in mono-articular muscle length change (Figure 4B). The minimum relative length of each biarticular muscle was significantly shorter during the flexed exercise only when barefoot (Figure 4C). However, the minimum relative muscle length of Soleus was found to be larger during the flexed knee exercise.

Triceps surae activation

At peak Achilles tendon force, the relative activations of Soleus and Gastrocnemius were not different between knee flexion conditions when barefoot or in running shoes (Table 2).

Discussion

The main aim of this study was to quantify any differences between the extended and flexed knee versions of the recommended eccentric heel-drop exercise, to investigate the mechanics which drive the tendon healing process. Macroscopic outputs such as ankle range of motion, frontal plane kinematics and peak Achilles tendon force suggest little differences exist between the extended and flexed knee versions of the exercise. However, the observation that the ankle is essentially working in a more dorsiflexed position and the significant increases in knee flexion *during* the flexed knee exercises should be noted. This latter point in particular highlights a possible oversight by previous studies where only mean values of knee angles are reported during the flexed knee exercise. While not a directly comparable measure, increased variability in mean knee flexion angle during the flexed knee exercise has been previously reported (Hebert-Losier et al., 2011b) and as such, an increase in knee flexion angle during the flexed knee exercise should not invalidate the data, but could in fact be considered an unavoidable characteristic of the exercise. While it could be argued that significant changes in Soleus activation can only be achieved with substantial knee flexion during this exercise, a compromise between stability of the exercise and isolating the effects of knee flexion to the triceps surae has seen a seated squat position similar to that adopted here gain acceptance in practice (Hebert-Losier et al., 2009b).

Several observations from this study have implications for the clinical basis of treatment of this pathology. Achilles tendon load is a key output of this study, and the observed reductions in peak ankle plantarflexion moment without a corresponding reduction in peak Achilles tendon force when going from an extended to flexed knee warrant further discussion, particularly as the link between knee angle and Achilles tendon force is one of the reasons for incorporating a flexed knee version of the exercise.

Several factors will affect the Achilles tendon forces estimated here, including changes in ankle moments, ankle angle (affecting the mono-articular muscle moment arms) and knee angle (affecting the bi-articular muscle moment arms), and as such, a reduction in peak ankle plantarflexion moment alone should not be assumed to lead to a reduction in peak Achilles tendon load. Indeed, despite the statistical reductions in ankle plantarflexion moments, this was not reflected in peak Achilles tendon force, highlighting the importance of knee and ankle kinematics during this exercise. As knee flexion angle increased during the flexed knee exercise, this would have helped maintain the moment arm of Gastrocnemius. However, the increase in ankle dorsiflexion during the flexed knee exercise would have reduced the moment arm of Soleus, requiring a greater muscle force, resulting in the observed small, but statistically insignificant change in overall Achilles tendon force.

Aside from magnitudes of load, relative loading of the Gastrocnemius and Soleus muscles are known to be influenced by the amount of knee flexion (Hebert-Losier et al., 2011b; Reid et al., 2012). As was stated earlier, performing the knee flexed exercise shortens the Gastrocnemius, making it mechanically less efficient, due to the force-length relationship of muscle, in theory increasing the demands on the Soleus muscle. However, whether the effect of muscle shortening was offset by the increase in Gastrocnemius moment arm is unclear.

An unexpected observation was the decrease in biarticular muscle length *changes* with the knee flexed. Not only were the Gastrocnemius muscles operating at a shorter absolute length (expected with knee flexion) (Figure 4A), but changes in Gastrocnemius muscle lengths were also smaller (Figure 4B) despite the unchanged range of ankle motion. This decrease in Gastrocnemius muscle length change can be attributed to the increase in knee flexion during the flexed knee exercise, as a dorsiflexing ankle coupled with a flexing knee will result in a smaller change in muscle length than with a fixed knee angle, as was the case in the extended knee exercise. This is clinically relevant as the aim of this exercise is to strengthen the Achilles through loading while stretching the tendon at the same time (Allison and Purdam, 2009). A reduction in the change of muscle length and peak Achilles force could be seen as a reduction in the work load of the tendon, which is not the intention of the exercise. In the context of a treatment protocol, the reductions in peak Achilles force and triceps muscle length change could be considered less demanding on the Achilles tendon, possibly reducing the amount of pain experience during the initial acute phase of treatment.

Limitations

A limitation of the study is the assumption that in-shoe kinematic data represents the motion of the foot in the shoe. Practically, this manifests itself as the necessity to digitise points *over* bony landmarks, rather than the physical locations themselves. However, absolute ankle plantarflexion angles were found to be very similar between barefoot and shod exercises, suggesting any underestimates in ankle kinematics due to the presence of shoes were minimal. Additionally, by maintaining shoe conditions in the comparisons made here, differences associated with in-shoe kinematics would be consistent for the knee conditions being compared.

