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Task- and intensity-dependent modulation of arm-trunk neural interactions in the corticospinal pathway in humans

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2 Task- and intensity-dependent modulation of arm-trunk neural interactions in the corticospinal
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4
5 **Abbreviated title:**

6 Arm-trunk neural interaction in the corticospinal tract

7
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53

54 **Abstract**

55 Most human movements require coordinated activation of multiple muscles. Although many
56 studies reported associations between arm, leg, and trunk muscles during functional tasks, their
57 neural interaction mechanisms still remain unclear. Therefore, the aim of our study was to
58 investigate arm-trunk or arm-leg neural interactions in the corticospinal tract during different arm
59 muscle contractions. Specifically, we examined corticospinal excitability of the erector spinae
60 (ES; trunk extensor), rectus abdominis (RA; trunk flexor), and tibialis anterior (TA; leg) muscles
61 while participants exerted: (1) wrist flexion; and (2) wrist extension isometric contraction at
62 various contraction intensity levels ranging from rest to 50% of maximal voluntary contraction
63 (MVC) effort. Corticospinal excitability was assessed using motor evoked potentials (MEPs)
64 elicited through motor cortex transcranial magnetic stimulation. Results showed that ES MEPs
65 were facilitated even at low contractions (>5% MVC) during wrist flexion and extension, while
66 stronger contractions (>25% MVC) were required to facilitate RA MEPs. The extent of
67 facilitation of ES MEPs depended on contraction intensity of wrist extension, but not flexion.
68 Moreover, TA MEPs were facilitated at low contractions (>5% MVC) during wrist flexion and
69 extension, but contraction intensity dependence was only shown during stronger wrist extension
70 contractions (>25% MVC). In conclusion, trunk extensor corticospinal excitability seems to
71 depend on the task and the intensity of arm contraction, while this is not true for trunk flexor and
72 leg muscles. Our study therefore demonstrated task- and intensity-dependent neural interactions
73 of arm-trunk connections, which may underlie anatomical and/or functional substrates of these
74 muscle pairs.

75 **Significance Statement**

76 Although it is known that most human movements require coordinated activation of multiple
77 muscles, understanding of how they are controlled in the central nervous system still lacks. Our
78 study investigated the characteristics of neural interactions of arm-trunk and arm-leg muscles in
79 the corticospinal tract of human participants using motor evoked potentials elicited by
80 transcranial magnetic stimulation. We showed that arm muscle contractions can facilitate
81 corticospinal excitability of the trunk and leg muscles. Specifically, arm-trunk neural interactions
82 depended on the task and intensity of arm movements. Our findings therefore suggest that
83 corticospinal neurons have complex output patterns to distinct muscles in different body
84 segments, which may depend on the anatomical and/or functional relationship of these muscle
85 pairs.
86

87 **1. Introduction**

88 Most human movements, even simple acts such as grasping an object, require
89 coordinated activation of multiple muscles. Specially, interactions between arm and trunk
90 muscles are important for performing activities of daily living. It is well known that trunk
91 muscles are activated before the proceeding arm movements (Aruin and Latash, 1995; Hodges
92 and Richardson, 1997). By assessing motor evoked potentials (MEP) using transcranial magnetic
93 stimulation (TMS) of the primary motor cortex (M1), it was recently demonstrated that voluntary
94 activation of upper-limb muscles can facilitate corticospinal circuits, which are responsible for
95 controlling the trunk muscles (Chiou et al., 2018; Sasaki et al., 2018a). Moreover, it was reported
96 that subcortical excitability evaluated by cervicomedullary MEP was not changed by voluntary
97 contraction of arm muscles (Chiou et al., 2018; Sasaki et al., 2020b). These results indicate that
98 trunk corticospinal facilitation induced by arm movement may be mediated in the cortical
99 networks. Therefore, motor control centers of trunk and arm muscles may not be embedded
100 within the central nervous system as separate units. Rather, they seem to interact closely.
101 Although corticospinal remote facilitation may be responsible for controlling arm-trunk
102 coordinated movements (Chiou and Strutton, 2020), its mechanisms are yet to be fully
103 understood.

104 Corticospinal remote facilitation has been studied extensively between upper- and lower-
105 limb muscles (Kawakita et al., 1991; Pereon et al., 1995; Tazoe and Komiyama, 2014) and this
106 phenomenon is known as remote effect or crossed facilitation (Tazoe and Komiyama, 2014).
107 Specifically, contraction of upper- or lower-limb muscles is known to facilitate corticospinal
108 excitability of muscles located in different and remote segments of the body (Chiou et al., 2013a,
109 2013b; Hortobágyi et al., 2003; Kawakita et al., 1991; Komeilipoor et al., 2017; Pereon et al.,
110 1995; Tazoe et al., 2009, 2007b). Such interlimb corticospinal remote facilitation was achieved
111 regardless of whether different tasks (e.g., flexion or extension) was performed (Chiou et al.,
112 2013a, 2013b; Tazoe et al., 2009, 2007b; Tazoe and Komiyama, 2014). Moreover, the extent of
113 corticospinal remote effect facilitation between upper- and lower-limb muscles was shown to
114 depend on the voluntary effort level of the contracted muscle (Kawakita et al., 1991; Tazoe et al.,
115 2009, 2007b). Regardless of the neurophysiological characteristics of remote effect facilitation,
116 its functional role in human motor control is still unknown (Tazoe and Komiyama, 2014).
117 Moreover, arm-trunk neural interaction mechanisms in corticospinal tract have not been

