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31 **Abstract**

32 Neuroplastic changes in the primary motor cortex accompany performance improvements following motor
33 practice. Recent evidence suggests that the corticospinal responses to strength and skill training are similar,
34 following both a single session and repeated bouts of training, promoting discussion that strength training is a
35 form of motor learning. However, these findings are limited by the lack of a light-load strength training group.
36 Therefore, the aim of the current study was to determine whether a **single-session** of heavy-load strength training,
37 light-load strength training or skill training differentially modulates the corticospinal pathway. Transcranial
38 magnetic stimulation was used to assess the excitatory and inhibitory circuitry of the motor cortex following a
39 **single-session** of skill training, and following a **single-session** of light-load and heavy-load strength training.
40 Following a **single-session** of training, participants in all groups experienced comparable increases in corticospinal
41 excitability (ranging from 38%-46%, all $P < 0.05$), however disparity was observed in the inhibitory responses.
42 Corticospinal inhibition was reduced in all three **single-sessions**, although to a greater magnitude in the heavy-
43 load and skill training **sessions** (22% and 18% respectively, compared to 11% following light-load training. All
44 $P < 0.05$). Short-interval intracortical inhibition was reduced immediately following **single-sessions** of heavy-
45 load strength training (40% $P < 0.05$) and skill training (47% $P < 0.05$), but remained unchanged following light-
46 the load strength training **session**. It appears that the corticospinal responses to **single-sessions** of different types
47 of strength and skill training **are** task-dependant. These findings reinforce the notion that strength training, at least
48 when heavily-loaded, can be considered a form of motor learning, potentially due to the sensory-feedback
49 involved.

50

51 **Key words:** Corticospinal excitability, corticospinal silent period, intracortical inhibition; neuroplasticity, skill
52 training; strength exercise.

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61 Introduction

62 There is empirical evidence that shows that neuroplastic changes in the primary motor cortex (M1) play
63 a critical role in the acquisition of motor skills (19). The ability of the **primary motor cortex** to change in
64 response to environmental stimuli has been associated with both anatomical and physiological changes
65 following skill acquisition (24). In humans, the use of neuroimaging techniques and transcranial magnetic
66 stimulation (TMS) measurements have comprehensively shown that motor skill training provokes changes in the
67 cortical representation of the trained muscles in the form of increased corticospinal excitability (18).
68 Interestingly, nonskilled or passive motor training tasks elicit no changes in the excitability of cortical
69 movement muscle representations (29). Specifically, movement repetition in the absence of skill acquisition
70 may be inadequate to induce changes in corticospinal excitability (19). Therefore, at a minimum, learning seems
71 to be a necessary step for driving neuroplastic changes in the M1.

72 Recently, it has been suggested that strength training is a form of motor learning and thus should be
73 associated with changes in the excitability of the trained muscles cortical representation (18). However, very
74 little is known about the neuronal mechanisms that could be involved in neural drive during the early stages of
75 strength training. One mechanism that has been proposed is a change in the excitability of the micro-circuitry of
76 the **primary motor cortex** (15). For example, it could be hypothesised that strength training is a type of motor
77 training that involves learning and thus there should be neuroplastic changes in cortical muscle representations
78 that occur as a result of strength training (15). Further, because athletes are required to learn the movement
79 pattern, i.e. activate agonist/antagonist muscles appropriately (20), it is reasonable to suggest that strength
80 training is a form of motor learning. However, the type of strength training may be important in comparing the
81 two forms of training, with factors such as pacing (18) and training load potentially dictating the corticospinal
82 responses. Preliminary evidence for the role of training load comes from cross-education literature, whereby
83 ipsilateral cortical responses are proportional to force production, with greater contraction force producing
84 greater effect on the ipsilateral primary motor cortex (4).

85 In recent years, there have been attempts to identify the potential mechanisms through which motor
86 learning and strength training may be similar. Leung and colleagues [1] showed that the elbow flexor cortical
87 representation increased its excitability and reduced its inhibitory projections following both **single sessions of**
88 visuomotor skill training and heavy-load strength training. Interestingly there were no differences between
89 heavy-load strength training and skill training in the responses to TMS, suggesting that skill and strength
90 training share similar neuroplastic responses. In addition, Leung and colleagues [3] further identified that the

91 corticospinal responses to skill and strength training over a 4-wk training period were also similar, indicating
92 that strength training is a type of motor learning because the longer-term TMS responses were not different to
93 skill training. However, a limitation to the studies conducted to date is that skill training has typically been
94 performed with little or no external load and strength training has been performed with relatively high loads.
95 Thus, it remains unclear whether the corticospinal responses following a **single session** of light-load and heavy-
96 load strength training are different or the same. If the responses are in fact the same, then we can conclude that
97 strength training is a type of motor training. Since the hypothesis that strength training and skilled motor tasks
98 share common neuroplastic responses has been raised but remains untested with low training loads, the purpose
99 of the current study was to determine whether a **single session** of light-load or heavy-load strength training
100 differentially modulates the human corticospinal pathway.

101 **Methods**

102

103 **Experimental Approach to the Problem**

104 **Prior to beginning the study, subjects underwent a familiarization session that involved: (i)**
105 **anthropometric measurements of height and weight (ii) strength testing to evaluate maximal voluntary dynamic**
106 **elbow flexor muscle strength (1-RM),(iii) maximal voluntary isometric strength testing (MVIC) of the elbow**
107 **flexor muscle and (iv) exposure to transcranial magnetic stimulation, surface electromyography and peripheral**
108 **nerve stimulation. Following this visit, in a randomized-control design, participants attended the laboratory**
109 **once, which was separated by 7 days from the familiarization session. A purpose made Excel macro was used**
110 **to randomize subjects to the training sessions and was designed to match the training sessions to include equal**
111 **numbers of males and females. Subjects were randomized (based upon gender) into four training session groups**
112 **(control n = 10; heavy-load strength training n = 10; light-load strength training n = 10 and skill training n = 10)**
113 **(see Figure 1). Dynamic and isometric muscle strength of the biceps brachii of the participants dominant limb**
114 **for each participant was measured and determined by completing a one repetition maximum (1-RM) strength**
115 **test which was collected during familiarization. The dynamic strength test data was used to determine the**
116 **training load for participants allocated to either the light-load or heavy-load strength training session, while the**
117 **MVIC data was used to control pre-stimulus surface electromyography during TMS testing.**

