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Technical Note

The effect of external compression on the mechanics of muscle contraction

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Abstract

The velocity at which a muscle fascicle will shorten, and hence the force that it can develop, depends on its gearing within the muscle belly. Muscle fascicle length depends on both its pennation and the thickness of the muscle. It was expected that external compression would reduce the muscle thickness and pennation and thus cause a reduction to the gearing of the fascicles relative to the muscle belly. Structural properties of the medial gastrocnemius muscle were visualized using B-mode ultrasound in six subjects. Measurements were taken during cyclical isotonic contractions at three different ankle torques and with the application of no, one or two elastic compression bandages to the lower leg. Ankle torques and angular velocities were unaffected by the external compression. External compression did however, reduce the muscle thickness, the fascicle pennation and resulted in a decrease in the gearing within the muscle belly. Reductions in gearing would result in an increase in the muscle fascicle shortening velocity that would reduce the force generating potential of the fascicles. It is suggested that externally applied compression should not be considered a way to enhance muscle performance when based on the structural mechanics.

Key words: muscle, gearing, pennation, ultrasound, contraction, compression
Introduction

There is an increasing usage of compression garments for both rehabilitation and athletic performance. Compressive stockings and tights can have a positive effect on venous blood flow\(^1\) and blood lactate concentrations after maximal exercise\(^2\) and they lead to longer times to fatigue.\(^3,4\) These previous studies have used graduated compression that exert a decreasing pressure on the lower leg: decreasing from 15-24 mm Hg at the ankle to 8-20 mm Hg at the calf. Compressive shorts have been shown to reduce muscle oscillations\(^5\) that in turn may result in a reduction in the muscle activity required to damp those oscillations.\(^6\) Compressive garments can also result in elevated skin temperature\(^5,7\) that may cause enhanced muscle force and power due to the shift in force-velocity characteristics at higher temperatures.\(^8,9\) The elastic properties of compression garments can contribute to joint stiffness and even enhance countermovement jump height,\(^5\) although in sprint tests there was no difference in performance when using compression shorts.\(^5,7\) To date there have been no studies that have investigated how compressive garments influence the structural mechanics of a muscle during contraction.

When a muscle belly shortens it must increase in cross-sectional area in order to maintain its volume, and this can occur as increases in thickness (in the fascicle planes), or width (perpendicular to the fascicle planes). External compression may oppose increases in thickness during contractions. Muscle fascicle lengths and rotations are mechanically linked to the muscle belly thickness,\(^10,11\) and these factors, in turn, affect the belly gearing which is the ratio of the shortening velocity of the muscle belly to the shortening velocity of the muscle fascicles. Changes to the gearing affect both the force and velocity properties of
the muscle\textsuperscript{10} and so it may be expected that external compression would affect the mechanical output of a muscle.

The purpose of this study was to evaluate the effect of external compression of the lower leg to changes in the muscle thickness, fascicle rotations and gearing in the medial gastrocnemius during cyclical isotonic contractions. We hypothesized that the external compression would reduce both the muscle thickness and its ability to bulge and thus limit the ability of the fascicles to rotate (increase in pennation) with a subsequent reduction in the gearing of the fascicles during contraction.

**Methods**

Six male subjects were tested (age 27.4 ± 6.6 years; height 1.80 ± 0.08 m; mass 79.2 ± 11.1 kg; mean ± st. dev.). The subjects provided informed written consent to participate in accordance with policy from the Office of Research Ethics of the university. Structural properties of the medial gastrocnemius were imaged during a series of isotonic contractions with the application of elastic compressive bandages around the calf.

Subjects were seated on a dynamometer (System 3, Biodex, New York, USA) with the right ankle securely strapped to the plantar/dorsiflexion footplate. The knee was held extended at an angle of 150 °. A neutral ankle angle was considered to be 0 °, with positive angles representing dorsiflexion and negative angles plantarflexion. A 2D linear ultrasound probe (Echoblaster 128 EXT-1Z, Telemed, Lithuania) was positioned over the medial gastrocnemius muscle so that the scanning plane aligned with the fascicle plane in the muscle and so that continuous fascicles could be visualized during the full range of plantar-
dorsiflexion. The probe was supported in a custom shape foam block that had flat contact surface with the leg of 120 × 70 mm. The probe was secured to the leg using medical adhesive tape. The maximum girth around the calf muscle and attached ultrasound probe was measured with a flexible tape.

