The effects of knee joint angle on neuromuscular activity during electrostimulation in healthy older adults

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The effects of knee joint angle on neuromuscular activity during electrostimulation in healthy older adults

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Abstract

Electrostimulation devices stimulate the common peroneal nerve, producing a calf muscle-pump action to promote venous circulation. Whether ~~leg~~ knee joint ~~position~~ angle influences calf neuromuscular activity remains unclear. Our aim was to determine the effects of knee joint angle on lower-limb neuromuscular activity during electrostimulation. Fifteen healthy, older adults underwent 60 min of electrostimulation, with the knee joint at three different angles (0°, 45° or 90° flexion; random-order; 20 min each). Outcome variables included electromyography (EMG) of the *peroneus longus*, *tibialis anterior*, and ~~*gastrocnemii*~~ *gastrocnemius* ~~(~~*medialis* and *lateralis*~~)~~, and discomfort. Knee angle did not influence *tibialis anterior* and *peroneus longus* neuromuscular activity during electrostimulation. Neuromuscular activity was greater in the *gastrocnemius medialis* (p=0.002) and *lateralis* (p=0.002) at 90°, than 0° knee angle. Electrostimulation intensity was positively related to neuromuscular activity for each muscle, with a knee angle-effect for the *gastrocnemius medialis* (p=0.05). Results suggest that during electrostimulation, knee joint angle: influenced *gastrocnemii* neuromuscular activity; increased *gastrocnemius medialis* activity across all intensities (at 90°), when compared to 0° and 45° flexion; and did not influence *peroneus longus* and *tibialis anterior* activity. Greater electrostimulation-evoked *gastrocnemii* activity has implications for producing a more forceful calf muscle-pump action, potentially further improving venous flow.

Keywords

Electrical stimulation, knee joint, electromyography, gastrocnemius, isometric contraction, peroneal nerve

Introduction

Reduced mobility following surgery, such as hip or knee arthroplasty, presents a risk of deep vein thrombosis (DVT) in patients.[1] Clot formulation arising from venous stasis[2] and lower-limb muscle inactivity[3] can be prevented by mechanical counter-measures (i.e., compression stockings/devices). Although commonly used, the bulk and discomfort of mechanical devices can result in poor compliance.[4] In contrast, neuromuscular electrostimulation devices offer a non-invasive, practical and economical alternative to reduce the risk of venous thromboembolism.[5, 6]

Electrostimulation devices stimulate the common peroneal nerve to initiate action potentials in the intramuscular nerve pathways, resulting iinduce an involuntary, isometric muscle contraction of calf extensor muscles (i.e. *tibialis anterior* and *peroneus longus*) and an additional stretch of the flexor *gastrocnemii* muscles. The passive stretch compresses the antagonist *gastrocnemii*, as the muscle is pulled in a distal direction during dorsiflexion.[8] The passive motion of the flexor *gastrocnemii* acts as the calf muscle pump to promote venous circulation by raising intramuscular pressure. s and activation of the calf muscle pump. The nerve lies between the anterior-posterior bifurcation of the lower leg and activates the *peroneus longus* and *tibialis anterior* muscles, leading to *gastrocnemii* co-contraction. In healthy adults, 5 min periods of lower leg electrostimulation has been shown to enhance venous volume (flow up to 100%) and velocity, with minimal discomfort at maximum stimulation intensity.[7] Recently, Zhang et al.[8] trialed an geko™ electrostimulation device by modelling venous stasis in healthy adults, using an automated tourniquet. Short-periods (10 min) of electrostimulation were shown to i) augment calf muscle-pump action and, ii) reduce DVT-associated rises in blood volume and tissue deoxygenation. Alongside reduced limb volume, others have shown reduced venous transit-time and venous ambulatory pressure in the young.[9] Clinically, stimulating lower-limb venous circulation with electrostimulation can also reduce limb volume oedema in orthopaedic,[10] diabetic and cardiovascular-disease patients.[11] During electrostimulation the activated *tibialis anterior* becomes an agonist, and the *medial gastrocnemii gastrocnemius* an antagonist. Force and electromyogram (EMG) recordings indicate that electrostimulation intensity relates directly to ankle dorsiflexion (and muscle-pump) force.[8] This involuntarily stretches the *gastrocnemii*, reducing the muscle anatomical cross-sectional area, and subsequently venous diameter to eject blood to a greater extent than voluntary contraction alone.[12]

Interestingly, Khanbhai et al.[9] reported greater change in limb volume and venous function with electrostimulation applied in a lying position, when compared to sitting and standing. Standing elevates lower-limb volume[13] and venous pressure,[14] in comparison to lying and sitting. In these positions, knee joint angle (and therefore muscle length) may influence muscle tension of the bi-articular *gastrocnemii* ~~muscle tension~~ prior to innervation.[15] Furthermore, altering muscle length (via joint angle) during electrostimulation ~~it~~ is recommended to ~~alter muscle length (via joint angle) during electrostimulation to~~ promote spatial motor unit recruitment.[16] Clinical observations from our group support a visible twitch response during electrostimulation when seated (~90°knee joint angle), but little visible twitch with the knee extended (~0°knee joint angle) in orthopaedic patients. Receiving electrostimulation whilst lying may be preferable to standing, in terms of gravitational pressure influencing peripheral haemodynamics. However, the common peroneal nerve becomes displaced from the fibular head by approximately 17 mm when standing or sitting with 0° knee flexion, when compared to sitting with 90° knee flexion.[17] It is reasonable to assume that if an individual is upright and unable to sit whilst receiving electrostimulation, they will experience less calf muscle activation (and potentially muscle-pump action). This proof-of-concept study will assess the impact of knee joint position on the neuromuscular responses of calf muscles during electrostimulation. A subsequent study will incorporate haemodynamic, alongside neuromuscular assessments, with post-operative orthopaedic patients.

What is not clearly understood is whether knee joint angle influences the neuromuscular activity of the lower-leg muscles, particularly the *gastrocnemii* co-contraction (and therefore the effectiveness muscle pump action) during electrostimulation. This pilot study aimed to assess the effect of seated, knee joint angle on the neuromuscular activity of the i) *gastrocnemii* (co-contractor muscle pump) and, ii) *peroneus longus* and *tibialis anterior* (innervated) muscles during electrostimulation in healthy, older adults.

Methods

Participants

Fifteen community-dwelling, older adults (Table 1) were recruited by advertisement from ~~the~~ Dorset, ~~region~~UK. Sample size estimation was based upon a minimum of n = 12, as deemed adequate for a pilot study,[18] whereby data will inform the power analyses of a follow-up, clinical-cohort study. Volunteers were initially screened by the completion of an online pre-test health questionnaire, followed by a telephone-call by an investigator to further discuss eligibility. Table 2 details inclusion and exclusion criteria, which served to limit confounding variables and provide a control to compare future age-matched, orthopaedic cohorts with. Eligible volunteers provided written informed consent and completed a Physical Activity ~~Score~~ Scale for the Elderly (PASE) questionnaire[19] on the day of experimental testing. The experimental protocol was approved by the Bournemouth University Research Ethics Committee (Ref: 8029), and accepted on the International Standard Randomised Controlled Trial Number Register on http://isrctn.org (Ref number: ISRCTN28232918).