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121 **Subjects**

122 40 participants (20 male, 20 female, age: 25.9 ± 6.4 years, height: 172.4 ± 3.17 , weight: 71.5 ± 4.29)
123 were selected on a voluntary basis. All volunteers provided written informed consent prior to participation in the
124 study, which was approved by the Monash University Human Research Ethics Committee (project number:
125 11882) in accordance with the standards by the Declaration of Helsinki. All subjects provided written informed
126 consent prior to participation in the study and were informed of the benefits and risks of the investigation prior
127 to signing the approved informed consent document to participate in the study. All subjects were right hand
128 dominant, had not participated in strength training for a minimum of 12 months and were free from any
129 peripheral or neurological impairment. Overall, subjects had little or no history of resistance training. Only 4 of
130 the 40 participants reported that they had been completing strength training of the elbow flexors >1 day per
131 week in the months prior to data collection. **Consequently, they were randomly allocated to either the control or**
132 **the skill-training group.** All participants completed the adult safety-screening questionnaire to determine their
133 suitability for TMS (14) **and were excluded if there was a family history of epilepsy, were taking any**
134 **neuroactive drugs, or had undergone neurosurgery. Where possible, factors known to confound TMS responses,**
135 **subjects were instructed to avoid caffeine, medications, and exercise on the day of testing. The two visits to the**
136 **laboratory were at the same time of day.**

138 **Procedures**

139 ***Voluntary strength testing***

140 Subjects in all groups performed a standard unilateral 1-RM test for the right biceps brachii, **which was**
141 **completed prior to the single session of strength or skill training.** Following previous work [3], participants were
142 asked what they believed that their 1-RM elbow flexion strength was and this load served as their initial starting
143 weight. Participants performed the 1-RM test standing, holding a weighted dumbbell with one hand, with their
144 elbow in full extension, forearm supinated, and the opposite arm placed behind their back while standing against
145 a wall to prevent extraneous body movement. Participants were then asked to flex their arm and lift the
146 dumbbell as if performing a standard Biceps curl. If the trial was successful, the weight of the dumbbell was
147 increased accordingly (0.5 kg increments) on each trial following a 3-min recovery to minimise the development
148 of muscular fatigue (16). This procedure continued until the subject could no longer complete one repetition and
149 their prior successful trial served as their 1-RM isotonic biceps brachii strength (16). Participants completed on

150 average three trials to achieve their 1-RM strength. The maximum weight lifted, was then used to calculate the
151 training intensity for light-load strength training (20% 1-RM) and heavy-load strength training (80% 1-RM).

152 **In addition, in order to quantify the appropriate level of muscle activity during TMS testing,**
153 **participants completed a maximal voluntary isometric contraction (MVIC) of the dominant biceps brachii.**
154 **Participants stood in the anatomical position, with the hand supinated and maintaining 90 degrees of elbow**
155 **flexion. The researcher placed an adjustable weighted dumbbell in the palm of their hand. Participants were**
156 **instructed to grasp the dumbbell and maintain 90 degrees of elbow flexion for 3 s, without movement of the**
157 **abdomen or altering their posture. The maximal load that could be held static with correct technique served as**
158 **their MVIC. Maximal root mean squared electromyography (rmsEMG) for the bicep brachii was obtained**
159 **during the 3 s hold of their MVIC.**

160

161 ***Skill Testing***

162 Motor skill performance of the biceps brachii was determined by calculating the sum of errors during
163 an elbow-flexion visuomotor tracking task according to the procedures by Leung et al., [1, 3]. Briefly,
164 participants stood with their back straight against the wall with their forearm supinated in order to replicate the
165 position that was used during the strength-training protocol. Participants performed three sets of 10 s of
166 visuomotor tracking on a purpose built computer program (Jgcode V2.0, Australia). Each 10 s of visuomotor
167 tracking had a range of motion from 30° to 140° elbow flexion-extension, and the animated arm moved at 0.2
168 Hz, 0.8 Hz and 1.3 Hz, respectively. The visuomotor tracking task required each participant to move their arm in
169 response to the movement patterns of an animated arm displayed on a computer screen. The position and
170 movement of the elbow joint was tracked by a wireless electromagnetic goniometer (ADInstruments, Bella
171 Vista, Australia). Participants were provided with a percentage score of time spent in the correct tracking
172 position **while** performing the tracking task.

173

174 ***Strength training session protocol***

175 Participants allocated to **the strength training session groups** performed supervised unilateral elbow
176 flexion/extension exercise (i.e., a standard series of dumbbell bicep curls) to a repetition timing monitored by a
177 metronome (2 s concentric; 4 s eccentric) (16). For the **heavy-load strength training session**, participants
178 completed four sets (6–8 repetitions; 80% 1-RM) with 2.5 min rest between sets. For the **light-load strength**
179 **training session**, participants completed four sets of 20 repetitions (20% 1-RM) with 30 s rest between sets. The

180 total time to complete the **heavy-load strength training session** was 9 min and 6.5 min following the **light-load**
181 **strength training session**. On average, the total work performed for the **heavy-load strength training session**
182 **group** was 28, **while** the **light-load strength training session group** completed 80 repetitions during the
183 intervention.

184

185 ***Skill training session***

186 For the **skill training session group**, participants performed four sets of 56 s of visuomotor tracking on a
187 custom-built computer program (Jgcode V2.0, Australia). The position and movement of the elbow joint was
188 tracked by a wireless electromagnetic goniometer (ADInstruments, Bella Vista, Australia). During visuomotor
189 tracking, participants observed two animated arms, one automated and the other controlled by the participant to
190 track the movement of the automated arm. Participants were provided with a report of a percentage score of time
191 spent in the correct position **while** performing the tracking task. The visuomotor tracking task has been
192 previously reported [1, 3]. The tracking task had a range of motion from 30° to 140° and the animated arm
193 moved within a 0.2–1.3 Hz range. This position was similar to the strength training session, and only elbow
194 flexion and extension movements were permitted (similar to a biceps curl). The difficulty of the tracking task
195 was adjusted by randomising the speed of the task throughout the training block. Specifically, participants
196 performed four sets of the visuomotor tracking task by synchronizing the dominant arm to a computer-
197 controlled arm that moved through 120° range of motion timed to a pseudo-random frequency selected from a
198 range between 0.2 Hz and 1.3 Hz. The tracking task was also matched to the duration of the strength training
199 task and each set consisted of 56 s of visuomotor tracking. A 2.5 min recovery period separated each set.

200

201 ***Control condition:***

202 The control group reported to the laboratory under the same conditions as the experimental strength
203 training and skill training session groups and completed the exact same testing procedures; however, they did
204 not complete any intervention, rather they sat quietly in the laboratory for the same duration as it took to
205 complete the heavy-load strength-training session. Following this, they received the same post-testing
206 measurements as the experimental groups.