118 examined in detail, compared to more widely studied interlimb remote effects. Since trunk
119 muscles are activated in a highly coordinated manner during voluntary arm movements (Aruin
120 and Latash, 1995; Hodges and Richardson, 1997), characteristics of arm-trunk neural interactions
121 may be different from those observed in interlimb remote effect facilitation (Tazoe and
122 Komiyama, 2014). Moreover, since previous studies investigating arm-trunk neural interaction
123 used only one contraction intensity (i.e., either 20 or 30% MVC level) (Chiou et al., 2018; Chiou
124 and Strutton, 2020; Sasaki et al., 2018b, 2020b), it was not clear how neural interactions between
125 arm and trunk muscles would be modulated during different contraction intensities. Therefore,
126 investigating arm-trunk remote effect facilitation during different exertion levels and tasks may
127 provide new insights about underlying neural interaction mechanisms in the central nervous
128 system. Fundamentally, this could lead to a more comprehensive understanding of the basic
129 principles of human motor control. Moreover, it was recently reported that trunk muscle
130 corticospinal excitability could be facilitated after short-term upper-limb training (Chiou et al.,
131 2020). Arm-trunk corticospinal remote facilitation may also be attributed to quicker anticipatory
132 postural adjustments of the trunk during rapid shoulder flexion in patients with spinal cord injury
133 (Chiou and Strutton, 2020). Therefore, a thorough understanding of the characteristic of arm-
134 trunk corticospinal interactions may also be helpful to develop new rehabilitation interventions
135 for targeting improvements in arm-trunk interactions.

136 It was reported that trunk flexor (i.e., rectus abdominis: RA) and extensor (i.e., erector
137 spinae: ES) muscle activity depends on the direction of the arm movements (e.g., flexion or
138 extension) during various motor tasks (Aruin and Latash, 1995; Hodges et al., 1997). We
139 therefore hypothesized that arm muscle contractions would facilitate corticospinal excitability of
140 the trunk muscles, as recently demonstrated (Chiou et al., 2018; Sasaki et al., 2018a).
141 Specifically, our hypothesis was that the extent of arm-trunk corticospinal remote facilitation
142 would depend on the task performed during upper-limb muscle contractions (i.e., flexion or
143 extension), as indicated by studies that examined muscle-level outputs (Aruin and Latash, 1995;
144 Hodges et al., 1997). We also hypothesized that muscle contraction intensity would affect the
145 extent of arm-trunk remote effect facilitation, similar to that of interlimb facilitation (Kawakita et
146 al., 1991; Tazoe et al., 2009). Moreover, we also expected that the abovementioned task- and
147 intensity-dependent arm-trunk corticospinal remote facilitation profiles would change depending
148 on the functional role of the trunk muscles (i.e., RA or ES), as suggested by a previous study that

149 showed differences between RA and ES muscles for muscle-level outputs (Aruin and Latash,
150 1995). Therefore, the overall objective of our study was to first confirm arm-trunk (and arm-leg)
151 remote effect facilitation. If remote effect facilitation was indeed elicited using our current study
152 paradigm, the second objective was to examine whether task (flexion or extension) and intensity
153 (various exertion levels) of muscle contractions would affect remote effect facilitation. To test
154 our hypotheses, we used TMS to investigate MEPs in the trunk extensor and flexor muscles
155 during wrist flexion and extension tasks at the various contraction intensity levels. Lower limb
156 MEPs were also measured under same experimental conditions to identify whether the observed
157 modulations were specific to arm-trunk interactions, or whether co-activation of any two muscles
158 would produce similar facilitation patterns. Moreover, investigating remote effects of multiple
159 body segments, including limb and trunk muscles at the same time under the same condition,
160 could lead to a better understanding of neural interaction mechanisms of multiple muscles in
161 human motor control.

162

163 **2. Materials & Methods**

164 **2.1. Participants**

165 Twelve healthy male volunteers were recruited for this study. The age, weight, and height
166 of the participants were 24.8 ± 1.5 years, 67.2 ± 6.6 kg, and 173.5 ± 5.3 cm (mean \pm SD), respectively.
167 All participants were right-handed. None of the participants had any history of neurological or
168 musculoskeletal impairments. Specifically, for the TMS study, we confirmed that all participants
169 had no metal implants, cardiac pacemaker, history of epilepsy, brain injury, neurosurgery, or
170 psychological disorders, have never had a convulsion or a seizure, and did not regularly take
171 medications such as anti-depressants or other neuromodulatory drugs (Rossi et al., 2011). All
172 participants gave written informed consent in accordance with the Declaration of Helsinki. The
173 experimental procedures were approved by the local institutional ethics committee.

174

175 **2.2. Experimental procedures**

176 During the experiment, participants were seated comfortably on a chair with a back
177 support to keep their trunk muscles relaxed. Following a gentle warm-up and task practice,
178 maximum voluntary contraction (MVC) level was first measured by asking the participants to
179 perform three isometric wrist flexions and three isometric wrist extensions in a randomized order

180 between participants with their right (dominant) arm. Force level of the wrist flexion and wrist
181 extension was measured using a strain gauge sensor (LCB03K025L, A&D Company Limited,
182 Japan), which was fixed to a metal frame located on the distal part of the forearm (Figure 1A).
183 During the experiments, corticospinal excitability was assessed during: (a) wrist flexion; and (b)
184 wrist extension. In order to control for the biomechanical effects of performing flexion and
185 extension movements, both tasks were performed by rotating the arm such that the resultant
186 movements were in the opposite direction to gravity (Figure 1A). During wrist flexion and
187 extension tasks, participants were asked to match the forces corresponding to a range from 0
188 (Rest) to 50% of MVC force level and maintain this contraction intensity by matching the force
189 target level which was displayed on a monitor in real-time (Figure 1A). Each task consisted of
190 target force (0 (Rest) to 50% MVC with steps of 5%), corresponding to 11 blocks (Figure 1B)
191 which were separated by at least 3 min rest. The order of the target force levels was randomized
192 between participants. TMS stimuli were delivered when participants maintained the
193 corresponding contraction target level for a period of 3-5 seconds (i.e., steady-state part of the
194 contraction). Each block consisted of eight trials, which were separated with approximately 10
195 sec between trials. Moreover, the order of the experimental tasks (flexion or extension) was
196 randomized between participants, with at least 5 min rest between tasks.

