Corticospinal and spinal responses following a single session of lower limb motor skill and resistance training

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Abstract

Prior studies suggest resistance exercise as a potential form of motor learning due to task-specific corticospinal responses observed in single sessions of motor skill and resistance training. While existing literature primarily focuses on upper limb muscles, revealing a task-dependent nature in eliciting corticospinal responses, our aim was to investigate such responses after a single session of lower limb motor skill and resistance training. Twelve participants engaged in a visuomotor force tracking task, self-paced knee extensions, and a control task. Corticospinal, spinal, and neuromuscular responses were measured using transcranial magnetic stimulation (TMS) and peripheral nerve stimulation (PNS). Assessments occurred at baseline, immediately post, and at 30-minute intervals over two hours. Force steadiness significantly improved in the visuomotor task ($P < 0.001$). Significant fixed-effects emerged between conditions for corticospinal excitability, corticospinal inhibition, and spinal excitability (all $P < 0.001$). Lower limb motor skill training resulted in a greater corticospinal excitability compared to resistance training (mean difference [MD] = 35%, $P < 0.001$) and control (MD; 37%, $P < 0.001$). Motor skill training resulted in a lower corticospinal inhibition compared to control (MD; -10%, $P < 0.001$) and resistance training (MD; -9%, $P < 0.001$). Spinal excitability was lower following motor skill training compared to control (MD; -28%, $P < 0.001$). No significant fixed effect of Time or Time*Condition interactions were observed. Our findings highlight task-dependent corticospinal responses in lower limb motor skill training, offering insights for neurorehabilitation program design.

Keywords: Corticospinal excitability, motor skill training, resistance training, lower limb, transcranial magnetic stimulation.

Introduction

Adaptations in neural function from motor skill and resistance training are pivotal for acquiring and retaining skills, as well as developing strength (Adkins et al. 2006; Mason et al. 2020; Tallent et al. 2021). Use-dependent changes in the central nervous system (CNS) are evident even after a single session, driven by cellular and structural mechanisms. These mechanisms fortify existing neural connections and form new ones within the primary motor cortex (M1) following voluntary motor activity (Ackerley et al. 2011). Using transcranial magnetic stimulation (TMS), studies demonstrate increased corticospinal excitability (CSE) and intracortical facilitation (ICF), along with reduced corticospinal inhibition (silent period duration) and short-interval intracortical inhibition (SICI) after a single session of motor skill and resistance training (Alibazi et al. 2021; Christiansen et al. 2018; Leung et al. 2015; Mason et al. 2019). The convergence of these neural adaptations prompts considerations of resistance training as a form of motor learning, highlighting that individuals not only gain strength but also learn specific movement patterns associated with optimal performance (Carroll et al. 2001; Tallent et al. 2021). This perspective holds true despite differing focuses and outcomes for each motor intervention. An extensive evidence base supports the individual neural responses to motor skill and resistance training (e.g., Holland et al. 2015; Ho et al. 2022; Latella et al. 2016; Selvanagam et al. 2011). However, only a subset of studies directly compares corticospinal responses after a single session of motor skill and resistance training, with all assessments focused on the upper limbs (Leung et al. 2015; Mason et al. 2019). Unravelling the differences (or similarities) in corticospinal responses is central for clinical practitioners. This understanding will aid in designing neurorehabilitation programs to improve functional outcomes after injury.

Studies have highlighted stronger corticospinal projections from M1 to spinal motoneurons innervating upper limb muscles compared to specific lower limb muscles, though this distinction is not uniform across all lower limb muscles, such as the tibialis anterior (TA) (Brouwer & Ashby, 1990). Investigations have documented varying brain activation patterns between upper and lower limb muscles, suggesting potential neurological distinctions between the two regions (Kapreli et al. 2006; Luft et al. 2002; Volz et al. 2015). Despite these differences, most studies have predominantly focused on upper limb muscles. Initial evidence suggests that challenging and unfamiliar tasks induce cortical changes contributing to task performance (Pascual-Leone et al. 1998). Neural function changes are also inferred from modulations in corticospinal excitability (CSE) and inhibition, indicating task-dependent plasticity (Leung et al. 2015; Mason et al. 2019). Common use-dependent methods, such as visuomotor tracking and sequential learning, modulate the M1 and corticospinal pathway (Coxon et al. 2014; Dickins et al. 2015; Ho et al. 2022). Externally-paced resistance training with visual or audible feedback enhances CSE compared to self-paced movements, as well as increases in CSE observed between complex and simple finger tapping sequences (Ackerley et al. 2011; Tinazzi & Zanette, 1998). A recent meta-analysis reported increased CSE and muscle strength following externally-paced resistance training compared to self-paced and isometric modalities (Gomez-Faria et al. 2023). Task-dependent responses are also evident in lower limb muscles, particularly the TA, where visuomotor tracking increases CSE, while non-skilled and passive movements show no alteration (Perez et al. 2004). However, a meta-analysis with best evidence synthesis found conflicting evidence on CSE following lower limb motor skill training (Woodhead et al. 2023), with increases reported within the synthesis suggesting some parallels with upper limb responses (Woodhead et al. 2023).

Corticospinal projections to motoneurons innervating the TA are notably stronger than those to other leg muscles, and are even comparable to hand muscles (Petersen et al. 2003). Anticipating similar changes as observed in upper limb research following motor skill training prompts an examination of the functional roles of both upper and lower limb muscles and their consideration in potential corticospinal responses. For instance, the quadriceps, pivotal for generating high force, plays a vital role in gross motor control during walking, while the TA is involved in the fine motor control of foot trajectory during gait patterns (Winter and Bishop, 1992). On this basis, further investigation into corticospinal responses related to the quadriceps is warranted.

Given the physiological disparities between upper and lower limb muscles (Brouwer & Ashby, 1990), studies comparing motor skill and resistance training have predominantly concentrated on upper limb muscles (Jensen et al. 2005; Leung et al. 2015; Leung et al. 2017; Mason et al. 2019). These investigations unveil contrasting responses, such as increased and decreased CSE after a four-week regimen of skill and strength training targeting the elbow flexors (Jensen et al. 2005). Importantly, it is worth noting the disparity in training volume between skill and strength exercises, and recent evidence highlights that high-intensity elbow flexion training leads to greater increases in CSE compared to low-intensity training (Mason et al. 2019). The inclusion of self-paced contractions introduces a potential task-dependent effect, providing an added rationale for the observed variations. While immediate alterations in CSE and SICI following visuomotor tracking and metronome-paced strength training have been well-established in upper limb responses (Leung et al. 2015; Leung et al. 2017), the knee extensors exhibit a dose-response relationship during both high- and low-intensity strength training. This manifests as modulation in CSE and SICI, particularly following high-intensity training (Alibazi et al. 2021). These outcomes partially coincide with those reported in upper limb studies (Mason et al. 2019) but diverge from lower limb responses (Ansdell et al. 2020). The inconsistencies underscore the imperative for further exploration into how lower limb muscles respond to motor skill and resistance training, discerning whether adaptations align with those observed in upper limb muscles or present distinctive characteristics.

The temporal dynamics of corticospinal responses have been explored, revealing enhanced CSE, ICF, and diminished SICI following a single resistance training session (Brandner et al. 2015; Mason et al. 2019; Colomer-Poveda et al. 2020). In the upper limbs, an initial CSE reduction is succeeded by facilitation at 48- and 72-hours post-training (Latella et al. 2016). Knee extensors exhibit immediate CSE elevation without altering SICI (Latella et al. 2017). High-intensity strength training induces CSE and SICI modulations up to 60-min, contrary to squat training, which affects lumbar evoked potentials (LEP) without affecting CSE and SICI and elicits a facilitation at 45-min (Alibazi et al. 2021). Understanding the immediate corticospinal responses to motor training aids precise rehabilitation program design, a key factor in neurological recovery (Lang et al. 2016). Determining optimal dosing for task-specific practice in post-neurological incident recovery is subject to debate (Kwakkel et al. 2004). A detailed comprehension of the progression from acute corticospinal response to short-term adaptation, concurrent with motor function improvement, enables precise frequency and duration adjustments for effective learning or re-learning of impaired movements. This approach prevents overtraining in movement-compromised individuals and facilitates the development of efficient prescriptive guidelines. Despite its significance, limited research on the time-course of corticospinal responses underscores the need for further investigation.

To address these questions, our study aimed to evaluate the corticospinal and spinal responses elicited by a single session of lower limb motor skill and resistance training. We hypothesized that lower limb motor skill training would bring about distinctive modulations in corticospinal responses when compared to resistance training. This proposition stems from the belief that neural adaptations linked to motor skill acquisition may exhibit differences from those originating from resistance training, especially within the lower limb musculature. Furthermore, our investigation aims to enhance our understanding by evaluating LEPs and voluntary activation (VA). This approach is designed to provide insights into the excitability of the motoneuron pool and its associated inputs; an aspect that has not been explored in prior studies following both motor skill and resistance training sessions.