207

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209

210 *Transcranial magnetic stimulation and surface electromyography*

211 TMS was applied over the left **primary motor cortex** using a BiStim unit attached to two Magstim 200²
212 stimulators (Magstim Co, Dyfed, UK) to produce **motor-evoked potentials** recorded from the right biceps
213 brachii. A figure-eight coil, with an external loop diameter of 9 cm, was held over the left **primary motor cortex**
214 at the optimum scalp position to elicit **motor-evoked potentials** in the right biceps brachii. The induced current
215 flowed in a posterior-to-anterior direction. Sites near the estimated **center** of the biceps brachii were first
216 explored to determine the ‘optimal site’ at which the largest **motor-evoked potential amplitude** could be evoked,
217 and **active motor threshold** was established as the stimulus intensity at which at least five of ten stimuli
218 produced **motor-evoked potential amplitudes** of greater than 200 μ V [3]. Following all conditions (i.e. skill and
219 strength training), **active motor threshold** was retested and adjusted if required. In order to ensure that all TMS
220 stimuli were delivered consistently throughout pre and post-testing, participants wore a fitted cap that was
221 marked with a latitude-longitude matrix, positioned and referenced to the nasion-inion and interaural lines. All
222 TMS stimuli were delivered during low-level isometric contraction of the biceps brachii ($5 \pm 1\%$ of maximal
223 root-mean squared electromyography [rmsEMG]), which required the participants to maintain an elbow joint
224 angle of 90° elbow flexion. Joint angle was measured with an electromagnetic goniometer (ADInstruments,
225 Bella Vista, Australia), with visual feedback provided on a screen visible to both the participant and the
226 researcher. Holding the lower arm in this joint position equated to $5 \pm 1\%$ rmsEMG maximum. Because this
227 position resulted in a low level of muscle activity, and to ensure that background muscle activity was consistent
228 between TMS stimuli, rmsEMG were recorded 100 ms before the delivery of each TMS pulse. During the TMS
229 trials, visual feedback was presented to the volunteer to display an upper limit of 5% rmsEMG; participants
230 were instructed to maintain their muscle activation levels below this upper limit. The stimulus delivery software
231 (LabChart 8 software, ADInstruments, Bella Vista, NSW, Australia) was set, so that stimuli were not delivered
232 if the rmsEMG, 100 ms immediately prior to the stimulus, exceeded $5 \pm 1\%$ (see Table 1). Single-pulse TMS
233 was used to assess corticospinal excitability and inhibition (silent period duration), **while** paired-pulsed TMS
234 assessed short-interval cortical inhibition pre and post the training **sessions**. The single-pulse TMS protocol
235 comprised of 20 stimuli elicited at a stimulus intensity of 130% **active motor threshold**, and the peak-to-peak
236 amplitude was analysed. This was then followed by 20 paired-stimuli comprised of a subthreshold
237 conditioning stimulus at 70% **active motor threshold**, followed by a suprathreshold test stimulus at 130% **active**
238 **motor threshold**, with an interstimulus interval of 3 ms. For both single-pulse and paired-pulse TMS, the 40

239 stimuli were delivered in random order every 6-12 s to avoid stimulus anticipation, and 1 min rest was provided
240 between the single-and paired-pulse phases to reduce muscle fatigue.

241

242 *Maximal compound muscle action potential*

243 Direct muscle responses were obtained from the trained biceps brachii muscle by supramaximal
244 electrical stimulation (pulse width 200 μ s) of the Brachial plexus (Erbs point) during light background muscle
245 activity (DS7A, Digitimer, UK). An increase in current strength was applied to Erbs point until there was no
246 further increase observed in the amplitude of the EMG response (M-wave). To ensure maximal responses, the
247 current was increased an additional 20% and the average M-wave was obtained from five stimuli, with a period
248 of 6-9 s separating each stimulus. M_{MAX} was recorded at baseline and following the interventions, to ensure that
249 there were no changes in peripheral muscle excitability that could influence motor-evoked potential amplitude.

250

251 *Data analysis*

252 Pre-stimulus rmsEMG activity was determined in the biceps brachii muscle 100 ms before each TMS
253 stimulus during pre- and post-testing. Any trial in which pre-stimulus rmsEMG was greater than $5 \pm 1\%$ of
254 maximal rmsEMG was discarded and the trial was repeated. The peak-to-peak amplitude of motor-evoked
255 potentials were measured in the right biceps brachii muscle contralateral to the cortex being stimulated in the
256 period 10–50 ms after stimulation. Motor-evoked potential amplitudes were analyzed (LabChart 8 software; AD
257 Instruments) after each stimulus was automatically flagged with a cursor, providing peak-to-peak values in mV,
258 averaged and normalized to the M-wave, and multiplied by 100. Corticospinal silent period durations were
259 determined by examining the duration between the onset of the motor-evoked potential and the resolution of
260 background surface electromyography, which was visually inspected and manually cursored, with the
261 experimenter blinded to each condition. The average from 10 stimuli was used to determine corticospinal silent
262 period duration. Short-interval cortical inhibition was expressed as a percentage of the unconditioned single-
263 pulse motor-evoked potential amplitude.

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269 *Sample size and Statistical analysis*

270 The target sample size of 40 was based on a priori calculation, which included the observed effect size
271 from our previous experiment [1]. In previous experiments, samples sizes of ~10 have been adequate to observe
272 statistically significant changes in **motor-evoked potentials** and **short-interval cortical inhibition** after a **single**
273 **session of skill and strength training** [1].

274 All data were first screened to ensure they were normally distributed. To have sufficient data to test for
275 questions of normality, all data from baseline **motor-evoked potentials**, **short-interval cortical inhibition** and
276 corticospinal silent period trials were used to establish the distributional properties. No variable's z-score of
277 skew or kurtosis was excessive. Further, the Shapiro-Wilk test suggested that the variable **motor-evoked**
278 **potential** amplitude for the skill training group was non-normal ($W=0.791$; $P = 0.01$) and **corticospinal silent**
279 **period duration** for the control group ($W=0.791$; $P = 0.01$). However, these violations appeared to only be mild
280 from examination of frequency histograms and detrended Q-Q plots, and was not considered sufficient to
281 warrant a more conservative analytical strategy, thus it was decided to treat the data as essentially normally
282 distributed. A one-way ANOVA was conducted on all baseline values, which included corticospinal excitability
283 (**motor-evoked potential** expressed as percentage of M-wave), **short-interval cortical inhibition** (expressed as a
284 percentage of the test response) and **corticospinal silent period duration** (in milliseconds) to ensure that there
285 were no differences between groups. A 2-way repeated measures ANOVA (Factors: Two time points and Four
286 **Training Session Groups**) assessed changes in biceps brachii rmsEMG, **motor-evoked potential amplitude**,
287 **corticospinal silent period duration**, **short-interval cortical inhibition** and **M-wave**. If significant main effects
288 were found, univariate and post hoc analysis (Tukey's multiple comparisons test) was used to analyse the
289 percentage change comparing **the training sessions** (control, skill-training, **light-load strength training and**
290 **heavy-load strength training**). For all comparisons, effect sizes of 0.2, 0.5, and 0.8 were established to indicate
291 small, moderate and large comparative effects (Cohen's d). The level of significance was set at $P < 0.05$. SPSS
292 version 22.0 (SPSS Inc., Chicago, IL) and was used for all statistical analyses, and all results are displayed as
293 mean \pm SE and **95% confidence intervals (CI)** unless stated otherwise.