Subjects performed cyclic plantar-dorsiflexion motions and worked against an isotonic ankle torque that was 10 N m for dorsiflexion and either 10, 25 or 40 N m for plantarflexion. A metronome was used to keep the cycle frequency at 0.5 Hz, with the plantarflexion and dorsiflexion phases each lasting 1 second. Each trial consisted of 7 cycles of contraction and a 10 second rest period was provided between trials. Elastic compressive bandages (Tubigrip, Elasticated Tubular Bandage G) were placed on the right leg to cover the calf muscles, the ultrasound probe and its foam support. The isotonic contractions were tested for three conditions: with no compressive bandages and with either one or two bandages applied. B-mode ultrasound images were recorded at 50 Hz during the contractions, and these images were synchronized with torque, ankle angle and angular velocity information from the dynamometer.

The bandage stiffness was quantified by measuring the force required to stretch 1 cm wide strips of the material. A set of weights (0 to 0.5 kg) was hung from one end of the bandage strip and the bandage circumference measured with vernier calipers.

The ultrasound images were digitized by hand (ImageJ version 1.4, NIH, USA), with two points marking the superficial and deep aponeuroses and a fascicle in the middle of the belly. The same fascicle was digitized between successive frames. As the ultrasound probe had been placed over the centre of the muscle belly where the superficial and deep
aponeuroses were nearly parallel, the measurements from this fascicle would be representative of the general muscle belly. The fascicle length $L_f$ was calculated as the length of the extrapolated line through the fascicle points that intersected with the aponeuroses. The belly thickness $L_t$ was the shortest distance between the superficial and deep aponeuroses that passed through the centre of the digitized fascicle. The pennation angle $\beta$ was the mean angle that the fascicle intersected with the superficial and deep aponeuroses. The projected belly length $L_b$ was given by $L_f \cos \beta$. The fascicle and belly velocities, $V_f$ and $V_b$, were calculated as the rate of change of $L_f$ and $L_b$, respectively.

The mean trace was calculated for each parameter from the middle 5 cycles of each trial. From these the following outcome variables were quantified: the mean ankle joint angle $P$, change in angle $\Delta P$, and the maximum angular velocity during plantarflexion $V$ and maximum plantarflexor torque $T$. Also, the following muscle structural parameters were calculated: mean fascicle length $\bar{L}_f$, belly thickness $\bar{L}_t$ and pennation angle $\bar{\beta}$, as well as the change in these parameters ($\Delta L_f$, $\Delta L_t$ and $\Delta \beta$). Changes in parameters were calculated as the difference between the maximum and minimum values for each contraction cycle. The muscle belly gearing $G_b$ was calculated as $V_b/V_f$ at the moment that the muscle belly was shortening at its maximum rate.

The effect of the isotonic condition on the ankle kinematics and kinetics was tested using multivariate ANOVA, with $P$, $\Delta P$, $T$ and $V$ as dependent variables, and the following factors: subject (random), torque setting, and number of bandages. Initially, a torque $\times$ bandage interaction factor was additionally considered, but this was subsequently removed because it had no significant effect. The effect of the bandages on the muscle...
structural parameters was determined using ANCOVA with subject (random) and number of bandages as factors, and $T$ and $V$ as covariates. All statistical tests were considered significant at $p<0.05$, and results are reported as mean ± s.e.m..

Results

The bandages showed linear elastic properties. The force-circumference stiffness of the 1 cm wide strips of the bandages was $6.533 \text{ N m}^{-1}$, with $r^2=0.992$. The resting circumference of the bandages was 0.237 m, which was smaller than the circumference of the subjects’ calf and probe for every subject (mean girth of $0.505 \pm 0.011 \text{ m}$). Thus the application of one bandage to the calf resulted in tension within the bandage that exerted external pressure onto the calf muscle, and this would have been doubled with the application of the second bandage.\textsuperscript{12}

During the isotonic tasks, the ankle joint underwent cycles of plantarflexion and dorsiflexion. The ANCOVA showed a significant effect of isotonic torque on the peak ankle joint angle during the contraction cycles. The higher torque conditions resulted in the ankle cycling about a less plantarflexed position (mean ankle angles of -17.2, -13.5 and -9.21 ° for plantarflexor torques of 10, 25 and 40 N m, respectively). However, there was no significant effect of the isotonic torque on the total excursion of the ankle for each condition. There was no significant effect of the number of applied bandages on the mean ankle joint angle, the maximum angular velocity during plantarflexion, or the maximum plantarflexor torque (Fig. 2).
During each movement cycle there were cycles of muscle thickness, fascicle length, and pennation angles. All bandage conditions showed a slight decrease in muscle thickness during plantarflexion. Conditions with zero or one bandages showed a decrease in fascicle length and increase in pennation angle as plantarflexion began, however, when two bandages were applied the fascicles lengthened and the pennation decreased in this period (Fig. 2). The ANCOVA showed that application of bandages resulted in a significant increase in the mean muscle fascicle length, and a reduction in the mean muscle thickness and mean pennation angle. The gearing of the muscle fascicles within the muscle belly also showed a significant relation with bandage number, with increased bandages resulting in a decreased gearing (Fig. 3). The application of the bandages resulted in reductions in the changes in fascicle length, muscle thickness and pennation (Fig. 3), although these effects were not significant (ANCOVA, $p>0.05$).