The observation of a lack of difference in relative activation of Soleus and Gastrocnemius at peak Achilles tendon force questioned whether knee flexion would indeed be able to elicit a physiological response in individuals. However, this may require further investigation, as the modelling approach used to estimate muscle force did not incorporate force-length relationships and as such, including such a muscle model may affect the estimated activations. However, while a limitation, the intention of using a musculoskeletal model here was to investigate the changes in kinematics, triceps muscle length and Achilles tendon loading in order to assess the impact of altered ankle kinematics on triceps surae mechanics during the flexed and extended knee of the exercise. Speculatively, the reductions in muscle length observed here would necessitate an increase in Gastrocnemius activation to provide the same force calculated here due to the force-length relationship of muscles.

Related to the calculation of muscle lengths, direct measurement of muscle behaviour such as through ultrasound would help validate the measures derived here and it would be valuable for future studies to include.

The lack of EMG data to complement the model outputs regarding the influence of knee angle on Soleus and Gastrocnemius activity is a limitation. Furthermore, the use of EMG data would have allowed for a form of validation of the model predictions regarding changes in triceps muscle forces, particularly as use of a musculoskeletal model to assess eccentric heel-drop exercises has not previously been done. However, given the increasing use of such models in assessing muscle function in a variety of lower limb activities, their relevance to this exercise is clear. Despite the limitations regarding knee flexion to elicit maximal triceps EMG signals (Hebert-Losier et al., 2011a), addition of such data may have provided a useful supplementary measure of muscle activity during these exercises.

Finally, the lack of a patient cohort in this study is a limitation, particularly as differences in lower limb mechanics may exist between healthy individuals and those with Achilles tendonitis or tendinosis, when undertaking their respective treatments.

Conclusion

This study aimed to characterise the biomechanics of the extended and flexed knee versions of the eccentric heel-drop exercise when performed barefoot and in running shoes. While ankle ranges of motion were unaffected between the extended and flexed knee versions of the exercise, the combination of a more dorsiflexed ankle, reduced triceps muscle-tendon length changes and reduced ankle plantarflexion moments during the flexed knee exercise provided a biomechanical basis for previously unexplained observations regarding the role of the flexed knee exercise to elicit the intended changes within the triceps, specifically the Soleus muscle.

Acknowledgement

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References

Alfredson, H., Pietila, T., Jonsson, P. and Lorentzon, R. (1998) Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis. *American Journal of Sports Medicine* **26**(3), 360-366.

Allison, G.T. and Purdam, C. (2009) Eccentric loading for Achilles tendinopathy--strengthening or stretching? *British Journal of Sports Medicine* **43**(4), 276-279.

Challis, J.H., Winter, S.L. and Kuperavage, A.J. (2012) Comparison of male and female lower limb segment inertial properties. *Journal of Biomechanics* **45**(15), 2690-2692.

Diaz, R. A., Herrera, W. J. and Martinex, R. (2006) Moments of inertia for solids of revolution and variational methods. *European Journal of Physics* **27**, 11.

Donoghue, O.A., Harrison, A.J., Laxton, P. and Jones, R.K. (2008) Lower limb kinematics of subjects with chronic achilles tendon injury during running. *Research in Sports Medicine* **16**(1), 23-38.

Farris, D.J., Trewartha, G., McGuigan, M.P. and Lichtwark, G.A. (2013) Differential strain patterns of the human Achilles tendon determined in vivo with freehand three-dimensional ultrasound imaging. *Journal of Experimental Biology* **216,** 594-600.

Fradet, L., Siegel J., Dahl, M., Alimusaj, M. and Wolf, S.I. (2009) Spatial synchronization of an insole pressure distribution system with a 3D motion analysis system for center of pressure measurements. *Medical & Biological Engineering & Computing* **47**(1), 85-92.

Grigg, N.L., Wearing, S.C., O’Toole, J.M. and Smeathers, J.E. (2013) Achilles tendinopathy modulates force frequency characteristics of eccentric exercise. *Medicine & Science in Sports & Exercise* **45**(3), 520-526.

Haxton, H.A. (1944) Absolute muscle force in the ankle flexors of man. *Journal of Physiology* **103**(3), 267-273.

Hebert-Losier, K., Newsham-West, R.J., Schneiders, A.G. and Sullivan, S.J. (2009a) Raising the standards of the calf-raise test: a systematic review. *Journal of Science and Medicine in Sport* **12**(6), 594-602.

Hebert-Losier, K., Schneiders, A.G., Garcia, J.A., Sullivan, S.J. and Simoneau, G.G. (2011a) Peak triceps surae muscle activity is not specific to knee flexion angles during MVIC. *Journal of Electromyography and Kinesiology* **21**(5), 819-826.

Hebert-Losier, K., Schneiders, A.G., Garcia, J.A., Sullivan, S.J. and Simoneau, G.G. (2012) Influence of knee flexion angle and age on triceps surae muscle activity during heel raises. *Journal of Strength & Conditioning Research* **26**(11), 3124-3133.