294

295 **Results**

296 **Baseline electrophysiological and strength measures**

297 Table 1 displays the raw data for the percentage of stimulator output for **active motor threshold**,
298 rmsEMG for single and paired-pulse TMS, **while** Table 2 displays the raw data for **motor-evoked potential**

299 **amplitude, short-interval cortical inhibition and corticospinal silent period.** At baseline, there were no significant
 300 differences across groups for **motor-evoked potential amplitude** ($F_{3, 36} = 0.157$; $P = 0.924$), **short-interval**
 301 **cortical inhibition** ($F_{3, 36} = 1.16$; $P = 0.339$), **corticospinal silent period** ($F_{3, 36} = 0.157$; $P = 0.924$), SICI ($F_{3, 36} =$
 302 1.04 ; $P = 0.384$) or for **active motor threshold** ($F_{3, 36} = 1.65$; $P = 0.173$). There were also no differences in pre-
 303 stimulus rmsEMG across groups at baseline ($F_{3, 36} = 0.368$; $P = 0.776$) or M_{MAX} ($F_{3, 36} = 0.3004$; $P = 0.948$). **In**
 304 **a similar pattern, there were no differences in baseline 1-RM strength across the groups** ($F_{3, 36} = 2.63$; $P = 0.09$;
 305 **control: 14.7 ± 1.2 kg; heavy-load strength training: 17.6 ± 2.9 kg; light-load strength training: 15.8 ± 1.6 kg and**
 306 **skill training: 14.1 ± 3.1 kg). Further, there were no differences in MVIC strength across groups** ($F_{3, 36} = 1.37$; P
 307 $= 0.634$; **control: 182.5 ± 12.5 N; heavy-load strength training: 178.2 ± 16.1 N; light-load strength training:**
 308 **173.7 ± 14.8 N and skill training: 180.3 ± 17.1 N).**

309 *Insert table 1 here*

310 **Pre-stimulus EMGs**

311 Following the **training sessions**, there was no TIME ($F_{1, 36} = 2.99$; $P < 0.092$) or GROUP X TIME
 312 interactions ($F_{3, 36} = 0.355$; $P = 0.785$) for pre-stimulus rmsEMG. In a similar manner, there were no TIME ($F_{1,$
 313 $36 = 0.11$; $P < 0.740$) or GROUP X TIME interactions ($F_{3, 36} = 1.3$; $P = 0.290$) for **active motor threshold** or
 314 M_{MAX} ($F_{3, 36} = 0.066$; $P = 0.977$).

315

316 **Changes in corticospinal excitability**

317 **Motor-evoked potential amplitudes were** obtained at baseline and immediately post a single **training**
 318 **session** (see Fig. 2; Table 2). **Following the three training sessions** there was a main effect for TIME ($F_{1, 36} =$
 319 58.7 ; $P < 0.0001$) and a GROUP X TIME interaction ($F_{3, 36} = 11.3$; $P < 0.0001$). Immediately following the **skill**
 320 **and strength training sessions**, the increase in **motor-evoked potential amplitude** was significantly greater
 321 following skill training ($38\% \pm 11\%$, 95% CI 30.93 to 46.42, $d = 2.96$), **light-load strength training** ($46\% \pm$
 322 11.28% , 95% CI 37.55 to 53.70, $d = 3.47$) and **heavy-load strength training sessions** ($37\% \pm 10.68\%$, 95% CI
 323 29.29 to 44.58 , $d = 3.47$) compared to the control session ($3.72\% \pm 11.8\%$, 95% CI -4.27 to 12.18). There were
 324 no significant difference in **motor-evoked potential amplitudes** between skill-training, **light-load strength**
 325 **training** or **heavy-load strength training sessions** (all $P > 0.05$).

326

327 *Insert Figure 2 here*

328

329 **Changes in corticospinal inhibition**

330 The duration of the **corticospinal silent period** was obtained at baseline and immediately post the
 331 **training sessions** (see Fig. 3; Table 2). Following the three **training sessions** there was a main effect for TIME
 332 ($F_{1, 36} = 262$; $P < 0.0001$) and a GROUP X TIME interaction ($F_{3, 36} = 31$; $P < 0.0001$). Immediately following
 333 the skill **and strength training sessions**, the decrease in **corticospinal silent period** was significantly greater
 334 following skill training ($18\% \pm 3.5\%$, 95% CI 16.01 to 20.94, $d = 6.36$), **light-load strength training** ($11\% \pm$
 335 6.1% , 95% CI 6.49 to 15.23, $d = 2.24$) and **heavy-load strength training sessions** ($22\% \pm 5\%$, 95% CI 18.54 to
 336 25.59 , $d = 5.64$) compared to the control session ($1.36\% \pm 1\%$, 95% CI 0.64 to 2.09). Further, the magnitude of
 337 change following both skill training ($P = 0.002$, $d = 1.62$) and **heavy-load strength training sessions** ($P < 0.0001$,
 338 $d = 2.08$) was greater when compared to the **light-load strength training session**. There was no difference between
 339 skill training and **heavy-load strength training sessions** ($P = 0.273$).