Methods

Participants

Following institutional ethical approval from the university at which the lead researcher is based (SMEC_2019-20_019), twelve healthy and recreationally active males volunteered to take part in the study (mean ± SD age 28 ± 6 years; stature 181 ± 4 cm; body mass 82 ± 6 kg). All participants provided written informed consent, completed a health screening and TMS-safety questionnaire prior to the commencement of the study. Participants were free from cardiorespiratory, neurological, and neuromuscular health disorders, intracranial plates, medications that might have interfered with the nervous system, and absent from potential contradictions to the use of TMS. All participants were required to arrive in a well-hydrated state, abstain from alcohol for 24 hours or caffeinated products for 12 hours, and refrain from strenuous physical activity in the 48 hours prior to data collection.

Experimental design

Participants attended the laboratory on four occasions, completing a familiarisation followed by three experimental sessions (control, resistance training and motor skill training) in a counterbalanced randomised order. Each visit was separated with ~7 days (Vaseghi et al. 2015) and the time of day for each testing session replicated to account for diurnal variations in maximal force generating capacity and corticospinal excitability (Tamm et al. 2009).

Experimental protocol

During the initial familiarisation visit, each participant was exposed to all forms of non-invasive neurostimulation, consisting of TMS, electrical stimulation of the femoral nerve (peripheral nerve stimulation, PNS) and the lumbar spinal tract. Voluntary strength testing was also conducted to measure one-repetition maximum (1-RM) of the right quadricep and was used to determine the load intensity for the resistance training session. Participants were then placed onto a custom-built chair with hip and knee angles at 90° and 60°, respectively, determined from a starting position of 0° full knee extension. This set-up was recorded and replicated at subsequent testing sessions during the assessment of neuromuscular function.

Experimental testing sessions consisted of baseline measures to assess corticospinal and spinal responses, and neuromuscular function, after which participants were randomly allocated to either the control, resistance or motor skill training session. During the control condition, participants sat rested in the laboratory for ~20-min which matched the duration of time taken to perform the motor skill and resistance training sessions. Corticospinal and spinal responses, and neuromuscular function was then assessed immediately afterwards (i.e., < 5-min cessation of training), and at 30-min, 60-min, 90-min, and 120-min post-exercise (Figure 1).

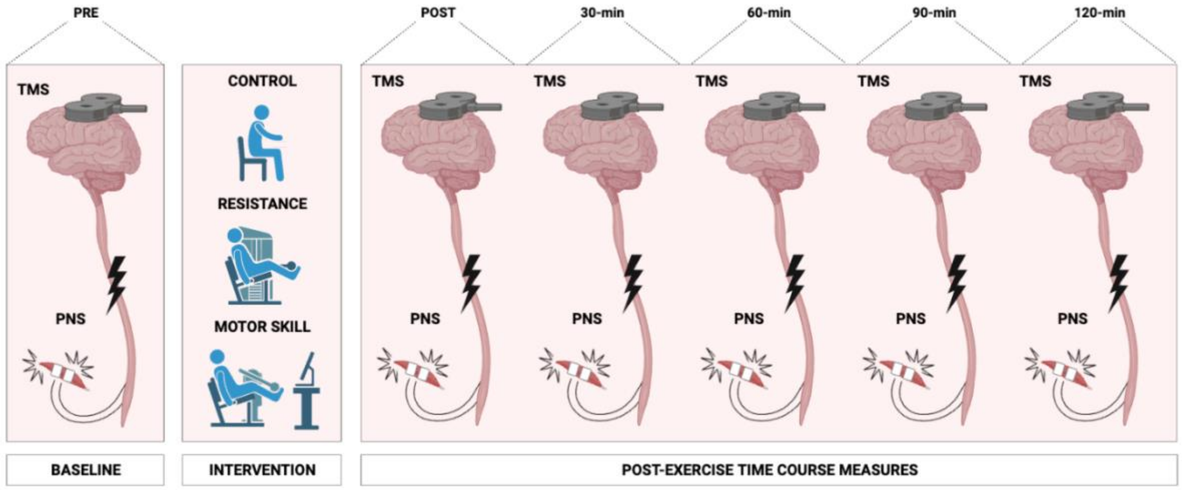

Figure 1. Schematic representation of the experimental design. Transcranial magnetic stimulation (TMS) and electrical stimulation of the femoral nerve and lumbar spinal tract were used to measure corticospinal and spinal responses, and neuromuscular function before and after (< 5-min cessation of training) a control, resistance or motor skill training session. Post time-course measures were also obtained at 30-min intervals across a two-hour period.

Neuromuscular function

Measures of neuromuscular function were assessed using electrical stimulation of the femoral nerve and lumbar spinal tract, and TMS of the M1 with evoked responses recorded via surface electromyography (EMG). Participants completed three isometric maximal voluntary isometric contractions (MVIC) separated by 30 s rest, with the peak value achieved used to calculate submaximal forces. Verbal encouragement was provided during each MVIC. Electrical stimulation of the femoral nerve was delivered during and 3 s after each MVIC to quantify maximal muscle compound action potential (M_{MAX}), VA and potentiated twitch force (Q.tw.pot). LEP amplitude was measured using electrical stimulation over the L1 and T8 spinous processes and normalised relative to M_{MAX}. Corticospinal excitability and inhibition were assessed across a range of stimulation intensities (see '*Transcranial magnetic stimulation*') during an isometric contraction at 10% MVIC.

Force and electromyography

Isometric knee extension (N) during voluntary and evoked contractions were measured with participants seated in a custom-built chair and secured via two adjustable belts across their hips and chest. A calibrated load cell (FSB-1.5 kN Universal Cell 1.5 kN, Force Logic, Reading, UK) was fixed ~2 cm superior to the medial malleolus of the participant's right leg using a non-compliant cuff. The custom-built chair was individually altered to meet the parameters of each participant, whilst ensuring the load cell was in direct line to the applied force. The hip and knee angles were placed at 90° and 60°, respectively, using a goniometer (66fit, Merseyside, UK) at the start of each session and continuously inspected to maintain a consistent set-up. EMG of the knee extensors and flexors was recorded from the rectus femoris and bicep femoris, respectively, with a reference placed over the patella according to SENIAM recommendations (Hermens et al. 2000). Following thorough skin preparation consisting of shaving, abrading, and wiping with an alcohol swab, surface electrodes (Ambu WhiteSensor, Ballerup, Denmark) were positioned with a ~2 cm inter-electrode distance over the muscle belly. The impedance was adjusted to be < 2 kΩ. The final placement was marked with indelible ink to ensure consistency throughout the session. EMG signals were amplified (x 1000), band pass filtered 10-1000 Hz (D440, Digitimer, Hertfordshire, UK) and sampled at 5000 Hz (CED Micro1401, Cambridge Electronic Design, Cambridge, UK).

Voluntary strength testing

During the familiarisation visit, the participants' voluntary strength was obtained through the completion of a unilateral knee extension 1-RM test. Before testing, participants received verbal instructions on how to perform each repetition and completed a set of warm-up contractions (1 x 10 repetitions at ~25% body mass) (Clark et al. 2019). The starting weight was then taken from the participants' estimation of their strength. During the test, participants were required to contract concentrically through the entire range of motion and rest eccentrically as the weight was subsequently lowered by the researcher. If this was successful, following a 3-min rest interval the load was progressively increased until failure of the knee extension occurred. In all tests, the participants reached their 1-RM within 5-8 attempts. The final weight was recorded as the participants 1-RM and used to determine the load intensity for the resistance training session. Verbal encouragement was provided during each contraction.

Training protocol

Control condition. Participants attended the laboratory at the same time of day as they would for the resistance and motor skill training sessions. They completed identical testing measures with the exception being that during the time the intervention would have taken place, participants sat quietly within the laboratory until post-testing measures were ready to commence.

Resistance training session. Participants completed a series of supervised unilateral knee extensions on a commercially available free weight machine (Cybex, EN 957, Stoughton, USA), set at a relative intensity of 80% 1-RM established during the familiarisation session. Training consisted of four sets with eight repetitions per set, separated by 3-min rest intervals, at a self-selected repetition timing. This was to ensure that any element of skill training was completely removed from the resistance task. Recent data has demonstrated a facilitation of corticospinal excitability following concentric contractions compared to eccentric contractions in the knee extensors (Clos et al. 2022). Therefore, participants contracted 90° through the concentric portion of the movement and rested during the eccentric phase with the researcher manually lowering the machine. This was to remove any confounding factors that could influence the corticospinal response. At the start of the session, hip angles were set at 90° and visually inspected to ensure consistency.