197

198 **2.3. Data acquisition**

199 **2.3.1 Electromyography (EMG) activity**

200 Electromyographic (EMG) activities were recorded unilaterally from right side of: (i)
201 erector spinae muscle on the 12th thoracic vertebral level (ES; trunk extensor muscle); (ii) rectus
202 abdominis muscle lateral to the umbilicus (RA; trunk flexor muscle); and (iii) tibialis anterior
203 muscle lateral to the tibia (TA; lower-limb muscle). Two bipolar Ag/AgCl surface electrodes
204 (Vitrode F-150S, Nihon Kohden, Tokyo, Japan) were placed over the muscle belly with 1 cm
205 separation. A ground electrode was placed over the right anterior superior iliac spine. Prior to
206 application of electrodes, skin was cleaned using alcohol to reduce impedance. All EMG signals
207 were band-pass filtered (5 - 1,000 Hz) and amplified ($\times 1,000$) using a multichannel amplifier
208 (MEG-6108, Nihon Kohden, Tokyo, Japan). All data were digitized at a sampling frequency of
209 4,000 Hz using an analog-to-digital (A/D) converter (Powerlab/16SP, AD Instruments, Castle
210 Hill, Australia) and stored on the computer for post-processing.

211

212 **2.3.2 Transcranial magnetic stimulation (TMS)**

213 TMS was delivered over the primary motor cortex using a mono-phasic magnetic
214 stimulator (Magstim 200, Magstim Co., Whitland, UK) through a double cone coil (outside
215 diameter of 110 mm; Magstim Co., Whitland, UK). The optimal stimulation spot (“hot spot”)
216 was searched over the left motor cortex where MEPs could be recorded from the right ES muscle.
217 Once the “hot spot” was defined, the coil position and orientation were monitored throughout the
218 experiment using a neuronavigation system (Brainsight, Rogue Research, Montreal, Canada) to
219 ensure same coil placement between tasks. The motor threshold (MT) was determined while the
220 participants remained relaxed. Specifically, the MT was defined as the minimum TMS intensity
221 for which ES MEPs had peak-to-peak amplitudes larger than 50 μ V and were evoked in at least
222 five out of ten consecutive trials (Rossini et al., 2015). The stimulus intensity was set at 120% of
223 the MT level ($73.3 \pm 12.3\%$ of maximal stimulator output) and remained consistent for the
224 duration of the experiment. Since the highest MT in the current study was 76% of maximal
225 stimulator output, we were able to apply 120% MT level for all participants. During preliminary
226 testing, it was confirmed that we could elicit MEP responses in RA and TA muscles when the
227 stimulation “hot spot” and intensity were optimized for the ES muscle. However, since two
228 participants for the RA and three participants for the TA had <0.05 mV amplitude of MEPs at
229 rest, these muscles were excluded for MEP analysis (i.e., RA: $n=10$ and TA: $n=9$). The average
230 MEP amplitudes with SD at rest in the ES, RA, and TA muscles were 0.08 ± 0.03 mV, $0.34 \pm$
231 0.25 mV, and 0.42 ± 0.27 mV, respectively.

232

233 **2.3. Data analysis**

234 Background EMG activity of a 50 ms window before each TMS stimulus was first
235 defined by calculating the root mean square value in each muscle and each trial using a custom
236 written script in MATLAB (2017a, The MathWorks Inc., Massachusetts, USA). It is well known
237 that MEPs elicited by single plus TMS are facilitated by background activation of the muscle
238 (Hess et al., 1987). Therefore, if trunk and lower-limb muscles were co-activated during upper-
239 limb muscles contraction tasks (i.e., wrist flexion and wrist extension), it would not be possible
240 to evaluate the remote effect. Comparing background EMG activity was therefore used to ensure
241 that remote muscles were not contracted during wrist flexion or extension tasks. If the

242 background EMG activity in any of the experimental tasks was significantly different from Rest
243 (0% MVC level), remote effect facilitation was not considered for these tasks (see Results
244 section).

245 To analyze remote effect facilitation, MEP peak-to-peak amplitudes were calculated for
246 each trial and each remote muscle (i.e., ES, RA, and TA). Eight repeated trials were averaged for
247 each task (i.e., wrist flexion and wrist extension) and each contraction intensity (i.e., % MVC
248 contraction levels for which the remote limb muscle background EMG activity was not different
249 from the Rest condition; see section 3.1). In preliminary experiments it was determined that eight
250 trials were sufficient to obtain consistent recordings since variability was sufficiently low,
251 consistent with previous studies (Groppa et al., 2012). MEP amplitudes were then normalized as
252 a percentage of the amplitude of the elicited responses during the Rest condition for each
253 participant.

254

255 **2.4. Statistics**

256 For each muscle (ES, RA, and TA) and each task (wrist flexion and wrist extension)
257 separately, background EMG activities were first compared between different muscle contraction
258 intensities (Rest and 5 to 50% MVC with steps of 5%) using the Friedman test, a non-parametric
259 equivalent for repeated-measure analysis of variance (ANOVA). Significant results were
260 followed up with post-hoc multiple comparisons using the Wilcoxon signed-rank test to compare
261 Rest (0% MVC) to each remote contraction condition level (5, 10, ..., 45, and 50% MVC). Since
262 background EMG activities of the ES muscle during wrist flexion and wrist extension at the
263 contraction levels above 25% MVC (i.e., 30, 35, 40, 45, and 50% MVC) were significantly
264 greater compared to that during Rest (0% MVC) (Wilcoxon signed-rank test, $p < 0.05$; see section
265 3.1 and Figure 2A), only data below 30% MVC (5, 10, 15, 20, and 25% MVC) was used for
266 remote effect MEP analysis for the ES muscle. Background EMG activities of the RA and TA
267 muscle during wrist flexion and wrist extension were not significantly different compared to Rest
268 (0% MVC) even if upper-limb muscles were contracted at 50% MVC level (Wilcoxon signed-
269 rank test, $p < 0.05$; see section 3.1 and Figure 2A). However, initially we also only included data
270 below 30% MVC (5, 10, ..., 20, and 25% MVC) for remote effect MEP analysis of the RA and
271 TA muscles since it is possible that their facilitation may also have been affected by the
272 background EMG activity of ES muscles.