<<<INSERT TABLE 1 HERE>>>

<<<INSERT TABLE 2 HERE>>>

Experimental protocol

Participants visited the laboratory once to undergo 60 min of lower-leg transcutaneous electrostimulation, with knee joint at three different angles (20 min administrations each (Figure 1)). Online software (sealedenvelope.com) was used to randomly allocate electrostimulation joint angle order (0° first, $n = 4$; 45° first, $n = 5$; 90° first, $n = 6$); no order effect was found for knee joint angle on neuromuscular activity for each muscle ($p > 0.1$). Each 20 min bout was separated ~~Brief~~ by 60 s rests~~. (60 s) separated each 20 min bout;~~ ~~pilot~~ Pilot testing ($n = 3$ [males], age 56 ± 2 years) confirmed no ~~electrostimulation~~ fatigue-effect from monitoring EMG signals during three, 25 min electrostimulation bouts. Instruction was given to arrive hydrated, having maintained habitual physical activity levels in the preceding 48 h (Appendix 1). Upon arrival at the laboratory, the experimental protocol was re-explained, body mass was then recorded ~~unshod~~ using digital scales (Seca Ltd., Birmingham, UK) and height with a stadiometer (Holtain Ltd., Crymych, UK). All subsequent measures and electrostimulation treatments refer to the non-dominant limb.

<<<INSERT FIGURE 1 HERE>>>

Once the electrostimulation device was fitted~~,~~ according to manufacturer instructions (full knee extension [0º]; Firstkind Limited, Bucks, UK~~)~~)~~,~~ and stimulation intensity determined, ~~three~~ four ~~electromyogram (~~EMG~~)~~ sensors were placed on the lower-limb with the participant lying prone, and for ~~;~~ the *tibialis anterior* ~~was positioned~~ lying supine. Electrostimulation was administered with participants seated upright (hip joint at ~90°) in an adjustable isokinetic dynamometer chair (Humac Norm, Cybex International Inc., NY, USA) to replicate clinical administration. The lateral femoral epicondyle of the tested limb was aligned to the rotational axis of the dynamometer and the ankle joint was secured to the lever-arm. Participants were guided to extension and flexion limits by the Investigator to determine knee joint range of motion (0° = full extension); the lever-arm was then mechanically set to the first knee joint angle (0°, 45° or 90°). Lower-limb neuromuscular activity was recorded for 20 min throughout electrostimulation.~~;~~ ~~participant~~ Participant discomfort was self-reported in the final 60 s only, so as not to interfere with EMG sensor recordings and ~~retrospectively~~summatively ~~quantify~~assess perceived discomfort for each 20 min bout. ~~This~~ The procedure above was then repeated for 20 min in the second knee angle, and 20 min in the third knee angle. Instruction was given to relax both lower-limbs throughout the entire electrostimulation period.

Electrical stimulator

A small (186 mm x 31 mm), non-invasive electrostimulation device (geko™ T2, Firstkind Limited, Bucks, UK) was attached horizontally below the fibula head on the lateral-posterior aspect of the knee, according to the manufacturer's instructions for use. The device stimulates the common peroneal nerve, which leads to isometric contraction of the *peroneus longus* and *tibialis anterior* muscles of the lower leg. Seven stimulation intensities can be selected (50, 70, 100, 140, 200, 280, 400 µs), to deliver a 27 mA pulse current (200 Ω – 5 kΩ load impedance), at a 1 Hz repetition rate. ~~Subsequent~~Hereafter, electrostimulation intensities are referred to as levels 1 to 7 ~~hereafter~~. Participant stimulation intensity (or level) was determined based upon i) maximal stimulation effect (slight visible dorsiflexion/eversion movement) and, ii) patient comfort. To investigate a potential ~~stimulation intensity~~ staircase effect[20] ~~of~~ for knee joint angle on electrostimulation neuromuscular activity, stimulation intensity was increased from the participant's ~~established~~ prescribed level~~,~~ up to ~~maximal~~ maximum (level 7) at 10 s intervals at the end of each 20 min period (Figure 1).

Perceived discomfort

Participants self-reported lower-limb discomfort during electrostimulation for each knee joint angle. The same investigator presented a 10 cm Visual Analogue Scale (VAS), ranging from 0 (no discomfort/pain) to 10 (extreme discomfort/pain); participants marked perceived discomfort on the 0 to 10 cm scale. A Verbal Rating Score (VRS) was also used, ranging from 1 (no sensation) to 7 (very severe discomfort) that aligned to the stimulation levels.~~;~~ ~~participants~~ Participants circled perceived sensation.

Electromyography (EMG) recording, normalisation and processing

Peroneus longus, tibialis anterior, gastrocnemius medialis and *gastrocnemius lateralis* EMG were recorded via SX230-1000 bipolar sensors from a portable Biometrics PS850 system (DataLOG, Biometrics Ltd., Newport, UK) during electrostimulation (Figure 2). The skin was shaved, cleansed and gently abraded to reduce sensor-to-skin impedance. Sensors were placed over the respective muscle bellies according to SENIAM recommendations [21] and the reference electrode was strapped over the lateral malleolus of the tested limb. To limit electrostimulation artifacts in the raw EMG signal, recording sensors were positioned orthogonal to the stimulation electrode and at an interelectrode distance of ≥ 2.5 cm. Raw signals were sampled at 1000 Hz by each amplifier-embedded sensor (10 mm diameter, 20 mm inter-electrode distance; bandwidth = 20 – 460 Hz; common mode rejection ratio = >96 dB [typically 110 Db]; input impedance = >10,000,000 MΩ), and ~~then~~ processed with a 2nd order Butterworth filter (bandwidth = 10 – 350 Hz) to remove DC offset. The root mean square (RMS) was then calculated using a 0.25 s moving window (overlap of 50% window length) ~~processed (DataLOG software v. 7.5, Biometrics Ltd., Newport, UK)~~. EMG data were manually checked for stimulation artifacts by overlaying the RMS envelope on to the raw EMG signal (DataLOG software v. 7.5, Biometrics Ltd., Newport, UK). For RMS analysis, at each knee joint angle 5 s capture periods were used at the end of the following time-points: 0–1 min, 9–10 min and 19–20 min (nine capture periods in total).

Prior to each 20 min period, the investigator increased the electrical stimulation intensity in a sequential, step-wise manner every 15 s from the lowest (1 [50 µs intensity]), to the highest (7 [400 µs intensity]) setting, whilst measuring muscle activity at respective knee angles. This was used to assess the relationship between stimulation intensity and muscle activity for each participant, at each knee angle. Maximum RMS was determined for a 1 s interval around the peak torque evoked from the participant's maximum voluntary contraction for each muscle. Joint torque was measured for each muscle using the same isokinetic dynamometer used to secure knee joint angle. In a prone position, participants produced three, 3-5 s maximal voluntary isometric contractions (60 s rests), with verbal encouragement provided by the investigator. ~~was measured using the same isokinetic dynamometer that was used to determine knee joint angle~~. Subsequent RMS data were normalised by dividing by the maximum RMS value and then multiplying by 100 to provide percentage of RMS maximum.[8, 22]

<<< INSERT FIGURE 2 HERE >>>

Statistical analysis

Shapiro-Wilk tests confirmed neuromuscular activity data were non-normally distributed; non-parametric tests were used to analyse RMS for each muscle. One-way, repeated measures Friedman's ANOVAs were used to compare i) RMS activity and ii) discomfort (VAS and VRS) between knee joint angle (0°, 45° and 90°) for each muscle. Paired Wilcoxon Signed-Rank tests identified angle-specific differences. Mixed design ANOVAs (within-group, repeated measures on levels (7) and degrees (3)) tested whether there was an electrostimulation intensity effect on RMS activity, dependent upon knee joint angle. Relationship between stimulation intensity and neuromuscular activity (normalised RMS) at each knee angle was determined by Spearman's correlation (based upon group mean (n = 15) for each stimulation intensity).