Motor skill training session. Participants performed a visuomotor force tracking task of the knee extensors using an isokinetic dynamometer (Cybex, Computer Sports Medicine, Stoughton, USA). The parameters of the task were identical to the resistance training session, consisting of four sets with eight repetitions per set, separated by

3-min rest intervals, with a contraction speed of 30°s^{-1}. Hip angles were maintained at 90° throughout the session. Similarly, participants were instructed to contract 90° through the concentric phase of the movement and rest during the eccentric phase as per the reasons highlighted above (see '*Resistance training session').* The visuomotor force tracking task consisted of a red line moving horizontally across a computer screen placed ~1 m in front of the participant (Signal v.6; CED; Cambridge, UK), in which they were required to produce an adequate force output to reach a load intensity of 2.5%, 5% and 20% MVIC. In doing so, participants were able to monitor and adjust their force using the concurrent visual feedback provided on the computer screen without being provided quantitative knowledge of results. Inter-set repetitions were randomised between the three load intensities (2.5%, 5% and 20% MVIC) with an equal volume across the entire visuomotor force tracking task. In addition, the load intensities used to provide a sufficient stimulus for the motor skill training session were calculated from the pre-testing maximal contractions of that day's experimental visit. Changes in motor performance were inferred from the measurement of force steadiness and quantified as the coefficient of variation (CV_{FORCE}; (SD Force / Mean Force x 100) calculated from a 1.5 s window to maximise signal stability at each submaximal target line of 2.5%, 5% and 20% MVIC (Mallette et al. 2019).

Peripheral nerve stimulation

Single electrical stimuli (200 μs duration) were delivered to the femoral nerve via self-adhesive surface electrodes (K3-ST-10, Saebo Trodes, 3.2 cm, Welwyn Garden City, UK) using a constant-current stimulator (DS7AH, Digitimer, Hertfordshire, UK). The cathode was positioned high in the femoral triangle, with the anode positioned midway between the greater trochanter and iliac crest. The cathode placement was manipulated to ensure optimal placement measured via the greatest twitch amplitude and M-wave response in the rectus femoris at rest. The intensity of the stimulation was then increased in 20 mA stepwise increments beginning at 20 mA until a plateau occurred in maximum Q.tw.pot (N) and M_{MAX} (mV). To ensure supramaximal stimulation the final intensity was then increased by a further 30% and the average M-wave was obtained from five stimuli, with a 6 s interval separating each stimulus (control, 251 ± 69 mA; resistance, 224 ± 91 mA; motor skill, 251 ± 45 mA). The intensity required to elicit M_{MAX} was re-assessed at each time-point post-exercise.

Lumbar spinal tract stimulation

Single electrical stimuli were delivered to the lumbar spinal tract using the same constant-current stimulator and pulse width as for the femoral nerve. The cathode electrode (5 x 9 cm) was centred over the first lumbar spinous process (L_1) with the long axis of the electrode aligned to the centre of the vertebral column (Ansdell et al. 2020). The anode was located over the eighth thoracic spinous process (T_8). The intensity of stimulation started at an initial 20 mA and increased in 40 mA until a response of 10-15% M_{MAX} was elicited (control, 349 ± 92 mA; resistance, 299 ± 82 mA; motor skill, 323 ± 94 mA). Once this had been achieved, the final stimulation intensity was recorded and maintained throughout subsequent time points. An average of five stimuli was then taken to obtain LEP amplitude.

Transcranial magnetic stimulation

Single-pulse TMS was delivered over the M1 via a double-coned coil (110 mm diameter; maximum output 1.4 T) using a Magstim 200^2 magnetic stimulator. The coil was held and tilted (1-2 cm) lateral to the vertex to stimulate the contralateral hemisphere to the right leg and induce a posterior-anterior cortical current. First, the optimal location ("hotspot") was determined by locating the coil position to elicit the largest MEP response in the rectus femoris at 50% maximal stimulator output and during a 10% MVIC, after which the optimal position was marked with indelible ink to ensure consistent placement. Active motor threshold (AMT) was determined at the beginning of each visit and at each experimental time point, established as the lowest stimulus intensity required to evoke an MEP amplitude larger than 200 μV in three out of five consecutive trials (Kidgell et al. 2010). Starting at 50% maximal stimulator output, the intensity was lowered in 5% decrements until the MEP response did not exceed 200 μV, after which the stimulator output was adjusted in 1% increments until the lowest intensity eliciting an MEP response was found (control: 37 ± 7%, resistance: 36 ± 4%, motor skill: 36 ± 6% of maximum stimulator output). Recruitment curves were constructed for the rectus femoris to assess corticospinal excitability and inhibition at each experimental time point. Ten single TMS pulses separated by a 6 s interval were delivered at 130, 150 and 170% AMT (30 in total), respectively, during a 10% MVIC of the rectus femoris. These intensities were delivered in a randomised order and selected based upon pilot data finding this range elicited the largest response in the quadricep.

Reliability coefficients

Test-retest reliability was calculated between the pre- and post-data from the control condition using two indices, intraclass correlation coefficients (ICC) and coefficient of variation (CV) (Hopkins, 2000). Reliability data was calculated for corticospinal excitability, corticospinal inhibition, spinal excitability, MVIC, VA, Q.tw.pot and M_{MAX}.

Data analysis

Pre-stimulus EMG activity was calculated as the root-mean-square (RMS) in the preceding 100 ms epoch before each TMS stimulus, determined in the rectus femoris at each experimental time point. MVIC force was calculated as the peak force level attained from three MVICs. Peak-to-peak amplitudes and twitch force for M_{MAX} were averaged across five electrical stimuli delivered with a 6 s interval. Peak-to-peak MEP amplitudes were measured in the rectus femoris muscle, recorded in mV, averaged for each stimulation intensity, normalised to M_{MAX}, and multiplied by 100. The total area under the recruitment curve (AURC) was calculated via the trapezoidal integration method using the corticospinal excitability (MEP/M_{MAX} ratio) and inhibition (silent period duration) data collected during the construction of the curves at each experimental visit and time point. The duration of the TMS-evoked corticospinal silent period was assessed from the stimulus artefact to the resumption of background EMG via visual inspection (Damron et al. 2008). VA was measured through stimulation of the femoral nerve and was quantified using the twitch interpolation technique (Merton, 1954). The amplitude of the superimposed twitch delivered during an MVIC was compared to the amplitude of a resting, potentiated twitch delivered ~2 s after the MVIC. The following calculation was used to assess VA:

$$\text{Voluntary activation (\%)} = (1 - [\text{SIT}/Q_{\text{tw.pot}}] \times 100)$$

Statistical analysis

Sample size was calculated using an *a priori* analysis which included a statistical power of $\beta = 0.80$ and α err prob of 0.05, with an observed effect size of 0.35 based on a conservative approach of MEP data from previous literature (Bakker et al. 2021; Colomer-Poveda et al. 2019; Colomer-Poveda et al. 2020). Similar studies have used a sample size of ~10 participants which has been adequate to observe a statistically significant effect (Leung et al. 2017; Mason et al. 2019), therefore 12 participants were recruited for the current study based on *a priori* calculations and to account for potential dropouts.

A Linear Mixed Model with Repeated Measures (LMM-RM), incorporating two factors with repetitions across both time and subjects, was employed to evaluate percentage changes in dependent variables, with baseline data represented as 100%.. Participants were entered into the model as random factors, with Time (ΔPre-Post, ΔPre-30-min, ΔPre-60-min, ΔPre-90-min, ΔPre-120-min), Condition (control, motor skill and resistance) and Time*Condition interaction entered as fixed factors. A LMM-RM was also used to assess changes in force steadiness (CV_{FORCE}) following the visuomotor force tracking task with Participants entered as random factors with Time entered as a fixed factor; however, raw data was included within the model instead of percentage change data. In all tests, statistical significance was set at $P < 0.05$ and if significant main effects or interactions were observed, analysis was continued using pairwise comparisons with Bonferroni correction. The LMM-RM was deemed the most appropriate choice of statistical test due to a missing data point from the assessment of lumbar stimulation. Wilkinson et al. (2022) demonstrated that LMM-RM are superior when handling missing data and can more accurately model neuromechanics data; therefore, to remain consistent with our approach a LMM-RM was conducted for each dependent variable. For all comparisons, Hedge's g with correction for small sample sizes were used to calculate effect sizes (< 0.2 = small, 0.2-0.8 = medium, > 0.8 = large effect). All statistical analyses were completed using SPSS Statistics v25.0 (SPSS, IBM, New York, New York).

Results

Motor performance

Force steadiness improved across the visuomotor force tracking task within the motor skill training session ($P < 0.001$). *Post hoc* analysis revealed a decrease in the CV_{FORCE} from set one compared to set two (mean difference [MD] = -11%, $P = 0.001$; $g = 1.02$), set three (MD = -11%, $P = 0.002$; $g = 0.83$) and set four (MD = -10%, $P = 0.006$; $g = 0.62$) (Figure 2).