273 For MEP analysis, we first investigated whether remote facilitation occurred in each
274 remote contraction condition (5 to 25% MVC) using the Friedman test, a non-parametric
275 equivalent for repeated-measure ANOVA. The Friedman test included MEP amplitudes in the
276 Rest, 5, 10, 15, 20, and 25% MVC. Significant results were followed up with multiple
277 comparisons using the Steel post-hoc test, which is a non-parametric equivalent for Dunnett's test,
278 to determine whether MEPs during remote contraction conditions (5, 10, 15, 20, and 25% MVC)
279 were significantly different from Rest for each muscle. When significant remote facilitation was
280 shown, the Friedman test was used to compare MEP amplitudes between contraction at 5, 10, 15,
281 20, and 25% MVC to investigate contraction intensity effects on remote facilitation for each
282 muscle. Significant results were followed up with post-hoc testing using the Wilcoxon signed-
283 rank test with Holm corrections. Specifically, five remote contraction conditions (5, 10, 15, 20,
284 and 25% MVC) were analyzed in post-hoc testing, and the statistical significance levels were
285 adjusted using the Holm corrections, as summarized by McLaughlin and Sainani (2014).

286 Additional analysis was conducted to investigate remote effect contraction intensity
287 dependence in RA and TA muscles during high intensity remote contraction (30, 35, 40, 45 and
288 50% MVC) since they were excluded from the main analysis due to larger ES background EMG
289 activities (Note: RA and TA background EMG activities were not statistically different
290 compared to Rest (0% MVC)). Specifically, since ES background EMG activities were
291 significantly increased during 30 to 50% MVC of wrist flexion and wrist extension (see section
292 3.1.), it could be considered that activation of ES background EMG (i.e., possible remote effect
293 facilitation from ES to RA and/or TA muscles) may have affected RA and TA corticospinal
294 excitability. Therefore, correlations between the remote effect in RA and TA MEPs and ES
295 background EMG activations during 30 to 50% MVC of wrist flexion and wrist extension were
296 first analyzed using Spearman's rank correlations. Since no significant correlations were shown
297 (see section 3.3), the same statistical tests were conducted for MEP amplitudes between
298 contraction at 30, 35, 40, 45 and 50% MVC as for those during lower contraction intensities (5 to
299 25% MVC).

300 Overall, non-parametric tests were chosen because the Shapiro-Wilk test showed that
301 most identified measures were not normally distributed. All statistical comparisons were
302 performed using the software package R (version 3.6.3). Significance level for all tests was set to
303 $p < 0.05$.

304

305 **3. Results**306 **3.1. Background EMG activity**

307 The background EMG activity results are shown in Figure 2. The Friedman test showed
308 that ES background EMG activities were significantly different between contraction intensities
309 (0-50%MVC) in both wrist flexion and wrist extension tasks [wrist flexion: $\chi^2(10)=54.9$,
310 $p<0.001$; wrist extension: $\chi^2(10)=82.2$, $p<0.001$]. Specifically, post-hoc analysis showed that the
311 ES background EMG activities during $\geq 30\%$ MVC wrist flexion and wrist extension were
312 significantly increased, compared to Rest (0% MVC) ($p<0.05$, Wilcoxon signed-rank test; Figure
313 2A).

314 The Friedman test showed that RA background EMG activities were not significantly
315 different between contraction intensities (0-50% MVC) during wrist flexion task [$\chi^2(10)=18.2$,
316 $p=0.052$], while they were significantly different during wrist extension task [$\chi^2(10)=26.2$,
317 $p<0.01$]. Post-hoc analysis showed no significant differences in RA background EMG activities
318 during wrist extension between Rest (0% MVC) and remote contraction condition ($p>0.05$,
319 Wilcoxon signed-rank test; Figure 2B).

320 Finally, the Friedman test showed that TA background EMG activities were not
321 significantly different between contraction intensities (0-50% MVC) in both wrist flexion and
322 wrist extension tasks [wrist flexion: $\chi^2(10)=11.1$, $p=0.354$; wrist extension: $\chi^2(10)=9.19$,
323 $p=0.514$] (Figure 2C).

324

325 **3.2. MEP modulation during low contraction intensities**

326 The MEP amplitude modulation results during 5-25% MVC of wrist flexion and wrist
327 extension are shown in Figure 3. For the ES muscle, the Friedman test showed that ES MEP
328 amplitudes were significantly different between contraction intensities (0-25% MVC) in each
329 task (i.e., wrist flexion and wrist extension) [wrist flexion: $\chi^2(5)=14.8$, $p=0.011$; wrist extension:
330 $\chi^2(5)=40.2$, $p<0.001$]. Specifically, post-hoc analysis showed that the ES MEP amplitudes during
331 $\geq 5\%$ MVC of wrist flexion and wrist extension were significantly increased compared to Rest
332 (0% MVC) ($p<0.05$, Steel test; Figure 3A and D). Moreover, the Friedman test showed no
333 significant differences in MEP amplitudes between 5-25% MVC of wrist flexion [$\chi^2(4)=4.73$,
334 $p=0.316$] (Figure 3A), while there were significant differences in MEP amplitudes between 5-

335 25% MVC of wrist extension [$\chi^2(4)=23.3$, $p<0.001$] (Figure 3D). Specially, post-hoc analysis
336 showed that MEP amplitudes during 15-25 % MVC of wrist extension were larger compared to
337 those during 5% MVC ($p<0.05$; Figure 3D).