Data were expressed as mean and standard deviation (SD). Non-normal data were expressed as mean, with 95% confidence intervals (CI), and the Friedman's ANOVA test statistic represented as Chi-squared (χ^2). Effect sizes (Cohen's d) were calculated to determine meaningful differences (small = 0.2, moderate = 0.5, large, 0.8) ~~with~~ and statistical significance set as $p < 0.05$.

Results

Anthropometry and discomfort

There were no significant differences in anthropometrical measures following 60 min of electrostimulation ($p >$ 0.05), when compared to baseline measures. There were no significant differences in values of discomfort (VAS and VRS) during electrostimulation at each knee joint angle ($p > 0.05$; Table 3).

<<< INSERT TABLE 3 HERE >>>

Neuromuscular activity and knee joint angle

During electrostimulation, knee joint angle did not affect RMS activity of the *tibialis anterior* ($\chi^2(2) = 1.857$, p = 0.4, d = 0.07; Figure 3a) and *peroneus longus* ($\chi^2(2) = 3.0$, p = 0.2, d = 0.08; Figure 3b). However, knee angle did influence *gastrocnemius medialis* RMS activity (χ2(2) = 12.0, p = 0.002, d = 0.54), with greater RMS activity at 90° knee joint angle, when compared to 0° (p = 0.003, d = 1.07) and 45° (p = 0.003, d = 1.06; Figure 3c) angles. Knee joint angle influenced *gastrocnemius lateralis* RMS activity (χ2(2) = 16.714, p = 0.0001, d =

0.49), with greater RMS activity at 90° knee joint angle, when compared to 0° (p = 0.002, d = 0.99) and 45° (p = 0.002, d = 1.31; Figure 3d) angles. *Gastrocnemius lateralis* RMS activity was greater at 45° knee joint angle, when compared to 0° (p = 0.02, d = 0.27) angle.

<<< INSERT FIGURE 3 HERE >>>

Joint angle-dependent effect on electrostimulation intensity

When increasing the electrostimulation intensity from minimum (level 1) to maximum (level 7), knee joint angle did not affect *tibialis anterior* RMS activity (p = 0.27, d = 0.09), although there was a linear trend (p = 0.004, d = 0.48; Figure 4a). *Peroneus longus* RMS activity was influenced by electrostimulation intensity and knee joint angle (p = 0.02, d = 0.21; quadratic trend: p = 0.01, d = 0.41; Figure 4b), with greater effect at 90° knee joint angle, than at 45° (p = 0.05). *Gastrocnemius medialis* RMS activity showed an interaction effect (intensity x knee joint angle) (p = 0.01, d = 0.15; quadratic trend: p = 0.05, d = 0.26), with greater effect at 90° knee joint angle, than 0° and 45° angles (see Figure 4c). The *gastrocnemius lateralis* was influenced by intensity only (p = 0.001, d = 0.52; quadratic trend: p = 0.03, d = 0.32; Figure 4d). There was a positive relationship between electrostimulation intensity and RMS activity for each muscle (n = 15; *tibialis anterior*: 0°, r = 0.96; 45°, r = 0.97; 90°, r = 0.94; *peroneus longus:* 0°, r = 0.89; 45°, r = 0.81; 90°, r = 0.90; *gastrocnemius medialis*: 0°, r = 0.76; 45°, r = 0.78; 90°, r = 0.91; *gastrocnemius lateralis*: 0°, r = 0.87; 45°, r = 0.85; 90°, r = 0.94; p < 0.001).

<<< INSERT FIGURE 4 HERE >>>

Discussion

~~The~~ This proof-of-concept ~~present~~ pilot study investigated whether knee joint angle influenced lower-limb neuromuscular activity during electrostimulation in healthy, older adults. It is recommended that the joint angle (and therefore muscle length) remains the same during ~~stimulator placement and during~~ electrostimulation,[15] as the~~The electrostimulation~~ device stimulates the common peroneal nerve ~~resulting in~~to ~~activation~~ activate ~~of~~ the calf muscle-pump to subsequently promote venous circulation in the lower-limb. We examined ~~those~~ the muscles responsible for the muscle-pump action~~, the~~: the *peroneus longus*, *tibialis anterior* and ~~particularly,~~ the co-contractor *gastrocnemii* (lateral and medial heads) at three different knee joint angles (~~at~~ i.e. 0º [full extension], 45º and 90º knee flexion). We found that during electrostimulation positioning the knee joint at 90°

flexion i) influenced *gastrocnemii* (ankle plantarflexor) muscle activation; ii) increased *gastrocnemius medialis* activation at each stimulation intensity (from minimum [level 1] to maximum [level 7]), when compared to 0° and 45° knee flexion; and, iii) did not affect activation of the *peroneus longus* (ankle plantarflexor and evertor) and the *tibialis anterior* (ankle dorsiflexor) muscles.

, knee joint angle: i) influenced the EMG activity of the *gastrocnemii* (ankle plantarflexor) muscle; ii) at 90° flexion, increased *gastrocnemius medialis* activity at each stimulation intensity (from minimum [level 1], to maximum [level 7]), when compared to 0° and 45° knee flexion; and, iii) did not affect the neuromuscular activity of the *peroneus longus* (ankle plantarflexor and evertor) and the *tibialis anterior* (ankle dorsiflexor) muscles. For each muscle, tThere was a strong significant positive correlation between stimulation intensity and neuromuscular activity (RMS)muscle activation for each calf muscle;. The strongest correlation was observed at 90º knee flexion for the *peroneus longus*, *gastrocnemius medialis* and *gastrocnemius lateralis* (Figure 4b-d).for the *peroneus longus*, *gastrocnemius medialis* and *gastrocnemius lateralis* with the strongest relationship at 90º knee flexion (Figure 4b-d).

When receiving calf electrostimulation seated, our cohort showed greater *gastrocnemius medialis* (co-contractor) activity with the knee at 90°, when compared to partial knee flexion (45°) and knee extension (0°). Similar A similar joint angle-dependent effect was shown for the *gastrocnemius lateralis*, which in addition, displayed greater activity at 45º, than at 0º knee flexion (full extension). The *gastrocnemius medialis* and *lateralis* are similar in fibre-type composition,[23] but controlled by different afferent pathways from the same neural origin.[24] We could did not determine examine thisneural pathways, but our differences in *gastrocnemius medialis* and *lateralis* neuromuscular activity at 45º flexion are likely stems to derive from a wider 95% CI for the *gastrocnemius lateralis*, and therefore a small-to-moderate effect size. Activation increased for the *gastrocnemius medialis* (by 31.3%) and *lateralis* (by 32.4%) throughout during 20 minutes of electrostimulation with the knee at 90º flexion, when compared to 0º flexion. Varying the knee and ankle joint angles influences the *gastrocnemii* muscle length[25] and force-producing capacity,[26] as well as the passive knee flexion moment.[27] As the human *gastrocnemii* operates on the ascending limb of the force-length relationship, passive tension begins to develop at short muscle lengths (i.e., in 90° knee flexion), before approaching near-maximum at longer muscle lengths (i.e., 0° knee extension).[28] As a consequence, at longer muscle lengths the contribution of the active, contractile component becomes near-maximum[11] with greater passive force exerted.[2] Therefore, Electrostimulation electrostimulation will may be less effective at activating the calf muscle pump with the knee extended, and with the *gastrocnemii* muscle-tendon unit in at a pre-stretched positionlonger muscle length.