Hebert-Losier, K., Schneiders A.G., Newsham-West, R.J. and Sullivan, S.J. (2009b) Scientific bases and clinical utilisation of the calf-raise test. *Physical Therapy in Sport* **10**(4), 142-149.

Hebert-Losier, K., Schneiders, A.G., Sullivan, S.J., Newsham-West, R.J., Garcia, J.A. and Simoneau, G.G. (2011b) Analysis of knee flexion angles during 2 clinical versions of the heel raise test to assess soleus and gastrocnemius function. *Journal of Orthopaedics and Sports Physical Therapy* **41**(7), 505-513.

Henriksen, Aaboe, M.J., Bliddal, H. and Langberg, H. (2009) Biomechanical characteristics of the eccentric Achilles tendon exercise. *Journal of Biomechanics* **42**(16), 2702-2707.

Kader, D., Saxena, A., Movin, T. and Maffulli, N. (2002) Achilles tendinopathy: some aspects of basic science and clinical management. *British Journal of Sports Medicine* **36**(4), 239-249.

Khan, K.M. and Scott, A. (2009) Mechanotherapy: how physical therapists' prescription of exercise promotes tissue repair. *British Journal of Sports Medicine* **43**(4), 247-252.

Kingma, J.J., de Knikker, R., Wittink, H.M. and Takken, T. (2007) Eccentric overload training in patients with chronic Achilles tendinopathy: a systematic review. *British Journal of Sports Medicine* **41**(6), e3.

Klein Horsman, M.D., Koopman, H.F., van der Helm, F.C., Prose, L.P. and Veeger, H.E. (2007) Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity. *Clinical Biomechanics* **22**(2), 239-247.

Kujala, U.M., Sarna, S. and Kaprio, J. (2005) Cumulative incidence of achilles tendon rupture and tendinopathy in male former elite athletes. *Clinical Journal of Sport Medicine* **15**(3), 133-135.

Magnussen, R.A., Dunn, W.R. and Thomson, A.B. (2009) Nonoperative treatment of midportion Achilles tendinopathy: a systematic review. *Clinical Journal of Sport Medicine* **19**(1), 54-64.

Ohberg, L., Lorentzon, R. and Alfredson, H. (2004) Eccentric training in patients with chronic Achilles tendinosis: normalised tendon structure and decreased thickness at follow up. *British Journal of Sports Medicine* **38**(1), 8-11.

Rasmussen, J., Damsgaard, M. and Voigt, M. (2001) Muscle recruitment by the min/max criterion - a comparative numerical study. *Journal of Biomechanics* **34**(3), 409-415.

Reid, D., McNair, P.J., Johnson, S., Potts, G., Witvrouwm, E. and Mahieu, N. (2012) Electromyographic analysis of an eccentric calf muscle exercise in persons with and without Achilles tendinopathy. *Physical Therapy in Sport* **13**(3), 150-155.

Saraswat, P., Andersen, M.S. and MacWilliams, B.A. (2010) A musculoskeletal foot model for clinical gait analysis. *Journal of Biomechanics* **43**(9), 1645-1652.

van der Plas, A., de Jonge, S., de Vos, R.J., van der Heide, H.J., Verhaar, J.A., Weir, A. and Tol, J.L. (2012) A 5-year follow-up study of Alfredson's heel-drop exercise programme in chronic midportion Achilles tendinopathy. *British Journal of Sports Medicine* **46**(3), 214-218.

Weinert-Aplin, R.A. (2014) Development of a Foot and Ankle Musculoskeletal Model: Implications for Achilles Tendinopathy. Bioengineering, Imperial College London. PhD thesis.

Winter, D.A. (2009) Three-Dimensional Kinematics and Kinetics. In: *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, Inc., 176-199.

Wyndow, N., Cowan, S.M., Wrigley, T.V. and Crossley, K.M. (2010) Neuromotor control of the lower limb in Achilles tendinopathy: implications for foot orthotic therapy. *Sports Medicine* **40**(9), 715-727.

Wyndow, N., Cowan, S.M., Wrigley, T.V. and Crossley, K.M. (2013) Triceps surae activation is altered in male runners with Achilles tendinopathy. *Journal of Electromyography and Kinesiology* **23**(1), 166-172.

Key points

- A more dorsiflexed ankle and a flexing knee are characteristics of performing the flexed knee heel-drop eccentric exercise.
- Peak ankle plantarflexion moments were reduced with knee flexion, but did not reduce peak Achilles tendon force.
- Kinematic changes at the knee and ankle affected the triceps muscle length and resulted in a reduction in the amount of Achilles tendon work performed.
- A version of the heel-drop exercise which reduces the muscle length change will also reduce the amount of tendon stretch, reducing the clinical efficacy of the exercise.

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