Corticospinal and spinal responses

A significant fixed effect between Conditions was found for corticospinal excitability ($F_{(2)} = 13.119$; $P < 0.001$; Figure 3). *Post hoc* comparisons revealed a greater CSE AURC following motor skill training compared to resistance training (MD = 35%; $P < 0.001$; CI 15.116 to 54.411; $g = 1.01$) and the control condition (MD = 37%; $P < 0.001$; CI 17.666 to 56.961; $g = 0.44$). No fixed effect was observed for Time ($P = 0.742$) or Time*Condition interaction ($P = 0.737$). ICC and CV for corticospinal excitability were 0.94 and 12%, respectively. A significant fixed effect between Conditions was observed for corticospinal inhibition ($F_{(2)} = 8.554$; $P < 0.001$; Figure 4). *Post hoc* comparisons revealed a lower silent period AURC following motor skill training compared to the control condition (MD = -10%; $P < 0.001$; CI -3.460 to -16.079; $g = 0.41$). *Post hoc* comparisons also revealed a lower silent period AURC following resistance training compared to the control condition (MD = -9%; $P < 0.002$; CI -2.586 to -15.205; $g = 0.38$). No fixed effect was observed for Time ($P = 0.171$) or Time*Condition interaction ($P = 0.776$). ICC and CV for corticospinal inhibition were 0.23 and 21%, respectively. A significant fixed effect between Conditions was found for spinal excitability ($F_{(2)} = 8.542$; $P < 0.001$; Figure 5). *Post hoc* comparisons revealed a lower LEP/M_{MAX} following motor skill training compared to the control condition (MD = -28%; $P < 0.001$; CI -11.764 to -44.930; $g = 0.47$). No fixed effect was observed for Time ($P = 0.882$) or Time*Condition ($P = 0.740$). ICC and CV for spinal excitability were 0.37 and 43%, respectively.

Neuromuscular function

No fixed effect for Time ($P = 0.716$), Condition ($P = 0.517$) or Time*Condition ($P = 0.999$) was observed for MVIC (Figure 6). ICC and CV for MVIC were 0.87 and 9%, respectively. VA showed a fixed effect for Time ($F_{(5)} = 7.101$; $P < 0.001$) with *post hoc* comparisons displayed in Figure 6. A significant fixed effect between Conditions was observed ($F_{(2)} = 8.646$; $P < 0.001$). *Post hoc* comparisons revealed a lower VA following resistance training compared to motor skill training (MD = -3%; $P = 0.001$; CI -1.094 to -5.406; $g = 0.45$). *Post hoc* tests comparisons also revealed a lower VA in the control condition compared to motor skill training (MD = -3%; $P < 0.001$; CI -1.025 to -5.336; $g = 0.47$). No fixed effect was observed for Time*Condition interaction ($P = 0.584$). ICC and CV for VA were 0.66 and 7%, respectively.

Potentiated twitch force showed a fixed effect for Time ($F_{(5)} = 2.552$; $P = 0.029$). *Post hoc* comparisons revealed a greater Q.tw.pot between baseline and 60-min (MD = 24%; $P = 0.042$; CI 0.432 to 48.402; $g = 0.92$). A significant fixed effect between Conditions was observed ($F_{(2)} = 7.412$; $P < 0.001$). *Post hoc* comparisons revealed a greater Q.tw.pot following resistance training compared to the control condition (MD = 22%; $P < 0.001$; CI 7.744 to 35.311; $g = 0.49$). *Post hoc* tests also revealed a greater Q.tw.pot following motor skill training compared to the control condition (MD = 15%; $P = 0.033$; CI 0.842 to 28.408; $g = 0.30$; Figure 6). No fixed effect for Time*Condition interaction was observed ($P = 0.722$). ICC and CV for potentiated twitch force were 0.58 and 21%, respectively.

A significant fixed effect for M_{MAX} was found between Conditions ($F_{(2)} = 7.059$; $P < 0.001$). *Post hoc* comparisons revealed a lower M_{MAX} amplitude following motor skill training compared to resistance training (MD = -13%; $P < 0.001$; CI -4.639 to -21.667; $g = 0.45$). No fixed effect was observed for Time ($P = 0.641$) or Time*Condition interaction ($P = 0.379$). No fixed effect for Time ($P = 0.975$), Conditions ($P = 0.101$) or Time*Condition ($P = 0.916$) was observed for AMT. Background muscle activity (RMS_{EMG}/M_{MAX}) showed a fixed effect for Time ($F_{(5)} = 3.235$; $P = 0.008$) and between Conditions ($F_{(5)} = 29.948$; $P < 0.001$). A significant Time*Condition interaction was also observed ($F_{(10)} = 2.232$; $P = 0.017$). All *post hoc* comparisons are displayed in Table 1. ICC and CV for M_{MAX} were 0.93 and 13%, respectively.

Discussion

The primary objective of our investigation was to examine the corticospinal and spinal responses subsequent to a single session of lower limb motor skill and resistance training. Our hypothesis posited that lower limb motor skill training would elicit unique corticospinal responses compared to resistance training, mirroring the observed task-dependency in upper limb muscles. The central finding reveals that a low-force visuomotor tracking task targeting the knee extensors induced greater corticospinal excitability than a non-fatiguing, self-paced resistance training session. Additionally, both motor skill and resistance training led to reduced corticospinal inhibition, as indicated by a shortened corticospinal silent period. Moreover, lower limb motor skill training, but not resistance training, resulted in diminished spinal excitability compared to the control condition. It is noteworthy that the visuomotor force tracking task implemented in our study as the motor skill training intervention was appropriately challenging, fostering improvements in motor performance.

Our study demonstrates task-dependent modulation of CSE following a single session of lower limb motor skill training compared to resistance training. Employing a visuomotor force tracking task challenging the visual and motor systems to achieve specific movements, and coupling this with self-paced resistive exercise, we investigated external constraints' influence on corticospinal responses. It is established that tasks of higher difficulty/complexity foster CSE facilitation compared to simpler tasks (Jensen et al. 2005; Leung et al. 2015; Leung et al. 2017; Mason et al. 2019). Our findings align with previous research, shedding light on the mechanisms underpinning modifications in the corticospinal pathway post-motor skill training. The visuomotor task's dynamic nature relies on factors accumulating to challenge the central nervous system (CNS), distinguishing it from self-paced regimes through novel somatosensory feedback via group III afferents (Hortobagyi et al. 1997; Kidgell et al. 2015). Neurorehabilitation often involves skill and strength training for positive physiological outcomes (Fimland et al. 2010; Williams et al. 2014), emphasising basic motor skill learning and muscular strength development. Our results reinforce the idea that external constraints, like visual cues, drive corticospinal plasticity. This suggests that clinical practitioners can enhance interventions by incorporating such constraints for more effective neurorehabilitation.

Studies comparing corticospinal responses between motor skill and resistance training have exclusively focused on upper limb muscles, leaving a gap in understanding lower limb muscle responses to these modalities (Jensen et al. 2005; Leung et al. 2015; Mason et al. 2019). A recent meta-analysis exploring lower limb motor skill training found conflicting evidence for CSE, with TA and soleus muscle studies included and lacking knee extensor stimulation (Woodhead et al. 2023). While TA and soleus exhibit similar ankle joint functionality, they differ in motor cortical control during specific movements, highlighting heterogeneity within lower limb muscles (Lauber et al. 2018). In contrast to the best evidence synthesis, two studies reported increased CSE, while three found no difference (Bakker et al. 2021; Hirano et al. 2015; Tatemoto et al. 2015) in the TA and soleus. Our study, consistent with upper limb findings, shows lower limb muscles (knee extensors) modulate CSE following motor skill training, aligning with the idea that muscles with specific motor requirements adapt similarly (Capaday et al. 1999). The knee extensors large force generation function contrasts with the corticospinal tract's fine motor movement preference, yet high-intensity resistance training induces responsiveness consistent with upper limb trends (Ansdell et al. 2020; Alibazi et al. 2021). The absence of a temporal effect may be ascribed to diverse methodological and physiological considerations, encompassing factors like background muscle activity and stimulation intensity (Darling et al. 2006) or genetic predisposition variations, such as the brain-derived neurotrophic factor polymorphism, impacting the corticospinal response (Cirillo et al. 2011; Frazer et al. 2018). Despite potential confounders, our methodology ensures confidence in the observed lower limb motor skill training-induced CSE modulation

In our present study, we have demonstrated that corticospinal inhibition is diminished following both lower limb motor skill and resistance training, aligning with findings in acute resistance training studies that reported reductions in the silent period and SICI (Alibazi et al. 2021; Latella et al. 2018). In contrast, squat training sessions showed no effect on both indices (Ansdell et al. 2020). It is plausible that disparities in the muscle tested and the knee angle during stimulation contribute to these differing outcomes, with Ansdell et al. (2020) focusing on the vastus lateralis at 90° while our study targeted the rectus femoris at 60°. Our findings are also congruent with the motor learning literature, indicating reductions in SICI across various motor tasks (Dupont-Hadwen et al. 2019; Mooney et al. 2019; Smyth et al. 2010), although intracortical inhibition measurement was not feasible in our study. Visuomotor tracking of the TA, due to the task constraints demanding enhanced attentional focus, reduced SICI, whereas no effect was observed following passive or self-paced motor training (Perez et al. 2004). This task-dependency aligns with literature comparing motor skill and resistance training, showing reductions in SICI after a single session (Leung et al. 2015) and short-term training (Leung et al. 2017), although these studies were conducted on upper limb muscles. Notably, we observed a shortened corticospinal silent period following a self-paced resistance training session, contrary to previous literature reporting that self-paced motor tasks do not alter the inhibitory response (Leung et al. 2015; Leung et al. 2017; Perez et al. 2004). A meta-analysis of resistance training interventions with different constraints (metronome-paced, self-paced, or isometric) found a reduction in corticospinal inhibition, but no change in SICI, in all three modalities (Gomez-Faria et al. 2023), with the largest reduction observed following metronome-paced strength training, confirming that external constraints accentuate the corticospinal response (Leung et al. 2015; Leung et al. 2017). Recent reviews have enhanced understanding of lower limb corticospinal responses to resistance training (Gomez-Feria et al. 2023) and motor skill training (Woodhead et al. 2023). However, the limited number of studies investigating how lower limb muscles respond to each motor intervention calls for further research. This research should assess indices of excitation (CSE, ICF) and inhibition (silent period, SICI), particularly following single sessions, and examine how acute responses transition into short-term adaptations over multiple training sessions.