In our study, to ensure potential changes in *gastrocnemii* neuromuscular activity were attributable to knee joint angle, and not ankle joint angle, the participant's ankle was held in a neutral position (~0°) throughout electrostimulation. Even so, dDuring electrostimulation we found greater *gastrocnemii* neuromuscular activity with the knee flexed (90°) and , with the muscle in a shortened position, when compared to the knee extended (0º), with and the muscle in a lengthened position. This is chiefly attributable to displacement of the common peroneal nerve from the fibular head (by ~17 mm) with the knee in 0° flexion,[17] which would result in sub-optimal *peroneus longus* and *tibialis anterior* activation. In addition, stimulating lengthened *gastrocnemii*, with longer contractile and/or elastic component would likely affect muscle activation. For example, as the *gastrocnemius* is an agonist in knee flexion, stimulation at 90° flexion would innervate an already 'active' muscle under tension. As an antagonist in knee extension, *gastrocnemii* activation increases during voluntary knee flexion,[29] but decreases during voluntary knee extension.[30] In a lengthened position (0º), the stimulation would have to overcome a stretched *gastrocnemii* tendon and greater passive force.[27, 31] Therefore, a proportion of muscular tension evoked by electrostimulation would be attenuated by the Achilles tendon of the *gastrocnemius*, which accounts for ~73% of the total muscle-tendon length change (in contrast, the *tibialis anterior* tendon accounts for ~45% length change).[25]

This may be attributable to electrostimulation stimulating a shortened *gastrocnemii*, with a shorter: i) contractile component and/or, ii) elastic component. Firstly, as the *gastrocnemii* is an agonist during knee flexion, stimulation would be innervating an already 'active' muscle under tension. As an antagonist in knee extension, *gastrocnemii* RMS activity increases during voluntary knee flexion,[29] but decreases during voluntary knee extension,[30] with plantarflexion. Secondly, in the lengthened position (0º), the stimulation would have to overcome a stretched tendon, and greater passive force.[27, 31] Therefore, any muscular tension evoked by electrostimulation may have been dissipated by the relatively long Achilles tendon of the *gastrocnemius*(total muscle-tendon length change taken by tendon: *tibialis anterior*, ~45%; *gastrocnemii*, ~73%).[25]

Another possible explanation for the increased *gastrocnemius medialis* activity with electrostimulation at 90° knee flexion arises from neuromuscular propagation. Decreases in contraction time and half-relaxation time during progressive muscle shortening[32] reflect a requirement for higher excitation rates to produce the same evoked torque. Greater activation at 90° knee flexion may indicate a need to increase activation at a shorter muscle length. However, this seems unlikely, given that the *gastrocnemii* muscle is at a favourable position on the length-tension relationship at 90° knee angle. Others have reported decreased *gastrocnemii* ~~activity~~ activation at pronounced knee flexion angles ~~(~~up to 60%~~)~~,[33, 34] which disagree with ~~the current~~our findings. However, it should be noted that these studies evoked muscle activity by maximal voluntary contraction, whilst manipulating ankle angle.

The neuromuscular activity of the *tibialis anterior* and *peroneus longus* during ~~geko™~~ electrostimulation were not influenced by knee joint angle. *Tibialis anterior* ~~RMS activity~~activation at 45° (59.3%) and 90° knee ~~angles~~ flexion (64%) appeared ~~elevated~~ greater ~~above~~ than 0° knee flexion ~~angle~~ (49.9%) after the first minute, yet this did not reach significance. ~~In addition, a~~Additional linear trend analyses (p = 0.008) ~~indicates~~ indicated that *tibialis anterior* neuromuscular activity ~~linearly~~ increased proportionally from minimum ~~[~~(level 1~~],~~) to maximum ~~[~~(level 7~~]~~) stimulation intensities similarly ~~at~~ across each knee joint angle. ~~These~~ However, these findings are ~~not~~ unsurprising given that both are mono-articular muscles and span only the ankle joint, whereas the bi-articular *gastrocnemii* spans the ankle and knee joints. The *tibialis anterior* is composed predominantly of slow twitch, type I fibres, with ~~long~~ slower contraction time,[32] which may also contribute to the electrostimulation-evoked ~~neuromuscular~~ muscle ~~activity~~ activation being lower at each knee angle, when compared to the other muscles (Figure 4a-d). Additionally, the common peroneal nerve first passes the *peroneus longus*, which when activated, will oppose ~~any~~ force produced by the *tibialis anterior*.[32]

Knee joint angle did not influence discomfort, with the majority ~~of VAS and VRS~~of perceptual ratings showing that ~~the~~ stimulation~~s~~ involved *minimal discomfort*, and only the highest stimulation setting, level 7 (pulse current: 27 mA; intensity: 400 µs; repetition rate: 1 Hz), reached *mild discomfort*. Similar discomfort values have been reported during percutaneous electrostimulation~~: –~~ administered intermittently (5 min stimulation, 10 min rest for 4 h) in healthy adults[7] and in hip arthroplasty patients of similar age.[3] Electrostimulation settings were participant-specific and determined according to the manufacturer's instructions ~~in~~ which recommend that the appropriate stimulation intensity should evoke a ~~palpable~~ visible twitch in the foot. ~~Neuromuscular activity~~Even at 0° knee flexion, *tibialis anterior* and *gastrocnemius medialis* activation increased by a minimum of ~49% maximum ~~increased by a minimum ~49% of maximum stimulation (*tibialis anterior* and *gastrocnemius medialis* at 0° knee flexion, or full extension) at participant-specific settings,~~ with little discomfort using prescribed settings. As lower-limb blood flow can be increased by a muscle producing 30% of maximal contraction,[35] our preliminary results show promise with regard to electrostimulation at 90° knee flexion enhancing neuromuscular activity, and potentially venous blood flow, with minimal discomfort~~ in the healthy~~.

From a clinical perspective, these pilot data from healthy, older adults suggest that receiving ~~geko™~~ electrostimulation when seated~~, with the knee flexed~~ at 90° knee flexion can enhance *gastrocnemii* ~~neuromuscular activity~~activation, when compared to seated~~, with the knee partially flexed~~at ~~(~~45°~~)~~ or ~~extended~~ ~~(~~0°~~)~~ knee flexion. The ~~geko™~~ electrostimulation device stimulates the common peroneal nerve~~,~~ to ~~evoking~~ evoke an involuntary, isometric contraction of the *peroneus longus* and *tibialis anterior* muscles simultaneously. The gastrocnemius then undergoes as passive stretch as the antagonist flexor muscle. This calf muscle-pump action ~~can~~ improves venous blood flow in bed-rest,[36] sitting for prolonged periods[7] and during venous stasis.[8] ~~Of the calf-muscle pump, t~~The *gastrocnemii* ~~has~~ contributes a greater physiological cross-sectional area (96.1 cm^2) of the calf-muscle pump, than the *tibialis anterior* (18.5 cm^2) and *peroneus longus*,[37] and therefore has ~~a~~ greater potential for force-producing capacity ~~to~~ and ~~distribute~~ venous ~~blood~~circulation. However, straightening the leg to 0° knee flexion may displace the common peroneal nerve from the fibular head, [17] and reduce the impact of the calf-muscle pump.~~[17]~~ Based on ~~these~~ our pilot observations, future work should determine whether receiving electrostimulation seated, with 90° knee flexion can increase *gastrocnemius* activation and, in turn, produce a more forceful muscle pump action to enhance venous blood flow in clinical cohorts (i.e., orthopaedic patients undergoing hip/ knee arthroplasty).~~: i) geko™ electrostimulation administered seated, with the knee in 90° flexion, can increase *gastrocnemius* muscle activity in clinical cohorts (i.e., orthopaedic patients undergoing hip/ knee replacement) and, ii) increase in *gastrocnemii* muscle activity during seated electrostimulation can produce a more forceful muscle-pump action to enhance venous blood supply.~~

The main limitations of this proof-of-concept pilot study were that we did not measure electrostimulation-evoked: i) torque-production or, ii) venous blood flow. Ankle torque would have been difficult to assess given that our experimental aim was to study the potential influence of knee joint angle on electrostimulation. Zhang and colleagues[8] assessed electrostimulation-evoked torque and during isometric ankle dorsiflexion with participants lying prone. They were able to fix a load-cell in this position, whereas our dynamometer lever-arm (measuring torque) was used to fix knee joint angle. Our 20 min electrostimulation periods were too brief to accurately apply both EMG~~,~~ and Doppler ultrasound to measure venous blood flow.