338 For the RA muscle, the Friedman test showed no significant difference in MEP
339 amplitudes between 0-25% MVC of wrist flexion and wrist extension [wrist flexion: $\chi^2(5)=9.14$,
340 $p=0.104$; wrist extension: $\chi^2(5)=5.76$, $p=0.330$] (Figure 3B and E).

341 For the TA muscle, the Friedman test showed that TA MEP amplitudes were significantly
342 different between contraction intensities (0-25% MVC) in each task (i.e., wrist flexion and wrist
343 extension) [wrist flexion: $\chi^2(5)=21.3$, $p<0.001$; wrist extension: $\chi^2(5)=18.2$, $p<0.01$]. Specifically,
344 post-hoc analysis showed that the TA MEP amplitudes during $\geq 5\%$ MVC of wrist flexion and
345 wrist extension were significantly increased compared to Rest (0% MVC) ($p<0.05$, Steel test;
346 Figure 3C and F). Moreover, the Friedman test showed no significant difference in MEP
347 amplitudes between 5-25% MVC of wrist flexion and wrist extension [wrist flexion: $\chi^2(4)=4.10$,
348 $p=0.600$ (Figure 3C); wrist extension: $\chi^2(4)=3.38$, $p=0.497$] (Figure 3F).

349

350 **3.3. MEP modulation during larger contraction intensities**

351 Since there was no significant correlation between ES background EMG activation and
352 RA and TA MEP facilitation during 30-50% MVC of wrist flexion and wrist extension (all
353 Spearman's correlations $p>0.05$), RA and TA MEP modulations during larger (30-50% MVC)
354 contraction intensities were also compared as additional analysis.

355 The results of the RA and TA muscle MEP amplitudes during 30 - 50% MVC of wrist
356 flexion and wrist extension are shown in Figure 4. For the RA muscle, the Friedman test showed
357 that MEP amplitudes were significantly different between Rest (0% MVC) and each remote
358 contraction condition (30, 35, 40, 45, and 50% MVC) in wrist flexion task [$\chi^2(5)=12.9$,
359 $p=0.0242$] (Figure 4A), while there were no significant differences in wrist extension task
360 [$\chi^2(5)=9.31$, $p=0.0971$] (Figure 4C). Specifically, post-hoc analysis showed that the RA MEP
361 amplitudes during 40 and 45 % MVC of wrist flexion were significantly increased compared to
362 Rest (0% MVC) ($p<0.05$, Steel test; Figure 4A). The Friedman test showed no significant
363 differences in MEP amplitudes between 30-50% MVC of wrist flexion [$\chi^2(4)=4.73$, $p=0.316$]
364 (Figure 4A).

365 For the TA muscle, the Friedman test showed that MEP amplitudes were significantly
366 different between Rest (0% MVC) and each remote contraction condition (30, 35, 40, 45, and
367 50% MVC) in both wrist flexion and wrist extension tasks [wrist flexion: $\chi^2(5)=21.6$, $p<0.001$;
368 wrist extension: $\chi^2(5)=31.2$, $p<0.001$] (Figure 4B and D). Specifically, post-hoc analysis showed
369 that the TA MEP amplitudes during 30 - 50% MVC of wrist flexion and wrist extension were
370 significantly increased compared to Rest (0%MVC) ($p<0.01$, Steel test; Figure 4B and D). The
371 Friedman test showed no significant difference in MEP amplitudes between 30 - 50% MVC of
372 wrist flexion [$\chi^2(4)=3.20$, $p=0.525$] (Figure 4B), while there were significant differences in MEP
373 amplitudes between 30-50% MVC of wrist extension [$\chi^2(4)=16.6$, $p<0.01$] (Figure 4D).
374 Specially, post-hoc analysis showed that MEP amplitudes during 45 and 50% MVC of wrist
375 extension were larger compared to during 30% MVC ($p<0.05$; Figure 4D).

376

377 4. Discussion

378 In the current study, we investigated whether the extent of corticospinal remote
379 facilitation of the ES (trunk extensor) muscle induced by upper-limb contractions would depend
380 on the task (wrist flexion or extension) and contraction intensity. Our results showed that
381 corticospinal excitability of the ES was significantly facilitated even during low level ($\geq 5\%$
382 MVC) wrist flexion and wrist extension contractions (Figure 3A and D). However, the extent of
383 corticospinal remote facilitation of the ES muscle during wrist flexion did not depend on
384 contraction intensity. On the other hand, higher levels of wrist extension contractions induced
385 greater extent of corticospinal remote facilitation in the ES, indicating contraction intensity
386 dependence (Figure 3D). For the RA (trunk flexor) muscle, our results also showed significant
387 corticospinal excitability facilitation during wrist flexion contractions above 25% MVC (Figure
388 4A), but not extension (Figure 4C). The extent of RA corticospinal remote facilitation was not
389 reinforced even when wrist flexion intensity increased at 50% MVC (Figure 4A). Finally, for the
390 TA (leg) muscle, corticospinal excitability was significantly facilitated during low level ($\geq 5\%$
391 MVC) wrist flexion and wrist extension contractions (Figure 3C and F). Specifically, the extent
392 of corticospinal remote facilitation in the leg muscles was not changed when remote muscle
393 contraction intensity was below 30% MVC (Figure 3C and F), while it was increased during
394 higher contractions (50% MVC) during wrist extension, but not flexion (Figure 4B and D). Since
395 there were statistically significant ES background EMG activations during wrist flexion and

396 wrist extension at 30 to 50% MVC, it could be stipulated that ES background EMG activation
397 may have affected RA and TA corticospinal remote facilitation. However, it must be noted that
398 since the ES activation levels were exceedingly low (i.e., on average 0.8-1.9% MVC, as shown
399 in Figure 2A) and there was no statistically significant correlation between ES background EMG
400 activation and RA and TA MEP facilitation during wrist flexion and wrist extension at 30 to 50%
401 MVC (see section 3.3.), it is highly unlikely that ES background EMG activation had any
402 considerable physiological effects on the remote facilitation in the RA and TA muscles.
403 Therefore, it can be assumed that remote facilitation observed in the RA and TA muscles is
404 predominantly related to wrist flexion or extension task performance. A discussion about
405 possible mechanisms of task- and intensity-dependent corticospinal remote facilitation follows.