340 *Insert figure 3 here*

341

342 **Changes in short-interval cortical inhibition**

343 **Short-interval cortical inhibition** was obtained at baseline and immediately post the **training sessions**
 344 (see Fig. 4; Table 2). Following the three **training sessions** there was a main effect for TIME ($F_{1, 36} = 22.5$; $P <$
 345 0.0001) and a GROUP X TIME interaction ($F_{3, 36} = 8.14$; $P = 0.0003$). Immediately following skill and **heavy-**
 346 **load strength training sessions**, the reduction in **short-interval cortical inhibition** was significantly greater
 347 following skill training ($47\% \pm 40\%$, 95% CI 17.6 to 75.9, $d = 1.56$), and **heavy-load strength training sessions**
 348 ($40\% \pm 28\%$, 95% CI 20.1 to 60.4, $d = 1.92$) compared to the **light-load strength training session** ($4\% \pm 19\%$,
 349 $95\% \text{ CI } -9.41 \text{ to } 18.2$, $d = 0.33$) and the control group ($3.72\% \pm 11.8\%$, 95% CI -4.46 to 3.59). There was no
 350 difference in the magnitude of **short-interval cortical inhibition** release between skill-training and the **heavy-load**
 351 **strength training session** ($P = 0.947$).

352 *Insert figure 4 here*

353 *Insert table 2 around here*

354

355 **Discussion**

356 The aim of the current study was to investigate whether a **single session** of **light-load strength training**
 357 and **heavy-load strength training** differentially modulates the corticospinal pathway when compared with skill
 358 training. The main findings of the study showed that all three types of training **sessions** increased **corticospinal**

359 excitability, with no difference in the magnitude of change observed between training session groups. Similarly,
360 there were significant reductions in corticospinal silent period following all three types of training sessions.
361 However, while the light-load strength training session group did experience a reduction in corticospinal silent
362 period, the change was less than the heavy-load strength training and skill training session groups, which
363 produced parallel reductions. While a single session of both skill training and heavy-load strength training
364 reduced short-interval cortical inhibition to a comparable extent, there were no changes in short-interval cortical
365 inhibition following the light-load strength training session. These data demonstrate that while heavy-load
366 strength training and skill training share similar corticospinal responses following a single session of training,
367 the inhibitory responses to strength training are specific to the parameters of the task, which may include factors
368 such as the sensory demands.

369 A major finding of this study was that both the light-load strength training and heavy-load strength
370 training sessions produced similar increases in corticospinal excitability, which are comparable with those
371 observed following skill training. This common increase shared between all training session groups is consistent
372 with the existing literature, including a recent systematic review that concluded that heavy-load strength training
373 and light-load strength training both acutely increase corticospinal excitability (20). This finding is unequivocal
374 across a range of contraction types (17, 23), as well as muscles trained ((17, 19, 23). Skill training is also well
375 reported to induce acute increases in corticospinal excitability in the period immediately post training (12),
376 including visuomotor tracking tasks similar to those used in this study (19). Although there is some debate
377 regarding whether corticospinal excitability increases or decreases following motor training, it is generally
378 accepted, that a shift in corticospinal excitability in either direction following a single session of training is a
379 shared property between most forms of focused motor practice (32). Importantly, this extends to relatively
380 uncomplicated tasks, including ballistic digit practice [12], indicating that task complexity may not be an
381 important factor in inducing changes in corticospinal excitability. It is therefore likely that light-load strength
382 training is also a sufficient stimulus to induce increases in corticospinal excitability. This is in contrast to early
383 findings, which observed that repetition in the absence of acquiring a skill is insufficient to induce changes in
384 corticospinal excitability (29). While the origin of the changes underpinning the increase in corticospinal
385 excitability in the current study is not clear, it has been reported that following both heavy-load strength training
386 (23) and visuomotor tracking (27), spinal excitability is also increased (9), which may indicate that changes in
387 corticospinal excitability are at least in part due to increased spinal excitability.

388 The notion that both **light-load strength training** and **heavy-load strength training** share similar
389 increases in corticospinal excitability following a single session of training which are akin to those following
390 skill training, raises the question of the functional purpose of such an increase. It could simply be that an
391 increase in corticospinal excitability following strength training is an attempt by the central nervous system to
392 diminish or circumvent any muscular fatigue developed throughout the training intervention (17). For example,
393 lactate accumulated during light-load training has the potential to increase corticospinal excitability (2).
394 However, whether or not **light-load strength training** is always sufficient to induce substantial muscular fatigue
395 and subsequent increases in corticospinal excitability is disputable. This may therefore, indicate that an increase
396 in corticospinal excitability following strength training could serve additional purposes. For example, it has been
397 suggested that increases in corticospinal excitability relate to processes of actively acquiring and consolidating a
398 task rather than mere activation of a muscle (28), and that early consolidation of a task commences in the
399 **primary motor cortex** from the first exposure to a task (13). Therefore, the acute increases in corticospinal
400 excitability following **a single session** of different types of motor training may be an early marker of
401 neuroplasticity related to the early phase of skill learning. This supports the view that strength training,
402 potentially regardless of load, could be considered a form of skill training.

403 The transient increase in corticospinal excitability potentially depends on a release of inhibitory
404 synaptic activity in the micro-circuitry of the **primary motor cortex** (6), as well as spinal influences (23).
405 Further, it is entirely plausible that **light-load strength training** and **heavy-load strength training** produce
406 increases in corticospinal excitability through separate and independent mechanisms. The increase in
407 corticospinal excitability following **light-load strength training** may be contingent on the accumulation of
408 metabolites, **while** increases following **heavy-load strength training** may be more reliant on factors such as
409 increased sensory feedback, which may increase neural drive to the motorneuron pool.

410 This study provides evidence that **heavy-load strength training** and skill training share comparable
411 responses, **while light-load strength training** produces a unique inhibitory response following a single bout of
412 training. While **light-load strength training** significantly decreased the **corticospinal silent period**, it did not do so
413 to the same magnitude as **heavy-load strength training** and skill training which shared parallel responses.
414 Intracortical inhibition, as assessed by the **corticospinal silent period**, remained unchanged by **light-load strength**
415 **training**, whereas both **heavy-load strength training** and skill training produced comparable reductions following
416 training.

417 Although there is some evidence that relatively lighter training loads can produce the same magnitude
418 of reduction in corticospinal inhibition as heavier training loads following a single session of training (17), these
419 findings were not replicated in this study. This disparity is likely due to the training loads employed, with
420 Latella and colleagues using a 12RM scheme at approximately 67% of 1RM, whereas the current study used
421 20% of 1RM. The reduction in cSP in response to **heavy-load strength training** supports existing evidence (17,
422 20). However, the observed reduction following skill training adds to the inconsistent findings regarding
423 corticospinal inhibitory responses to motor training. For example, no differences were detected in **corticospinal**
424 **silent period** following visuomotor tracking task (25)), but a similar follow-up study found a reduction in
425 **corticospinal silent period** following both slow and fast visuomotor tracking (26). Increases in **corticospinal**
426 **silent period** have been detected following each set during a heavy-loaded elbow flexion training session (33),
427 which is contradictory to the current finding.