Conclusions

This pilot study presents the first observation that knee joint angle can influence *gastrocnemii* activation during seated electrostimulation in healthy, older adults. The results suggest that receiving electrostimulation when seated, with the knee flexed at 90°, can augment increases in *gastrocnemii* activity shown with the knee partially flexed (45°), or extended (0°). This could have implications for ~~the~~ an ~~geko™~~ electrostimulation device stimulating a more forceful calf muscle-pump action and, in turn, further improving lower-limb venous blood flow with little discomfort.

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Conflict of interest: The authors declare that there are no conflicts of interest.

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Table 1. Demographic characteristics of recruited older adults

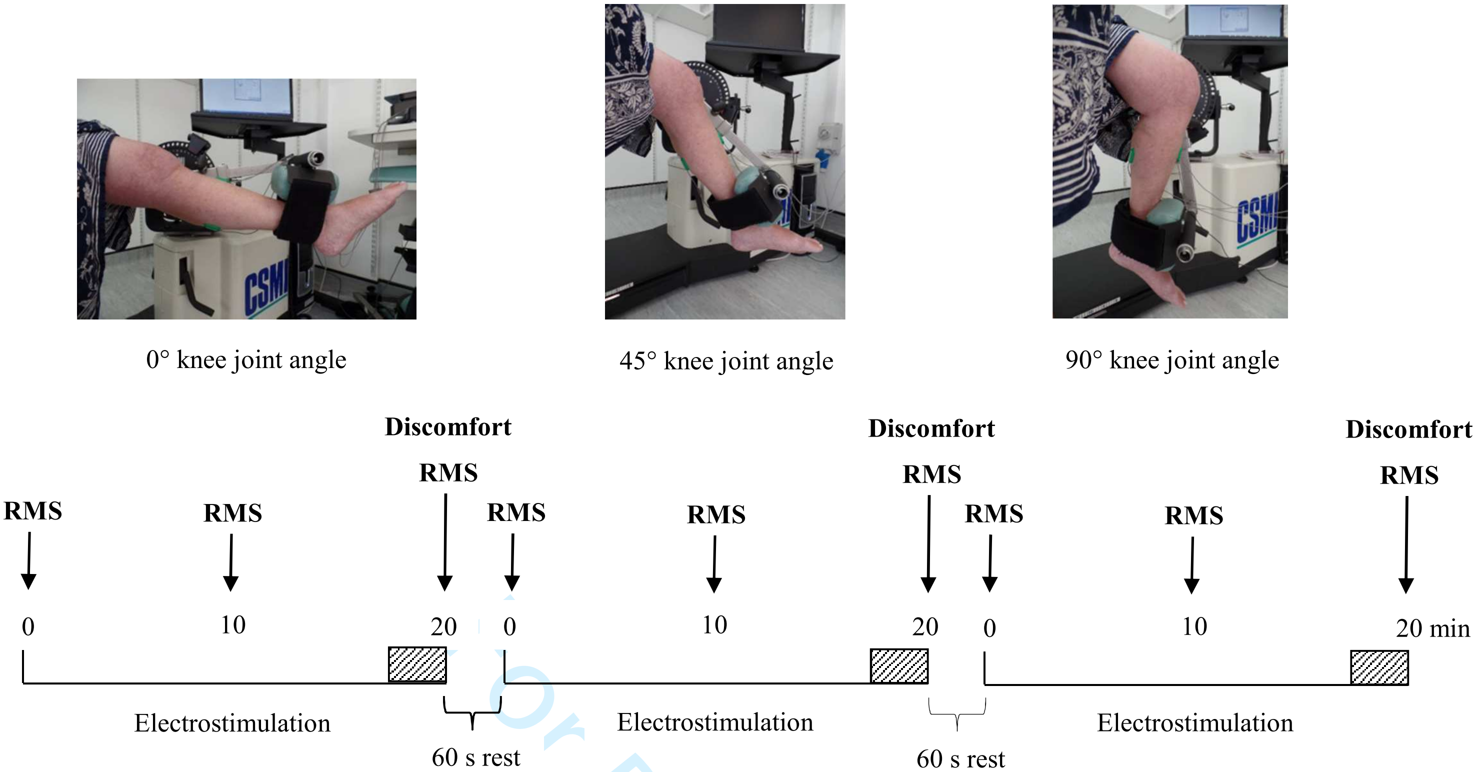
	Male	Female	All
N	7	8	15
Age (yr)	62 ± 3	70 ± 9	66 ± 8
Height (cm)	174.2 ± 6.7	163.1 ± 5.4	168.3 ± 8.2
Weight (kg)	79.0 ± 9.4	67.7 ± 15.9	73.0 ± 14.1
BMI (kg/m^2)	26.0 ± 2.2	25.2 ± 4.6	25.6 ± 3.6
Stimulation intensity (level 1 – 7)	4 ± 1	5 ± 2	5 ± 2
PASE Score	218 ± 79	136 ± 59	174 ± 79

Values are mean ± SD. BMI, body mass index; PASE, the Physical Activity Scale for the Elderly.

Table 2. Inclusion and exclusion criteria for participation

Inclusion	
Age	Between 55 years and 85 years
Health	Good general health (PASE Score > 70; norm 103 ± 64 (Washburn et al., 1993)
Cognitive	Able to understand the participant information and informed consent sheets; willing to follow the protocol requirements
Exclusion	
Age	<55 years
Health	Recently undergone surgery and/or suffered illness
Medical history	Neuromuscular, haematological and/or cardiovascular disorders; fitted with a pacemaker; history or signs of previous superficial or DVT/pulmonary embolism; varicosities, ulceration or erosion around lower-leg
BMI	Chronic obesity (BMI >40kg/m^2)

DVT, deep-vein thrombosis; BMI, body mass index; PASE, the Physical Activity Scale for the Elderly.



Electrostimulation increased from prescribed to maximum intensity (level 7) at 10

Figure 1. Schematic of the experimental protocol to examine the effect of leg position on electrostimulation. Leg position order was randomised. Black arrows indicate beginning (0 – 1 min), middle (9 – 10 min) and end (19 – 20 min) time-points for electromyography (EMG) root mean square (RMS) analysis; discomfort was assessed in the end time-point only~~grey arrows indicate the mid time-point (9 – 10 min)~~.