**Discussion**

In order for the muscle belly to maintain a constant volume, decreases in length must be matched by increases in cross-sectional area during contraction. This study measured the muscle thickness $L_t$ as the distance between the superficial and deep aponeuroses within the fascicle plane (Fig. 1), and the muscle width can be considered perpendicular to this plane. The bandages had circumferential elastic fibres that acted to compress the calf girth but not the length of the muscle. The muscles showed a decrease in thickness and increase in projected belly length $L_b$ as the bandages were applied. Changes to the muscle width $L_w$ can be estimated based on the isovolumetric assumption\cite{10,13} that the product of $L_t$, $L_b$, and $L_w$ is constant. In this study, the muscle compression that resulted
from the application of two bandages caused a 10 % increase in projected belly length, a 9 % reduction in muscle thickness, but only a 1 % reduction in width.

The placement of the ultrasound probe (with its foam support) between the bandages and the calf would result in the medial gastrocnemius being pressurized onto a flat surface. This is different from the situation that would occur without the probe insert when the bandage or compression garment would provide a more flexible contact surface. Indeed, it is likely that the pressure exerted on the calf would be concentrated in the middle of the block where the probe was embedded. Nonetheless, the fundamental purpose of the study was to identify if increased pressure changes the contractile mechanics, regardless of how the pressure was applied, and to this extent the results demonstrate a clear effect of pressure on some of the structural parameters (Figs. 2 and 3). It would be interesting to determine the extent to which these results would differ between different contact surfaces, movements and muscles.

When muscles contract the fascicles can both change length and rotate. Fascicle rotation results in a lower shortening velocity for the fascicles relative to the belly shortening (and hence higher belly gearing), than contractions where rotations are constrained. As fascicles in parallel fibred muscles are not able to rotate, it can be considered that the greater the resting pennation angle the greater the potential for fascicle rotations. In this study the decreased muscle thickness that resulted from the application of bandages caused a decrease in the pennation angle of the muscle and a trend towards smaller fascicle rotations (Fig. 3), and this resulted in a decrease in the muscle belly gearing. Muscle fascicle force decreases with increases in shortening velocity, and so it is
possible that the decreased gearing due to the application of external compression to the calf would result in a reduction in the force-generating potential of the muscle fascicles. However, the reduction in belly gearing with the compression was small (1.082 to 1.058), and so reduction in force generating potential would likely also be small. By contrast, the decrease in pennation that occurred with the two bandages (Fig. 3) would align the fascicles closer to the line-of-action of the muscle, increasing the muscle force by approximately 3%, and this effect would counter the force-reduction due to the gearing.

Evidence suggests that compression garments have a range of beneficial effects such as improving blood flow, reducing fatigue, or increasing performance due to elevated muscle temperature and their passive contributions to joint stiffness. However, sprint performances have previously been found to have no significant change with compressive garments. The changes in the mechanical behaviour in the medial gastrocnemius with applied compression in this study supports these whole-body measures of sprinting performance: the evidence from this study suggests that external compression should not be expected to increase the active force generated by a muscle.

Acknowledgements

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References


Figure 1. B-mode ultrasound image of the medial gastrocnemius showing measured and calculated features of the muscle. Digitized points are shown with small crosses. A fascicle is shown by the arrow, and intersects the superficial and deep aponeuroses with angles $\beta_1$ and $\beta_2$, respectively. Calculated lengths are for the fascicle length $L_f$, belly thickness $L_t$ and projected belly length $L_b$. 
Figure 2. Dynamometer readings and structural parameters of the medial gastrocnemius during isotonic contractions. Lines show the mean of the six subjects (thick) with the s.e.m. (thin). Contractions worked against a set 40 N m plantarflexor torque. Contractions were tested with no (light grey, dotted s.e.m.), one (dark grey, dashed s.e.m.) or two (black, solid s.e.m.) compressive bandages applied to the calf.
Figure 3. The effect of compressive bandages on the structure of the medial gastrocnemius during a series of cyclic isotonic contractions. Bars show the mean (+ s.e.m.) data pooled from three isotonic torques (10, 25 and 40 N m) and six subjects. Bars are shaded grey where there was a significant main effect of the number of bandages (ANCOVA, p<0.05).