428 It was also observed in the present study that intracortical inhibition, indexed by **short-interval cortical**
429 **inhibition**, was not reduced following a single bout of **light-load strength training**, but both **heavy-load strength**
430 **training** and skill training led to reductions. Reductions in intracortical inhibition have been observed in tandem
431 with increases in corticospinal excitability following motor practice, including **heavy-load strength training** (19)
432 and skill training (19, 28). However, changes in **short-interval cortical inhibition** following motor practice
433 remain relatively inconsistent. For example, decreases have been observed following skill training (3, 8),
434 alongside reports of no change (32). Similarly, inconsistent reports exist following strength training, with
435 decreases [1] and no changes (17) observed. Thus, changes in intracortical inhibition appear to be particularly
436 sensitive to the parameters of the motor task involved; a notion which is supported by the results of this study.
437 The separate and independent responses observed in **short-interval cortical inhibition** and **corticospinal silent**
438 **period** add to previous findings that motor training has distinctly different effects on separate inhibitory-
439 neuronal populations (17, 20, 21). Differences in inhibitory responses between training types may be due to the
440 unique demands of each training protocol and the subsequent fatigue status of an individual (36), however, a
441 limitation of the current study is that indices of fatigue were not measured, despite there being no changes in
442 M_{MAX} .

443 The disparity in inhibitory response between the **light-load strength training** and **heavy-load strength**
444 **training sessions** raises the question; what are the features of **heavy-load strength training** that ultimately
445 produce a more substantial response in markers of inhibition when compared with **light-load strength training**?
446 Further, what are the elements of **heavy-load strength training** which produce corticospinal responses akin to

447 those observed following a session of skill training? The answers could lay in the demands of the task;
448 particularly the sensory feedback. It is well established that sufficiently challenging the nervous system is
449 important in maximising the neuroplastic response (7, 19). For example, as observed in the current study,
450 externally-paced strength training **stimulus** generates significant increases in corticospinal excitability, as well as
451 reductions in **short-interval cortical inhibition** following both a single session (19), as well as following short-
452 term strength programmes (7), whereas self-paced strength training may be insufficient to induce substantial
453 changes (12, 19). Visuomotor tracking that is paced with a metronome increases corticospinal excitability
454 compared to non-paced tracking (1). These greater responses are purported to result, in part, through increased
455 sensory feedback from contracting muscles (10, 11) and the activation of specific neural pathways relevant to
456 the task (3, 28). However, despite external-pacing being utilised for both **light-load strength training** and **heavy-**
457 **load strength training** in the current study, **heavy-load strength training** still generated a greater magnitude of
458 reduction in inhibitory responses. This indicates that externally-paced training is not sufficient enough alone to
459 maximise the acute corticospinal responses to training, and that combining pacing with increased training load is
460 necessary to generate more substantial responses. This validates previous findings, whereby the inhibitory
461 responses to a simple digit abduction task is unique to the level of force employed during a contraction, with
462 **short-interval cortical inhibition** being reduced incrementally with increasing force production during graded
463 contractions (38). Further, the dynamic nature of externally-paced **heavy-load strength training** substantially
464 increases muscle afferent feedback (10, 11, 19), and motor tracing tasks engage the visual cortex, implying that
465 skill training and **heavy-load strength training** share the trait of challenging the sensory system more so than
466 **light-load strength training**. Indeed, the **light-load strength training session** completed training that shared many
467 qualities parallel with the **heavy-load strength training session**, including external-pacing and dynamic
468 contractions, showing the only point of difference was the force required. This may aid in explaining the unique
469 responses.

470 The acute corticospinal responses following a single session of training may reflect early offline
471 processes which are integral in the progression of acquiring and consolidating a task. Therefore, it is also
472 necessary to consider the performance consequences of such responses and how they may differ between **heavy-**
473 **load strength training**, **light-load strength training** and skill training. It has been demonstrated that both skill
474 performance (13, 30, 38) and force generating capacity can be enhanced immediately following a single session
475 of training. This suggests that the sites and processes of neural adaptation to skill training and **heavy-load**
476 **strength training** maybe similar, but it is unclear how different training loads and parameters specifically

477 influence the TMS responses. In light of this, following repeated training sessions, there are several lines of
478 evidence that show heavy training loads yield greater gains in strength compared to light training loads (5, 22,
479 37), and moderate training loads (35), even when overall training volume in heavy strength training groups is
480 less than in light strength training groups. Further, lightly loaded strength training consistently increases
481 muscular endurance (31), whereas training with heavy loads does not (34). This, combined with the findings of
482 the current study, provide evidence that both the corticospinal and performance responses to training are task-
483 specific. It is conceivable that the acute, transient responses following a single session of motor training, form
484 the basis for long-term neuroplastic changes which drive and accompany the aforementioned increases in
485 performance, although the link between the two remains relatively unclear. Maximising the neuroplastic
486 response to a single session, via increased training load, likely compounds from session to session, and may aid
487 in explaining the different functional outcomes of **light-load strength training** and **heavy-load strength training**
488 training-programmes.

489 Although the current study provides novel evidence suggesting that strength training with lighter loads
490 produces a unique set of corticospinal responses, the results can only be generalised to healthy and untrained
491 young adults, and the findings are limited to the current tasks involved. Future studies should seek to measure
492 both the strength performance and the **fatigue status of participants** prior to, during and following training, in
493 order to identify further mechanisms which may be responsible for the differential responses.

494

495 **Practical Applications**

496 The current study provides novel evidence of the corticospinal responses to a **single session of skill and**
497 **strength training**, and identifies, the unique acute responses of strength training with a lighter load. **Although a**
498 **strength-training stimulus using a light load increases corticospinal excitability to the same extent as a stimulus**
499 **from heavy strength training and motor skill training**, it reduces corticospinal inhibition to a lesser extent and
500 does not influence intracortical inhibition. The corticospinal responses to strength training with heavy loads are
501 akin to those observed following motor skill training, validating previous evidence from Leung and colleagues
502 (18, 19) and suggests that the processes and structures underlying early skill and strength acquisition during the
503 initial weeks of training may indeed have similarities. Taken together, these findings show the capacity for the
504 corticospinal pathway to alter its response based on the demands of the training task. Light-load strength
505 training may be insufficiently demanding on the motor system when compared with skill and heavy strength
506 training, leading to a diminished acute inhibitory response. This may be an early adaptation which drives greater

507 strength improvements following heavy strength training as opposed to training with lighter weights. Further, it
508 highlights the value of suitably challenging the motor system in order to maximise the acute corticospinal
509 response and, potentially, the longer-term corticospinal and performance adaptations. Further research should
510 seek to track how the corticospinal and behavioural responses to strength training may accumulate from a single
511 session across multiple sessions, and ultimately contribute to long-lasting changes in muscular strength.