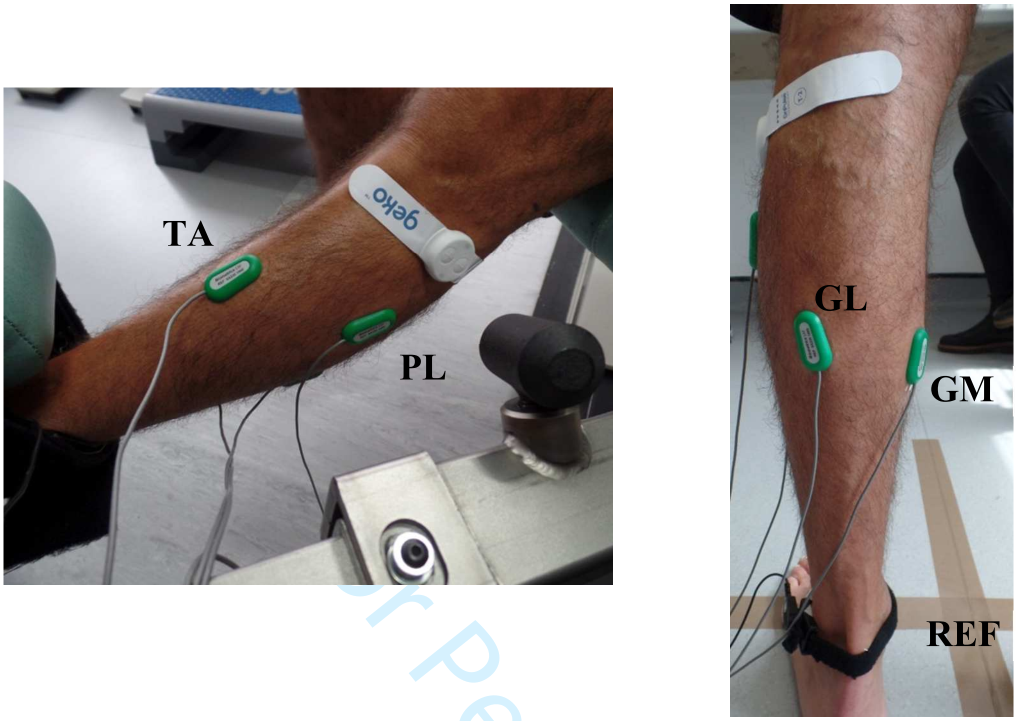
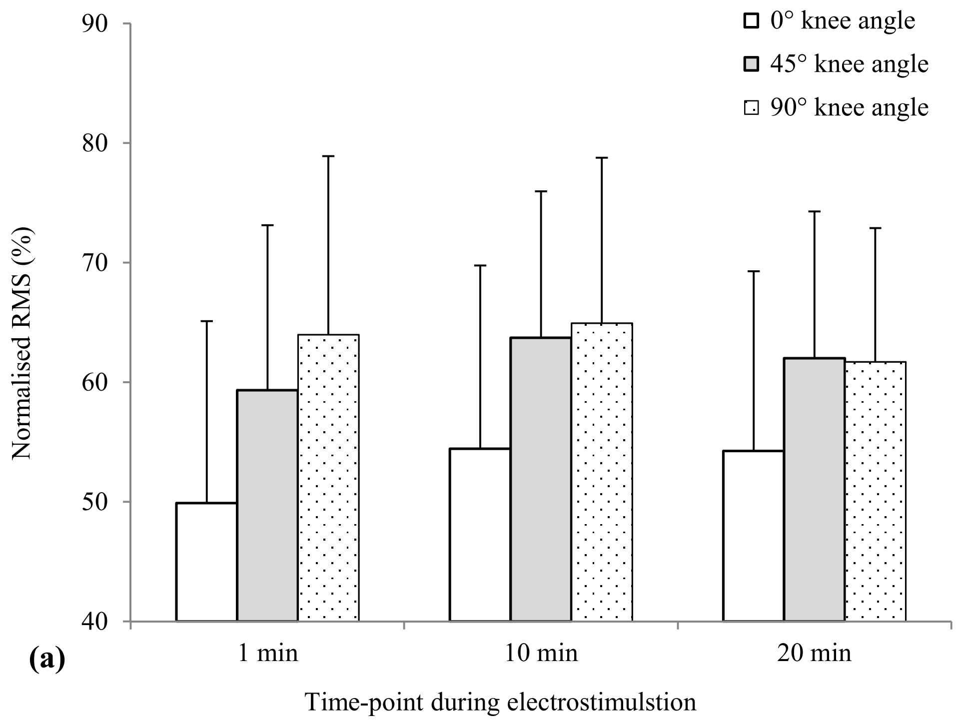


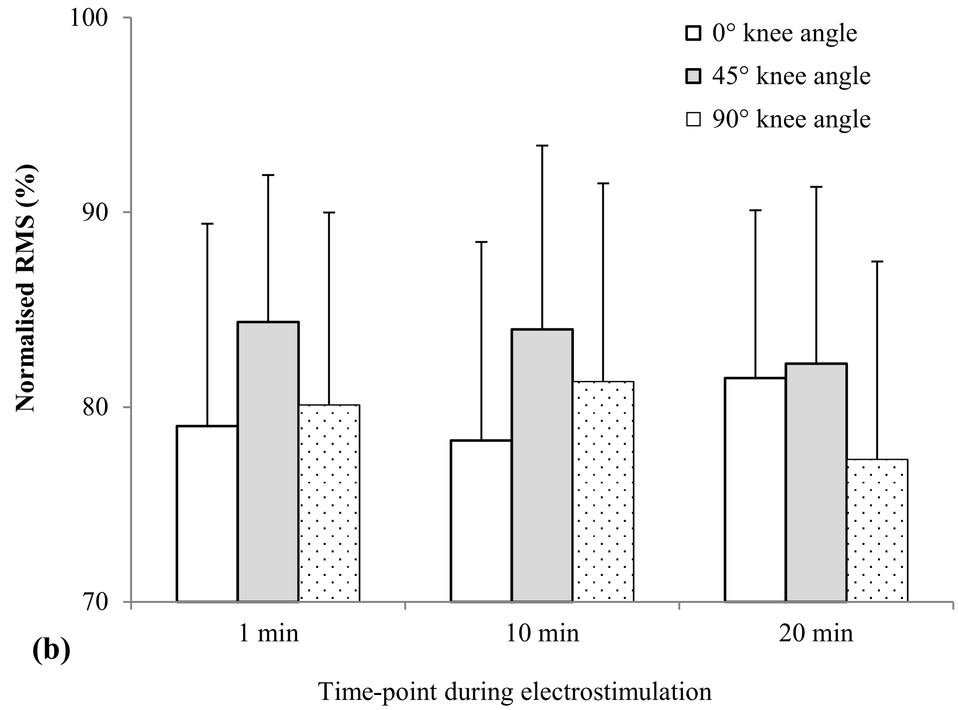
Figure 2. Left leg showing the EMG sensor placements for the *tibialis anterior* (TA), *peroneus longus* (PL) (left figure), and the *gastrocnemius lateralis* (GL), *gastrocnemius medialis* (GM) and reference electrode (REF) affixed to the lateral malleolus (right figure).

Table 3. Perceived discomfort (Visual Analogue Scale (VAS) and Verbal Rating Score (VRS)) during electrostimulation at each leg position

Discomfort scale		Male	Female	All
VAS (0 – 10)	0°	1.7 ± 0.8	2.3 ± 0.7	2.0 ± 0.8
	45°	1.9 ± 0.7	2.0 ± 0.5	1.9 ± 0.6
	90°	1.6 ± 0.8	1.8 ± 0.7	1.7 ± 0.7
VRS (1 – 7)	0°	2.1 ± 0.4	2.3 ± 0.7	2.2 ± 0.6
	45°	2.3 ± 0.5	2.0 ± 0.5	2.1 ± 0.5
	90°	2.1 ± 0.4	2.0 ± 0.4	2.1 ± 0.5

Values are mean ± SD. VAS, visual analogue scale; VRS, verbal rating score.