406

407 ***4.1. Task- and intensity-dependence of arm-trunk corticospinal remote facilitation***

408 The main findings of our current study are that: (1) corticospinal remote facilitation of the
409 ES muscle (trunk extensor) was elicited even during low-level wrist flexion and extension
410 contractions ($\geq 5\%$ MVC), while relatively strong wrist flexion and extension contractions ($\geq 25\%$
411 MVC) were required to induce remote facilitation of the RA muscle (trunk flexor); and (2) extent
412 of corticospinal remote facilitation of the ES (trunk extensor) was proportional to the contraction
413 intensity of wrist extension but not wrist flexion, while this was not observed for the RA (trunk
414 flexor) muscle during both wrist extension and flexion tasks. Moreover, corticospinal excitability
415 in the TA muscles was significantly facilitated during low level ($\geq 5\%$ MVC) wrist extension and
416 wrist flexion contractions. The extent of corticospinal remote facilitation in the leg muscles was
417 not changed when remote muscle contraction intensity was below 30% MVC, while the extent of
418 corticospinal remote facilitation increased during higher wrist extension contractions (50%
419 MVC), but not flexion. It has previously been reported that corticospinal remote facilitation
420 between upper- and lower-limb muscles (interlimb facilitation) was achieved regardless of the
421 task that was performed (Chiou et al., 2013b, 2013a; Tazoe and Komiyama, 2014). Moreover,
422 the extent of interlimb corticospinal remote facilitation was shown to depend on voluntary effort
423 level of the contracted muscle (Kawakita et al., 1991; Tazoe et al., 2009, 2007b; Tazoe and
424 Komiyama, 2014). However, it was unclear until now if these flexion / extension task
425 characteristics of interlimb neural interactions would remain similar during arm-trunk
426 interactions. Based on previous studies showing that trunk flexor and extensor muscle activity

427 depends on the direction of the arm movements (Aruin and Latash, 1995; Hodges et al., 1997),
428 we hypothesized that the extent of arm-trunk corticospinal remote facilitation would depend on
429 the task performed during upper-limb muscle contractions (i.e., flexion or extension). We also
430 hypothesized that muscle contraction intensity would affect the extent of arm-trunk remote effect
431 facilitation, similar to that of interlimb facilitation (Tazoe et al., 2009, 2007b; Tazoe and
432 Komiyama, 2014). Consistent with these hypotheses, our results demonstrated that the extent of
433 corticospinal remote facilitation between arm and trunk muscles depended on the task (i.e.,
434 upper-limb flexion or extension) and the level of remote upper-limb muscle contractions. A
435 study by Chiou *et al.*, (2016) previously reported that corticospinal excitability of the ES muscle
436 was greater during a rapid shoulder flexion task (phasic contractions) compared to a static
437 shoulder flexion task (tonic contractions), while the extent of remote facilitation of the RA
438 muscle was similar between these tasks. Our results also showed that the profiles of remote
439 facilitation during deferent level of contraction differed between tasks (i.e., wrist flexion and
440 extension). Therefore, ES muscle corticospinal facilitation was affected to a different extent
441 depending on the task during arm movements, while this was not true for the RA muscle.
442 Specifically, our study showed that ES muscles could be facilitated more when wrist extensor
443 (but not flexor) contraction intensities were increased, even if the effort changes were
444 exceedingly small (i.e., 5% MVC). This may suggest that wrist extensors have a stronger
445 connectivity with the trunk extensors (ES) compared to the trunk flexors (RA). Such functional
446 muscle connectivity (extensor-extensor / flexor-flexor connectivity) is also supported by our
447 results that remote facilitation of trunk flexors (RA) occurred during contractions of wrist flexors
448 as well as that contraction intensity dependent remote facilitation of the leg extensors (TA) was
449 observed during contractions of the wrist extensors.

450 On the other hand, it has previously been reported that ES corticospinal excitability was
451 facilitated to a larger extent by elbow flexion compared to elbow extension, which suggests that
452 elbow flexors have the stronger interactions with trunk extensors (Chiou et al., 2018). Therefore,
453 it is also possible that arm and trunk connectivity may not always depend on the flexor / extensor
454 remote muscle pairs, but also on the functional connectivity between these muscles. In our
455 current study, ES MEPs were facilitated during both wrist flexion and extension at contraction
456 intensities above 5% of MVC effort, although contraction intensity dependence was only shown
457 during wrist extension. Therefore, ES muscles could detect arm movements even at relatively

458 small contraction intensities regardless of whether wrist extension or flexion was performed. It
459 has been reported that activation of ES muscles has an important role for minimizing postural
460 displacement during arm movement-induced postural perturbations (Aruin and Latash, 1995;
461 Hodges et al., 1997). Taken together, such functional connectivity of the ES and remote limb
462 muscle pairs may perhaps explain greater sensitivity of trunk extensors to upper-limb movement
463 and changes in corticospinal excitability to contraction intensity, as demonstrated in our current
464 study.