Our objective was to elucidate the corticospinal and spinal contributions subsequent to a single session of lower limb motor skill and resistance training, revealing that a visuomotor force tracking task reduced spinal excitability, while the resistance session showed no effect. The concept of repetitively stimulating the corticospinal tract strengthening synaptic connections, leading to an augmented response to subcortical stimulation, has been proposed (Nuzzo et al. 2016). This notion aligns with observations of increased spinal excitability 15- and 45-min post-acute squat training in the vastus lateralis (Ansdell et al. 2020). Conversely, resistance training in the current study did not influence spinal structures, potentially attributed to the stimulation of a different knee extensor muscle (rectus femoris). The novel finding that motor skill training reduces spinal excitability sheds light on the locus of adaptation. Greater CSE following motor skill training compared to resistance training and control suggests a likely cortical origin of the observed change. However, the inability to assess cortical measures such as ICF and SICI prevents confirmation. This study, the first to employ lumbar stimulation after a single session of lower limb motor skill and resistance training, demonstrates the modulatory effect of visuomotor tracking on the spinal cord. Our methods extend previous research using the Hoffmann reflex (Motl & Dishman, 2003; Perez et al. 2005), indicating that lumbar stimulation is a more suitable technique for assessing lower limb muscles (Škarabot et al. 2019). Future investigations should further explore the spinal responses to motor skill and resistance training by integrating various neurophysiological variables to gain a comprehensive understanding of the entire neuroaxis (Martin, 2008).

The current study observed an overall reduction in VA as well as lower values following resistance training and the control compared to motor skill training. The novel approach of combining various neurophysiological measures has enabled the further investigation into the efficacy of activating the motoneuron pool; however, research studying the effect of resistance training on VA is lacking. There have been some attempts following short-term interventions which have reported no effect (Lee et al. 2009; Siddique et al. 2020), and given the lack of information, the lower VA observed in the current study could be attributed to a different physiological mechanism. In light of the high-intensity nature of the resistance training (80% 1-RM) compared to the motor skill session (2.5%, 5% and 20% MVIC) performed in the current study, the findings observed could be suggested as a consequence of central fatigue processes as the twitch interpolation technique provides a surrogate measure of fatigue mechanisms (Neyround et al. 2016). However, despite this high intensity, the volume performed should not have been adequate to induce acute fatigue. This is evident in the maintenance of MVIC force, which in addition to an unexpected finding that the control condition resulted in a lower VA compared to motor skill training, questions the possibility that central fatigue may be the primary cause for the reduced VA reported in the current study. This is the first study to assess VA following motor skill training and therefore an exact explanation for this finding is difficult; however, we tentatively suggest that by the virtue of repeatedly activating the CST during the visuomotor task, albeit at a low intensity, there may have been a potentiation effect that attenuated a smaller decrease in VA. Nevertheless, there is recent evidence that motor skill acquisition under fatigued conditions negatively affects learning rates (Branscheidt et al. 2019), and so the exploration of how motor skill training impacts upon the fatigue response, and vice versa, would be an interesting avenue for further research.

In the examination of peripheral responses to motor skill and resistance training in this study, a noteworthy increase in evoked force was observed compared to the control, along with an overall rise in potentiated twitch force from baseline to 60 minutes post-exercise. While reductions in potentiated twitch are indicative of 'peripheral fatigue' (Neyroud et al. 2013), the current study reports an augmented evoked force. Despite the distinct volumes of motor skill and resistance training, both modalities could have significantly potentiated the twitch response compared to the lack of contractions in the control. Hence, attributing this effect solely to peripheral fatigue is premature and warrants further quantitative analysis of peripheral responses post motor skill and resistance training. Additionally, a lower M_{MAX} amplitude following both motor skill and resistance training raises the possibility of peripheral fatigue as an underlying mechanism, particularly in the context of contractile function impairments at the sarcolemma, inferred from the decline in M_{MAX}. Surprisingly, this effect was observed following low MVIC intensity motor skill training. In contrast, the findings contradict those of Woodhead et al. (2023), where M_{MAX} remained unchanged based on the pooled effects of two included studies, but these studies utilized balance assessments. The lower M_{MAX} reported here lacks an exact rationale and necessitates cautious interpretation, given the influence of various physiological and methodological factors on the M_{MAX} response, including different assessment methods of M-wave phases that offer insights into underlying mechanisms (Rodriguez-Falces et al. 2017; Rodriguez-Falces et al. 2020). Given these considerations and the empirical data, future research should assess the M_{MAX} both as a normalization method and a dependent variable to scrutinize potential peripheral mechanisms following motor skill training specifically.

Summary and conclusions

This is the first study to investigate the corticospinal and spinal responses following a single session of lower limb motor skill and resistance training. We demonstrate that a visuomotor force tracking task of the knee extensors modulated CSE to a greater extent than a self-paced resistance training session, which infers that changes to the excitability of the corticospinal tract are induced by distinct mechanisms related to the acquisition of a novel motor skill rather than those implicated following resistance training. This indicates a task-dependent nature of CSE in the lower limb muscles which is similar to that reported in the upper limb muscles. Our results also demonstrate that both training modalities lowered corticospinal inhibition compared to our control condition. Furthermore, we provide initial evidence that motor skill training performed in the lower limb muscles is capable of modulating subcortical structures, inferred from a lower spinal excitability. Understanding both the responses to training as well as enhancements in motor performance, which are demonstrated in the current study via an improvement in force steadiness, can assist clinical practitioners in the design and implementation of neurorehabilitation programmes. This is with the aim of achieving positive functional outcomes that can have a significant impact on an individuals quality of life.

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Conflicts of interest

The authors declare no conflict of interest, financial or otherwise.

Data availability

The datasets generared during and/or analysed during the current study are available from the corresponding author on reasonable request.

Figures and Tables

Figure 1. Schematic representation of the experimental design. Transcranial magnetic stimulation (TMS) and electrical stimulation of the femoral nerve and lumbar spinal tract were used to measure corticospinal and spinal responses, and neuromuscular function before and after (< 5-min cessation of training) a control, resistance or motor skill training session. Post time-course measures were also obtained at 30-min intervals across a two-hour period.

Figure 2. Coefficient of variation for force ($CV_{FORCE,}$ %) during a visuomotor force tracking task of the knee extensors calculated from a 1.5 s window at each submaximal target line of 2.5%, 5% and 20% maximal voluntary isometric contraction. Solid black lines represent mean CV_{FORCE} whereas the dashed lines represent individual responses. Force steadiness improved across the visuomotor force tracking task ($P < 0.001$). * denotes a significant decrease in CV_{FORCE} from set one to set two ($P < 0.001$). # denotes a significant decrease from set one to set three ($P < 0.002$). † denotes a significant decrease from set one to set four ($P < 0.006$). Data is presented as means and 95% confidence intervals.