0° knee angle
45° knee angle
90° knee angle
90
80
70
60
50
40
Normalised RMS (%)
1 min
10 min
20 min
(a)
Time-point during electrostimulstion


0° knee angle
45° knee angle
90° knee angle
100
90
80
70
Normalised RMS (%)
1 min
10 min
20 min
(b)
Time-point during electrostimulation

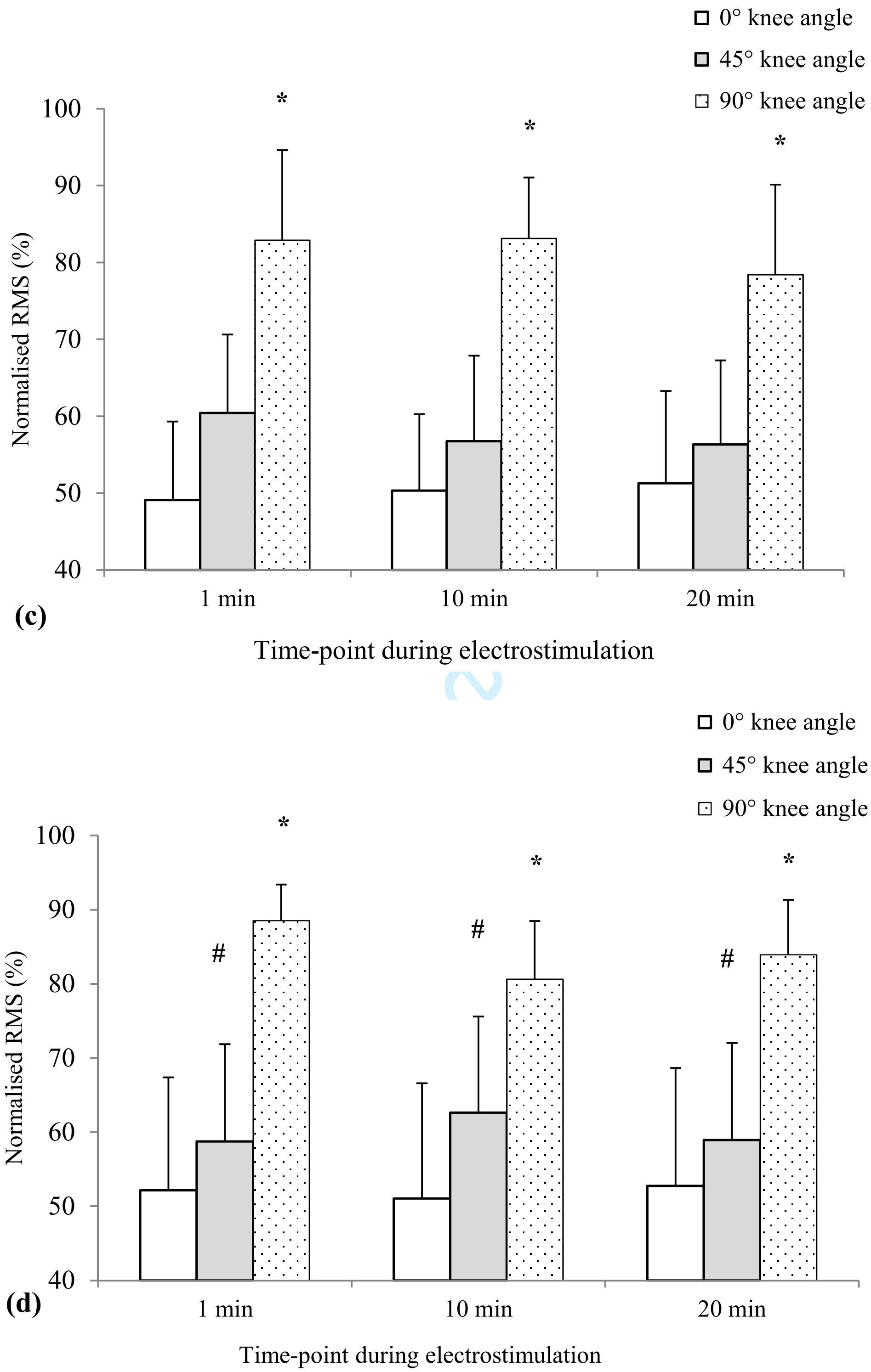
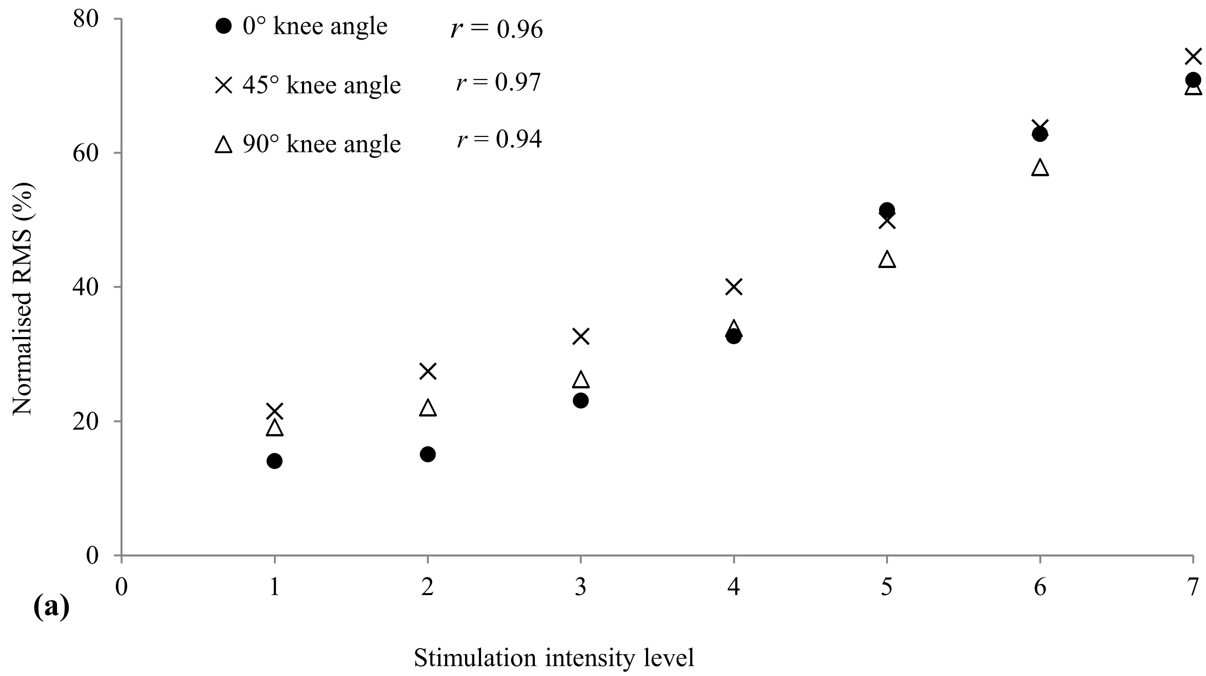