465

466 **4.2. Possible mechanisms of arm-trunk corticospinal remote facilitation**

467 Since it is well known that the excitability of the corticospinal pathway is affected by
468 excitation of both cortical and spinal circuits (Hess et al., 1987), arm-trunk corticospinal remote
469 facilitation, which was demonstrated in our current study, could also be attributed to cortical
470 and/or spinal circuits. Indeed, previous studies reported that inter-limb remote facilitation could
471 affect both cortical (e.g., Tazoe *et al.*, 2007a; Chiou *et al.*, 2013a, 2013b) and spinal (e.g.,
472 Jendrassik E, 1883; Kawamura & Watanabe, 1975; Borroni *et al.*, 2005) motor circuits.
473 Specifically, it was demonstrated that remote limb muscle contractions decreased upper-limb and
474 lower-limb muscle short-interval intracortical inhibition (induced by paired-pulse TMS), which
475 implies cortical inhibition mechanisms during remote muscle contractions (Chiou et al., 2013a,
476 2013b). Similarly, decreased duration of the cortical silent period (induced by TMS during low
477 levels of muscle contractions) of upper-limb muscles was shown to be elicited by contractions of
478 lower-limb muscle, also suggesting cortical inhibition (Tazoe et al., 2007a). These studies
479 suggest that cortical disinhibition may contribute to corticospinal remote facilitation between
480 upper- and lower-limb muscles. Moreover, H-reflex responses elicited by peripheral nerve
481 stimulation (e.g., Jendrassik E, 1883; Kawamura & Watanabe, 1975; Borroni *et al.*, 2005) as
482 well as posterior-root spinal reflex responses elicited by transcutaneous spinal cord stimulation
483 (Kato et al., 2019; Masugi et al., 2019; Sasaki et al., 2020a) in the upper- or lower-limb muscles
484 were facilitated by remote limb muscle contractions. These studies indicate spinal reflex remote
485 modulation mechanisms also contribute to interlimb remote facilitation. Therefore, arm-leg
486 remote facilitation observed in our current study (i.e., TA remote facilitation during wrist flexion
487 and wrist extension) may also be caused by cortical and/or spinal mechanisms. Taken together, it
488 may be speculated that arm-trunk corticospinal remote facilitation is also mediated in cortical

489 and/or spinal networks. Conversely, two recent studies suggested that cortical-levels networks
490 may primarily be attributed to arm contraction-induced trunk remote facilitation (Chiou et al.,
491 2018; Sasaki et al., 2020b). Specifically, Chiou *et al.*, (2018) showed decreased short-interval
492 intracortical inhibition, indicating disinhibition of intracortical circuits. However, no changes in
493 the cervicomedurally motor evoked potentials (induced by cervicomedullary junction magnetic
494 stimulation) of the trunk muscle during upper-limb contractions were observed, suggesting that
495 subcortical (spinal) excitability was unaffected (Chiou et al., 2018). Similarly, it was shown that
496 cervicomedurally motor evoked potentials of the trunk muscles were not affected by upper-limb
497 contraction, while corticospinal excitability was modulated (Sasaki et al., 2020b). Although it is
498 still possible that both cortical and/or spinal networks may be involved, recent evidence suggests
499 that arm-trunk remote facilitation is more likely mediated in the cortical-level networks. The
500 cortical remote facilitation mechanisms hypothesis is also supported by basic animal studies
501 which have demonstrated that intracortical facilitation may be involved in spreading of neural
502 activity within the motor cortex (Capaday et al., 2011, 2009). Specifically, it was shown that
503 neural activity initiated at a cortical locus can spread to the neighboring cortical regions which
504 represent different muscles via intrinsic horizontal connections between neurons within the
505 motor cortex (Capaday et al., 2011, 2009). In human studies using TMS, it was proposed that
506 similar cortico-cortical connections may exist (Borojerdi et al., 2000; Komeilipoor et al., 2017).
507 Specifically, previous studies investigating corticospinal remote facilitation mechanisms
508 proposed that activation of cortical motor networks by voluntary contraction of certain muscles
509 could spread to neighboring cortical areas representing different segment muscle (Borojerdi et
510 al., 2000) and that the extent of this spreading may depend on the distance between M1
511 representations of different muscles within the cortex (Borojerdi et al., 2000; Sasaki et al.,
512 2018a). This suggests that cortical remote facilitation mechanisms are dependent on the
513 anatomical somatotopic representations within the primary motor cortex. Moreover, it is well
514 known that somatotopy of muscles in the different body segments overlap within the motor
515 cortex (Brasil-Neto et al., 1992; Penfield and Boldrey, 1937). Since the trunk muscle
516 representations in the homunculus of the primary motor cortex (M1) in humans is located near
517 the upper-limb representations, it is likely that activation of trunk cortical motor circuits was also
518 induced during voluntary contraction of upper limbs due to the overlapping of the cortical
519 representations within the primary motor cortex (M1). Therefore, arm-trunk corticospinal remote

520 facilitations observed in our current study, are likely modulated via anatomical connections such
521 as intracortical connectivity networks, and/or overlapping of somatotopic representations at the
522 supraspinal level, although subcortical mechanisms cannot be fully ruled out. Indeed, previous
523 studies reported that subcortical circuits may be more involved as contraction levels increase
524 (Muellbacher et al., 2000; Stedman et al., 1998). Therefore, it is possible that subcortical
525 mechanisms may also have contributed to the remote facilitation when contraction levels were
526 higher. Moreover, the proximity of motor representations within M1 between remote muscles
527 may be one of the possible mechanisms related to the corticospinal remote facilitation
528 (Borojerdj et al., 2000). However, since our current study showed that profiles of remote effect
529 of ES and RA muscles were different, despite their proximity within M1, remote facilitation
530 mechanisms cannot only be explained by somatotopic relationships. A specific discussion related
531 to other possible mechanisms of corticospinal remote facilitation follows in section 4.3.