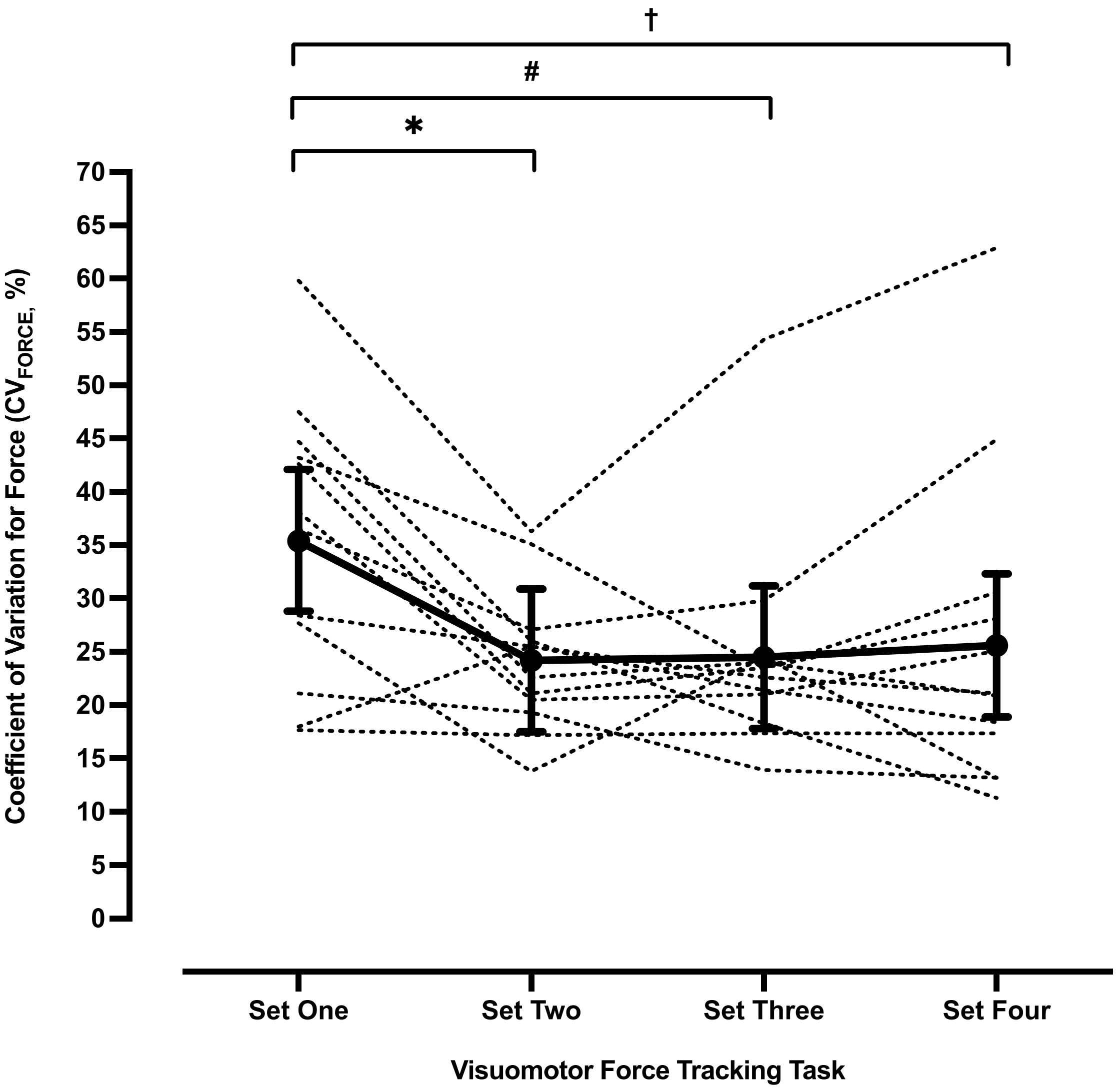
Figure 3. Mean changes (95% confidence intervals) in area under the recruitment curve (AURC) for corticospinal excitability (CSE) assessed at 130%, 150% and 170% active motor threshold (AMT). Values were obtained at baseline, immediately following (i.e., < 5-min cessation of training) a motor skill training session, resistance training session or control, and at 30-min, 60-min, 90-min and 120-min post-exercise. There was a significant fixed effect between Conditions ($P < 0.001$). * denotes a significantly greater CSE AURC following motor skill training compared to resistance training ($P < 0.001$). # denotes a significantly greater CSE AURC following motor skill training compared to the control ($P < 0.001$). No fixed effect was observed for Time ($P = 0.742$) or Time*Condition interaction ($P = 0.737$).

Figure 4. Mean changes (95% confidence intervals) in area under the recruitment curve (AURC) for corticospinal inhibition (duration of the corticospinal silent period, CSP) assessed at 130%, 150% and 170% AMT. Values were obtained at baseline, immediately following (i.e., < 5-min cessation of training) a motor skill training session, resistance training session or control, and at 30-min, 60-min, 90-min and 120-min post-exercise. There was a significant fixed effect between Conditions ($P < 0.001$). * denotes a significantly lower silent period AURC following resistance training compared to the control ($P < 0.002$). # denotes a significantly lower silent period AURC following motor skill training compared to the control ($P < 0.001$). No fixed effect was observed for Time ($P = 0.171$) or Time*Condition interaction ($P = 0.776$).

Figure 5. Mean changes (95% confidence intervals) in spinal excitability (LEP/M_{MAX}). Values were obtained at baseline, immediately following (i.e., < 5-min cessation of training) a motor skill training session, resistance training session or control, and at 30-min, 60-min, 90-min and 120-min post-exercise. There was a significant fixed effect between Conditions ($P < 0.001$). * denotes a significantly lower LEP/M_{MAX} following motor skill training compared to the control ($P < 0.001$). No fixed effect was observed for Time ($P = 0.882$) or Time*Condition ($P = 0.740$).

Figure 6. Mean changes (95% confidence intervals) were obtained at baseline, immediately following (i.e., < 5-min cessation of training) a motor skill training session, resistance training session or control, and at 30-min, 60-min, 90-min and 120-min post-exercise. **A** maximal voluntary isometric contraction (MVIC). No fixed effect for Time ($P = 0.716$), Condition ($P = 0.517$) or Time*Condition ($P = 0.999$) was observed for MVIC. **B** Voluntary activation (VA). There was a significant fixed effect for Time ($P < 0.001$). * denotes a significantly lower VA following resistance training compared to motor skill training ($P = 0.001$). # denotes a significantly lower VA following the control compared to motor skill training ($P < 0.001$). No fixed effect was observed for Time*Condition interaction ($P = 0.584$). **C** Potentiated twitch force (Q.tw.pot, N). There was a significant fixed effect for Time ($P = 0.029$). * denotes a significant increase in Q.tw.pot from baseline to 60-min ($P = 0.042$). # denotes a significantly greater Q.tw.pot following resistance training compared to the control ($P < 0.001$). † denotes a significantly greater Q.tw.pot following motor skill training compared to the control ($P = 0.033$). No fixed effect for Time*Condition interaction was observed ($P = 0.722$)

Table 1. Percentage change data for M_{MAX}, AMT and pre-stimulus EMG (RMS_{EMG}/M_{MAX}) calculated between baseline and immediately post-exercise (< 5-min cessation of training), 30-min, 60-min, 90-min and 120-min. Data is presented as percentage change and 95% confidence intervals.



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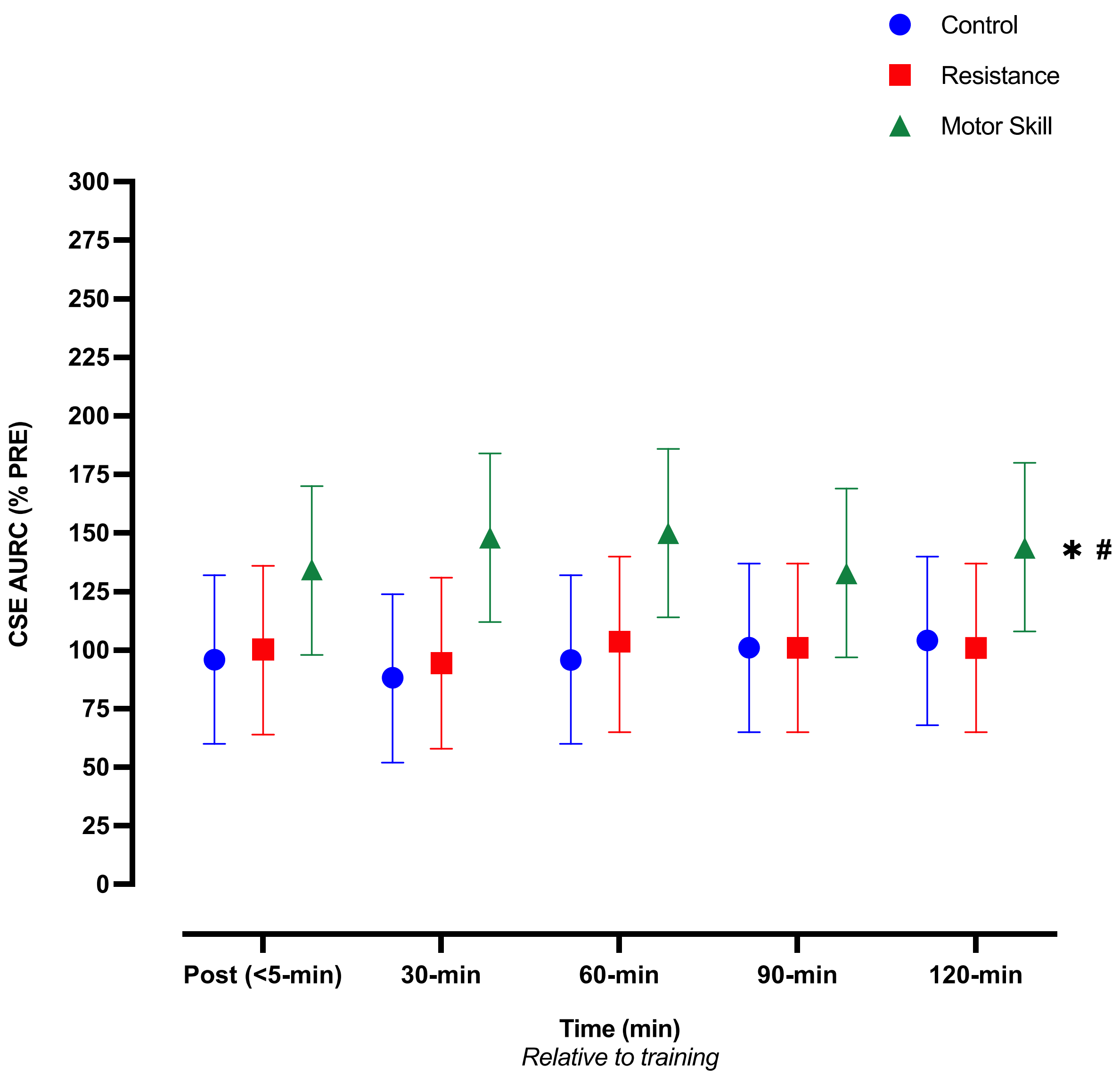