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514 not-for-profit sectors.

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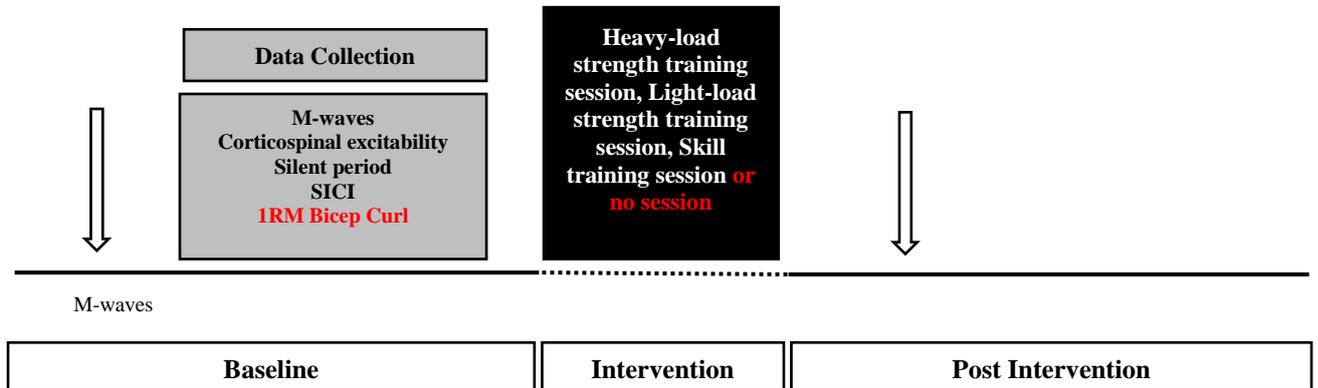
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652 **FIGURE LEGENDS**

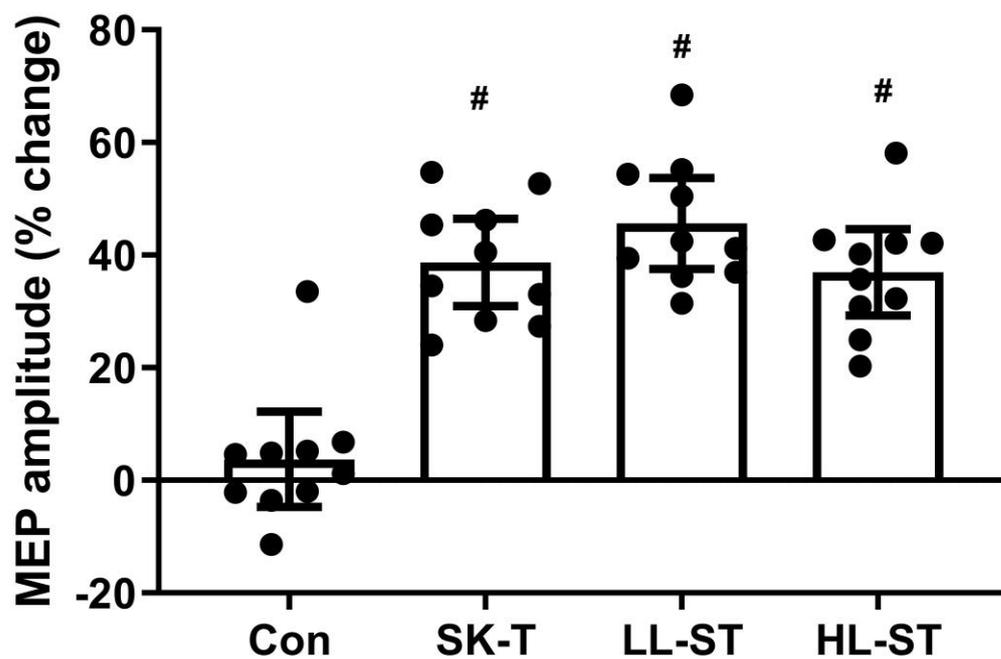
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655 **Figure 1: (A)** Schematic representation of the experimental design with measures obtained prior to and following
 656 heavy-load strength training, light-load strength training and visuomotor skill training. Pre- and post-measures
 657 included assessment of peripheral muscle excitability (M_{MAX}), corticospinal excitability, corticospinal inhibition
 658 and short-interval intracortical inhibition of the trained biceps brachii muscle.

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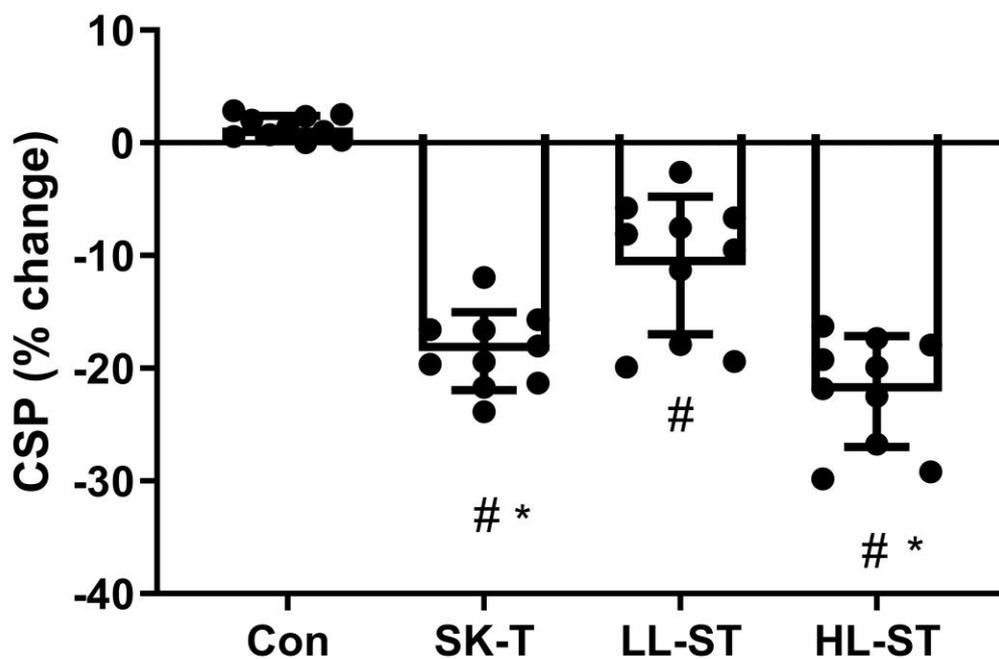


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661 **Figure 2:** Change in corticospinal excitability (% increase in MEP amplitude normalised to M_{MAX}) of the trained
 662 biceps brachii (mean \pm SE) following heavy-load strength training, light-load strength training and visuomotor
 663 skill training. #Denotes a significant increase in corticospinal excitability from baseline following skill –training,
 664 light-load strength training and heavy-load strength training compared to the control group (between groups
 665 effect).