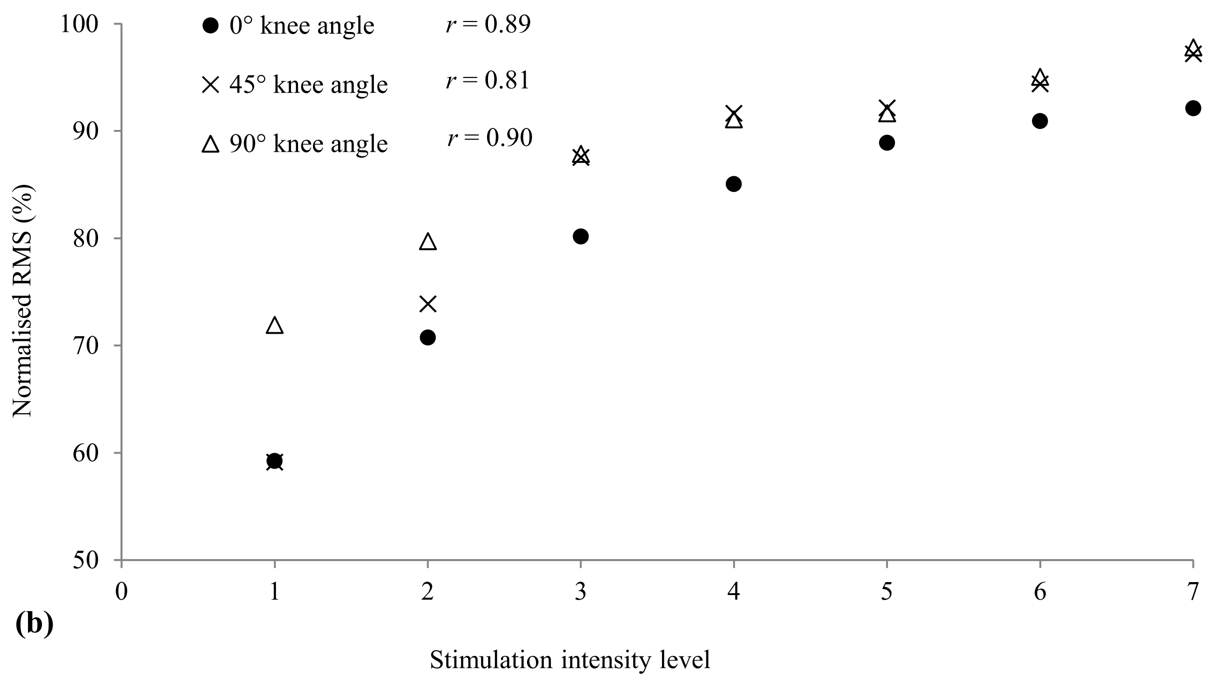
Figure 3. Normalised EMG activity of the (a) *tibialis anterior*, (b) *peroneus longus,* (c) *gastrocnemius medialis* and (d) *gastrocnemius lateralis* during 20 min of electrostimulation, at different knee joint angles. Time-points refer to:

beginning (0 - 1 min), mid (9 – 10 min) and end (19 – 20 min). * Significant difference at 90º, # significant difference at 45º, $p < 0.05$.


0° knee angle r = 0.96
45° knee angle r = 0.97
90° knee angle r = 0.94
Normalised RMS (%)
Stimulation intensity level

(a)

1


0° knee angle r = 0.89
45° knee angle r = 0.81
90° knee angle r = 0.90
Normalised RMS (%)
Stimulation intensity level

(b)

2

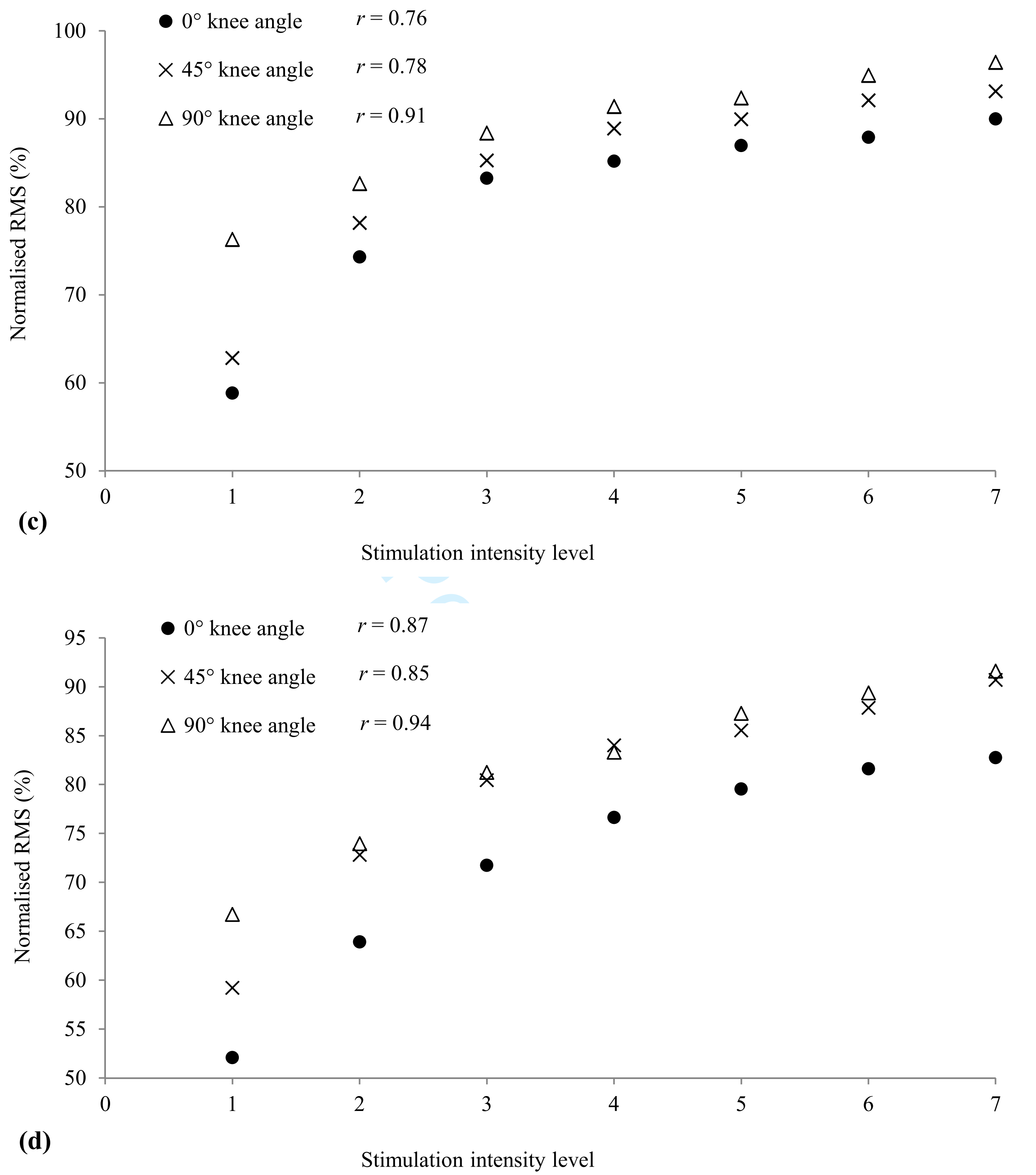


Figure 4. Relationship between the electrostimulation intensity and the normalised EMG activity (% of maximum stimulation intensity level 7) of the (a) *tibialis anterior*, (b) *peroneus longus,* (c) *gastrocnemius medialis* and, (d) *gastrocnemius lateralis*, at 0°, 45° and 90° knee joint angles. * Significant difference at 90º, $p < 0.05$.

1 **Appendix 1.** Participant physical activities in the 7 days prior to experimental electrostimulation testing.

Activity	Days per week	Hours per day
Sitting	5.83 ± 0.65	2.90 ± 1.06
Walk outside home	2.47 ± 0.92	1.37 ± 0.86
Light sport / recreational activities	0.73 ± 1.1	0.73 ± 0.79
Moderate sport / recreational activities	0.87 ± 1.06	0.59 ± 0.90
Strenuous sport / recreational activities	1.33 ± 1.45	0.92 ± 1.12
Muscle strength / endurance exercises	0.80 ± 1.01	0.20 ± 0.25
Light housework	0.93 ± 0.26	
Heavy housework or chores	0.80 ± 0.41	
Home repairs	0.20 ± 0.41	
Lawn work or yard care	0.40 ± 0.51	
Outdoor gardening	0.53 ± 0.52	
Caring for another person	0.20 ± 0.41	
Volunteering / paid work (*n* = 12)*	Hours per week	Hours per day
	29.88 ± 18.30	4.27 ± 2.61

2 Values are mean ± SD. Data was collected from the Physical Activities Scale for the Elderly (PASE). * Three

3 participants did not volunteer.