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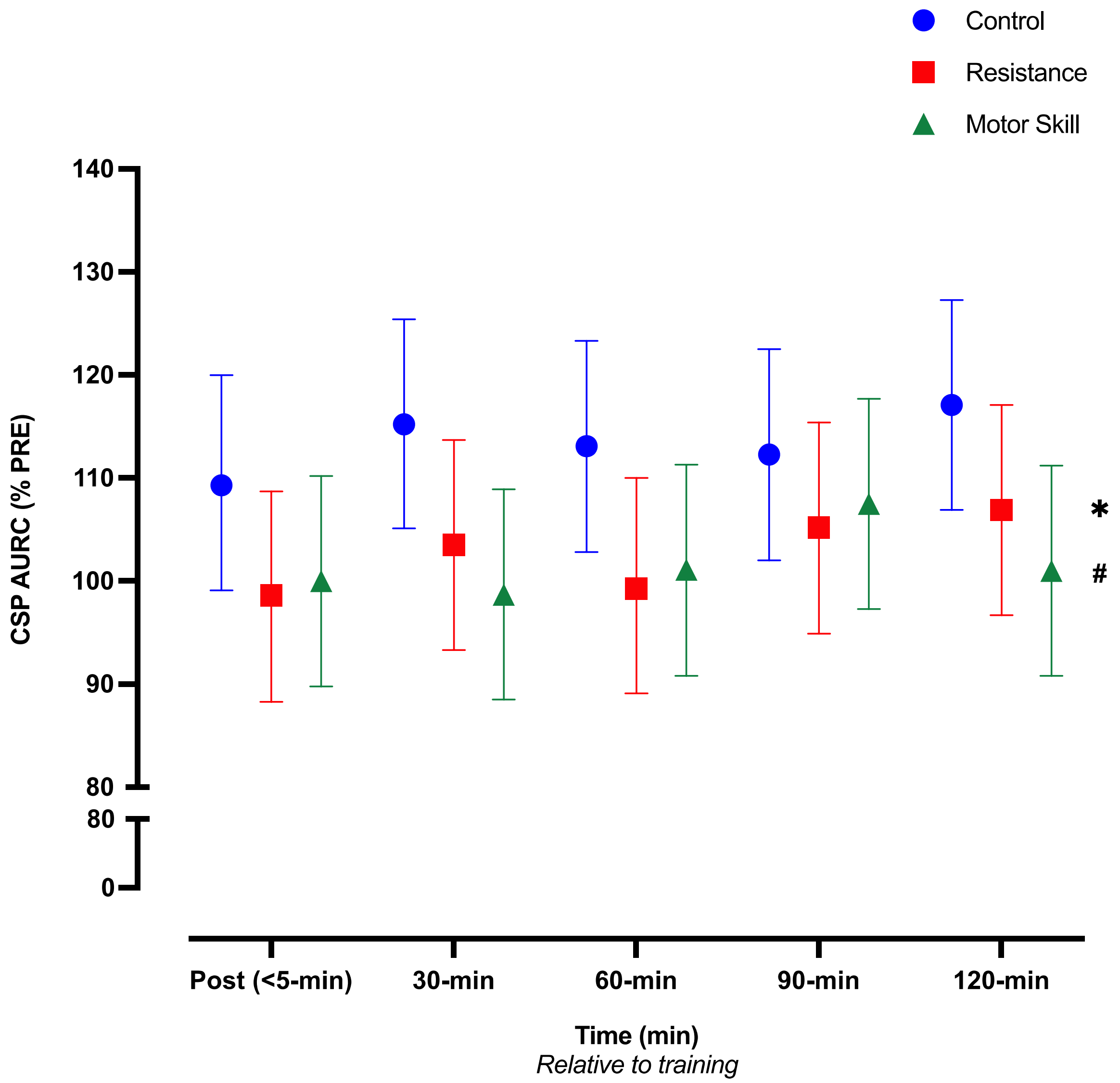

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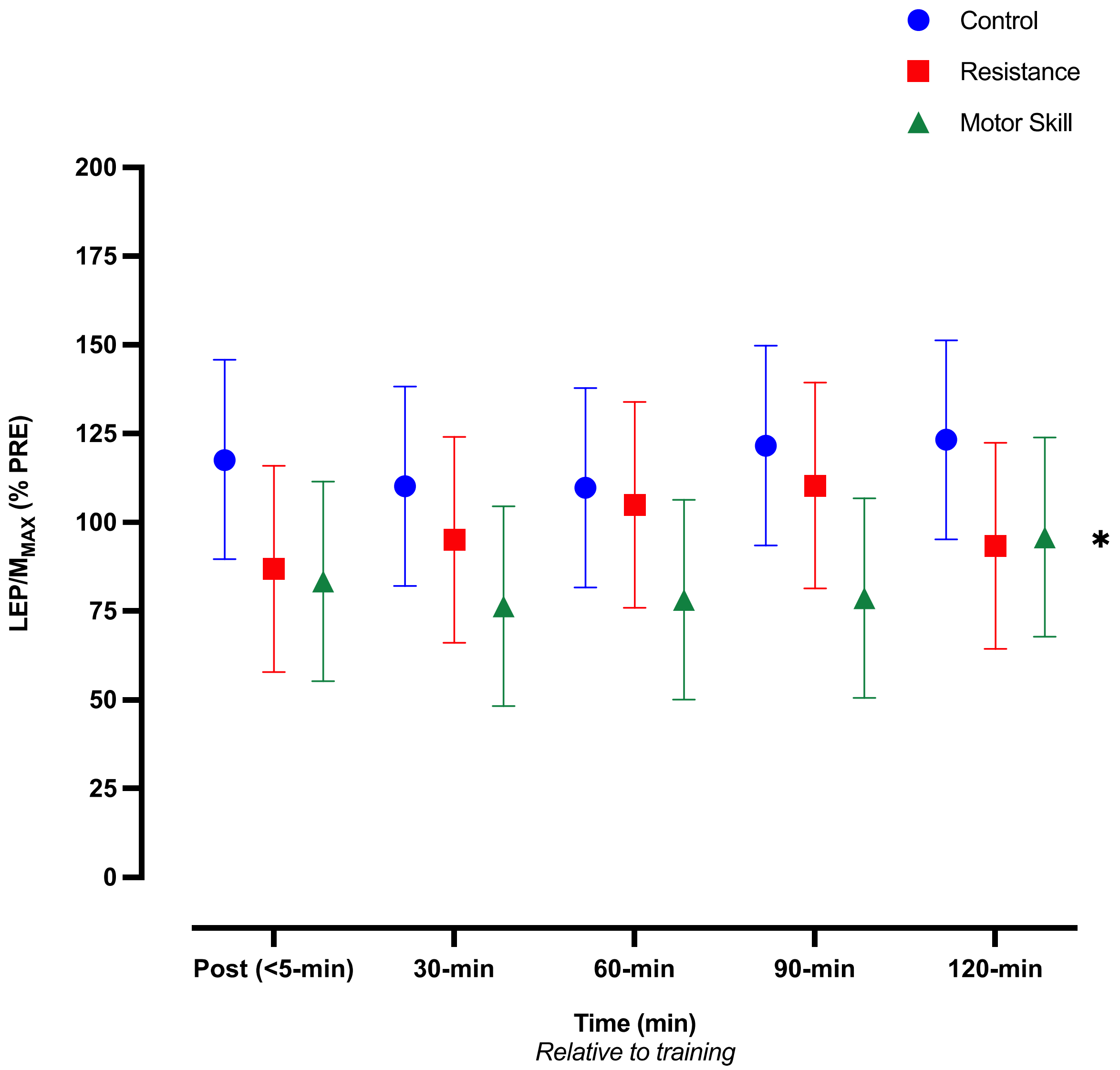