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669 **Figure 3:** Change in corticospinal inhibition (% decrease in silent period duration) of the trained biceps brachii670 (mean \pm SE) following heavy-load strength training, light-load strength training and visuomotor skill training.

671 #Denotes a significant decrease in corticospinal inhibition from baseline following heavy-load strength training,

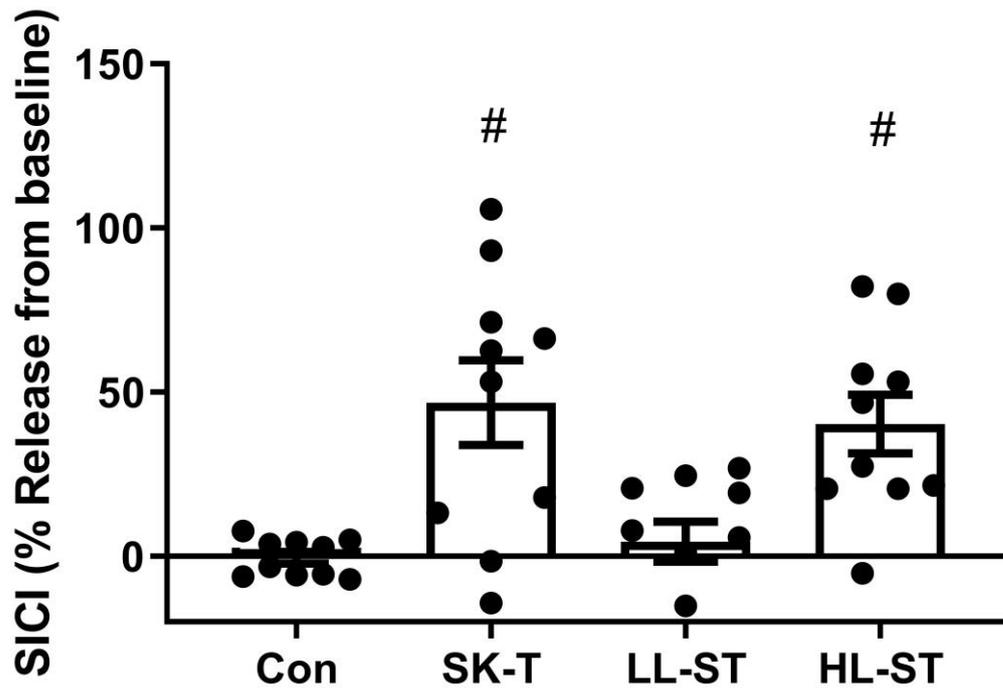
672 light-load strength training and visuomotor skill training (within group effect). *Denotes a significant reduction

673 in corticospinal inhibition following visuomotor skill training and heavy-load strength training when compared to

674 the light-load strength training and control groups (between groups effect). cSP; corticospinal silent period.

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678 **Figure 4:** Change in SICI (% change) of the trained biceps brachii (mean \pm SE) following heavy-load strength
 679 training, light-load strength training and visuomotor skill training. #Denotes a significant release in SICI from
 680 baseline following visuomotor skill training and heavy-load strength training compared to light-load strength
 681 training and the control group (between groups effect).

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Table 1. Mean (\pm SD) and percentage change for AMT stimulus intensity, M_{MAX} and single- and paired--pulse TMS pre-stimulus rmsEMG prior to and following a single session of motor training for the control and training groups.

	AMT SI (%)			SP rmsEMG (% rmsEMGmax)			PP rmsEMG (% rmsEMGmax)		
	Pre	Post	<i>P</i> value	Pre	Post	<i>P</i> value	Pre	Post	<i>P</i> value
Control Group	28.4 \pm 3.57	28.3 \pm 3.73	0.94	3.86 \pm 0.02	3.83 \pm 0.02	0.99	3.76 \pm 0.02	3.75 \pm 0.03	0.99
Visuomotor Skill Training	27.7 \pm 5.31	27.7 \pm 5.57	>0.99	4.14 \pm 0.02	4.11 \pm 0.03	0.99	4.05 \pm 0.02	4.10 \pm 0.02	0.93
Light Load Strength Training	30.8 \pm 3.01	30.6 \pm 3.16	0.57	3.81 \pm 0.03	3.69 \pm 0.02	0.58	3.64 \pm 0.03	3.73 \pm 0.02	0.65
Heavy Load Strength Training	30.6 \pm 2.32	30.8 \pm 2.40	0.58	3.42 \pm 0.02	3.28 \pm 0.03	0.49	3.3 \pm 0.03	3.35 \pm 0.01	0.92

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AMT SI: active motor threshold stimulus intensity. Single (SP) and paired pulse (PP) rmsEMG was pooled across the 20 stimuli.

713

Table 2. Mean (\pm SD) and percentage change for MEPs, silent period and SICI for control and training groups following a single session of motor training.

	MEP amplitude (% of M _{MAX})			Silent Period (ms)			SICI (% of test response)		
	Pre	Post	<i>P</i> value	Pre	Post	<i>P</i> value	Pre	Post	<i>P</i> value
Control Group	3.07 \pm 1.21	3.15 \pm 1.28	0.33	0.122 \pm 0.01	0.121 \pm 0.01	0.7631	52.47 \pm 20.17	51.59 \pm 17.94	0.99
Visuomotor Skill Training	2.50 \pm 1.28	3.50 \pm 1.29	0.001	0.135 \pm 0.01	0.108 \pm 0.01	<0.0001	33.69 \pm 6.53	49.87 \pm 6.11	<0.0001
Light Load Strength Training	7.81 \pm 5.04	11.41 \pm 5.28	0.001	0.129 \pm 0.01	0.106 \pm 0.01	<0.0001	42.06 \pm 13.96	42.30 \pm 14.18	>0.9999
Heavy Load Strength Training	6.80 \pm 3.36	9.24 \pm 3.55	0.0002	0.134 \pm 0.01	0.113 \pm 0.01	<0.0001	39.53 \pm 10.12	55.34 \pm 10.61	0.0001

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715 MEP and Silent Period measured at 130% of AMT.

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