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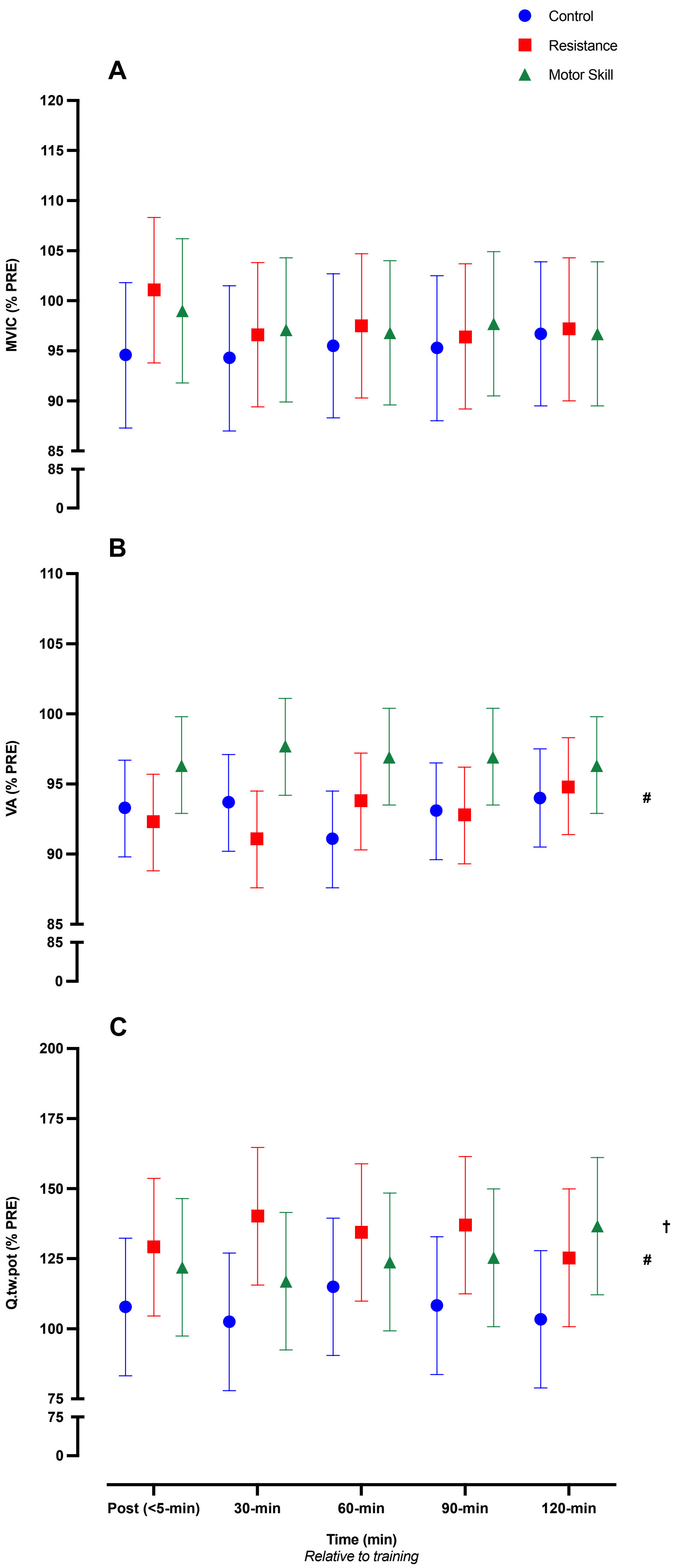
● Control
■ Resistance
▲ Motor Skill
A
MVIC (% PRE)
120
115
110
105
100
95
90
85
85
0
B
VA (% PRE)
110
105
100
95
90
85
85
0
#
C
Q.tw.pot (% PRE)
200
175
150
125
100
75
75
0
†
#
Post (<5-min)
30-min
60-min
90-min
120-min
Time (min)
Relative to training

Figure 6. Mean changes (95% confidence intervals) were obtained at baseline, immediately following (i.e., < 5-min cessation of training) a motor skill training session, resistance training session or control, and at 30-min, 60-min, 90-min and 120-min post-exercise. **A** maximal voluntary isometric contraction (MVIC). No fixed effect for Time (*P* = 0.716), Condition (*P* = 0.517) or Time*Condition (*P* = 0.999) was observed for MVIC. **B** Voluntary activation (VA). There was a significant fixed effect for Time (*P* < 0.001). * denotes a significantly lower VA following resistance training compared to motor skill training (*P* = 0.001). # denotes a significantly lower VA following the control compared to motor skill training (*P* < 0.001). No fixed effect was observed for Time*Condition interaction (*P* = 0.584). **C** Potentiated twitch force (Q.tw.pot, N). There was a significant fixed effect for Time (*P* = 0.029). * denotes a significant increase in Q.tw.pot from baseline to 60-min (*P* = 0.042). # denotes a significantly greater Q.tw.pot following resistance training compared to the control (*P* < 0.001). † denotes a significantly greater Q.tw.pot following motor skill training compared to the control (*P* = 0.033). No fixed effect for Time*Condition interaction was observed (*P* = 0.722).

Table 1. Percentage change data for M_{MAX}, AMT and pre-stimulus EMG (Root Mean SquareEMG/M_{MAX}) calculated between baseline and immediately post-exercise (< 5-min cessation of training), 30-min, 60-min, 90-min and 120-min. Data is presented as percentage change (95% confidence intervals).

	Relative to % Pre				
	Post (< 5-min)	30-min	60-min	90-min	120-min
M_{MAX} Amplitude					
Control	-0.3 (87-113)	-0.5 (87-112)	-5.1 (82-108)	-11.7 (76-101)	-11.2 (76-102)
Resistance	-5.4 (82-107)	-6.2 (81-106)	+1.6 (89-114)	+4.0 (91-117)	+8.3 (96-121)
Motor Skill	-11.3 (76-101)*	-16.1 ± (71-97)*	-16.1 (71-97)*	-15.2 (72-98)*	-17.9 (70-95)*
Active Motor Threshold (AMT)					
Control	+1.4 (97-105)	+2.3 (98-106)	+1.1 (97-105)	+1.3 (97-105)	+0.5 (96-104)
Resistance	-1.3 (95-103)	-1.6 (94-102)	-2.9 (93-101)	-0.5 (96-103)	+0.4 (97-104)
Motor Skill	-1.5 (95-102)	-0.1 (96-104)	+0.9 (96-105)	+1.0 (97-105)	-0.8 (95-103)
Pre-stimulus EMG (RMS_{EMG}/M_{MAX})					
Control	-6.2 (82-105)‡	-7.5 (81-104)‡	-4.4 (84-107)‡	+6.8 (95-118)‡	+8.8 (97-121)‡
Resistance	+10.6 (99-122)‡	+9.4 (98-121)‡§	+12.0 (100-124)‡	+8.6 (97-120)‡	+7.0 (95-119)‡§
Motor Skill	+22.2 (111-134)$^{\#\dagger\dagger\ddagger}$	+32.5 (121-144)$^{\#\dagger\dagger\ddagger\S}$	+23.3 (112-135)$^{\#\dagger\dagger\ddagger}$	+23.9 (112-136)$^{\#\dagger\dagger\ddagger}$	+28.7 (117-141)$^{\#\dagger\dagger\ddagger\S}$

EMG electromyography, *RMS* root mean square, *AMT* active motor threshold, M_{MAX} maximal muscle compound action potential. There was a significant fixed effect between Conditions ($P < 0.001$). * denotes a significantly lower M_{MAX} amplitude following motor skill training compared to resistance training ($P < 0.001$). No fixed effect on M_{MAX} was observed for Time ($P = 0.641$) or Time*Condition interaction ($P = 0.379$). No fixed effect for Time ($P = 0.975$), between Conditions ($P = 0.101$) or Time*Condition interaction ($P = 0.916$) was observed for AMT. Background muscle activity (RMS_{EMG}/M_{MAX}) showed a fixed effect for Time (P = 0.008), between Conditions ($P < 0.001$) and Time*Condition interaction ($P = 0.017$). # denotes a significantly greater RMS_{EMG}/M_{MAX} following motor skill training compared to the control ($P < 0.001$). † denotes a significantly greater RMS_{EMG}/M_{MAX} following motor skill training compared to resistance training ($P < 0.001$). ‡ denotes a significantly greater RMS_{EMG}/M_{MAX} following resistance training compared to the control ($P = 0.014$). † denotes a significant increase in RMS_{EMG}/M_{MAX} following motor skill training from baseline to Pre-Post ($P = 0.030$), Pre-30-min ($P = < 0.001$), Pre-60-min ($P = 0.017$), Pre-90-min ($P = 0.014$) and Pre-120-min ($P = 0.001$). ‡ denotes a significant increase in RMS_{EMG}/M_{MAX} between motor skill training compared to the control at Pre-Post ($P < 0.001$), Pre-30-min ($P < 0.001$), Pre-60-min ($P < 0.001$), Pre-90-min ($P = 0.050$) and Pre-120-min ($P = 0.017$). § denotes a significant increase in RMS_{EMG}/M_{MAX} between motor skill training and resistance training at Pre-30-min ($P = 0.004$) and Pre-120-min ($P = 0.007$).