532

533 ***4.3. Significance of corticospinal remote facilitation***

534 Overall, corticospinal remote facilitation relationship between certain remote muscles
535 (e.g., arm-trunk or arm-leg) may reflect anatomical relationships with the central nervous system
536 and/or functional connectivity between these muscles. If only the anatomical relationship
537 between remote muscles (i.e., proximity of motor representations within M1, as discussed in
538 section 4.2) were to determine the profile of remote corticospinal facilitation, remote effect
539 between arm-trunk would simply be effective compared to that of arm-leg. However, our current
540 results showed that even different trunk muscles (i.e., ES and RA), which are located very close
541 with the M1 (Tsao et al., 2011), had very distinct remote facilitation responses. Moreover, the leg
542 muscles (TA) showed lower threshold of remote facilitation, compared to the trunk flexor
543 muscles (RA). Therefore, our current study may suggest that functional relationships between
544 remote muscles are also represented within the corticospinal circuits, in addition to their
545 anatomical relationship (i.e., somatotopic representations with M1). Specifically, ES muscles
546 have an important functional role for maintaining postural stability during arm movements
547 (Aruin and Latash, 1995; Hodges et al., 1997), which may be why ES muscle showed lower
548 thresholds and task- and intensity- dependent modulation of corticospinal remote facilitation. On
549 the other hand, interlimb (arm-leg) coordinated movements are functionally relevant during
550 rhythmic movements which activate the central pattern generator, such as walking and cycling

551 (Zehr and Duysens, 2004). Indeed, it was shown that arm-leg neural interaction could be
552 strengthened to a larger extent during rhythmic movements, compared to tonic contractions
553 (Frigon et al., 2004; Zehr et al., 2007). Therefore, under the tonic contractions condition in the
554 current study, intensity-dependent changes in arm-leg corticospinal remote facilitation may not
555 be functionally required. However, intensity-dependent changes in arm-leg corticospinal remote
556 facilitation were observed only during high levels of wrist extension intensities in the current
557 study. It was reported that rhythmic ipsilateral hand and foot movements performed at the same
558 time are made more reliable when they are synchronized in the same direction (Baldissera et al.,
559 1982). A previous study investigating effects of rhythmic ankle plantar/dorsi flexion on H-reflex
560 excitability of wrist flexors (i.e., flexor carpi radialis) also reported that modulation peak of H-
561 reflex in the wrist flexors occurred at the same time as the contraction of the ankle plantar flexors
562 (i.e., soleus muscle) (Baldissera and Borroni, 2002). Moreover, preference of rhythmic hand and
563 foot movements reflects spatial rather than structural constraints. When the hand was pronated,
564 wrist flexor neural pathways were facilitated during the plantarflexion phase, while when the
565 hand was supinated, wrist extensors were facilitated during the plantarflexion phase, and wrist
566 flexors were facilitated during dorsiflexion (Borroni et al., 2004). Therefore, rhythmic
567 movements eliciting central pattern generator (CPG)-like activations were shown to strengthen
568 arm-leg connectivity depending on the direction of the movement, rather than based on specific
569 muscle pairs, which indicates that rhythmic interlimb interactions may reflect functional
570 connectivity (Borroni et al., 2004). On the other hand, tonic contraction tasks, which were
571 performed in our current study, strengthened the connectivity in specific muscle pairs (i.e., ECR
572 and TA) during high levels of contraction. This may possibly reflect a biological (structural)
573 characteristic, rather than a functional connection. Moreover, trunk flexors (RA) have an
574 anatomical advantage in that the representation within the homunculus of the motor cortex is
575 located close to the upper-limb representations. Despite this, the RA showed higher threshold of
576 remote facilitation and no task- and intensity- dependent modulation. This may reflect weak
577 functional connectivity between trunk flexors (RA) and arm muscles. Moreover, different neural
578 innervations of these muscles may also contribute to their remote facilitation profiles.
579 Specifically, the ES muscles at the T12 level are innervated by dorsal rami of thoracic and
580 lumbar spinal nerves (T8-L3), while the RA muscles are innervated by the intercostal nerve
581 (Pradhan and Taly, 1989). Therefore, it is possible that the neural innervations may also have

582 contributed to remote facilitation profiles in our study. Overall, multiple effect including
583 anatomical somatotopic relationships as well as functional connectivity may attribute to task- and
584 intensity-dependent modulation of remote facilitation between arm and trunk extensor. Our
585 findings therefore inform a more comprehensive understanding of the basic principles of human
586 motor control related to the arm-trunk neural interaction. Taken together, these results may also
587 suggest that functional movement synergy oriented training is crucial in rehabilitation to
588 strengthen arm-trunk interactions as a way for improving functional performance after
589 neurological impairments such as spinal cord injury (Chiou et al., 2020; Chiou and Strutton,
590 2020).

591

592 **4.4. Limitations**

593 Our work has several limitations that should be noted. First, some previous studies
594 investigating interactions between trunk and upper-limb muscles have examined contralateral
595 side trunk muscles to the contracted arm to elicit MEP responses (Chiou et al., 2018; Chiou and
596 Strutton, 2020; Davey et al., 2002), while we chose to investigate the ipsilateral side in the
597 current study. Davey et al., (2002) previously reported that ES muscle activity in the
598 contralateral side to contracted arm was increased when arm muscle contractions during shoulder
599 abduction were increased, while that of ipsilateral side was not affected considerably. Therefore,
600 ipsilateral side was investigated in our study with the aim to minimize co-contraction of ES
601 muscles during wrist flexion and extension, although it is also likely that ES background EMG
602 activations in the contralateral and ipsilateral side muscles were similar in sitting posture (Sasaki
603 et al., 2020b). Nonetheless, further work is warranted to systematically examine differences in
604 remote effect facilitation between ipsilateral and contralateral side trunk muscles during various
605 tasks at intensities.

606 Second, although significant ES background EMG activations during strong wrist flexion
607 and extension contractions (>25% MVC) were exceedingly low (i.e., on average 0.8-1.9% MVC,
608 as shown in Figure 2A), and there were no significant correlations between the remote RA and
609 TA MEPs and ES background EMG activations during 30-50% MVC of wrist flexion and wrist
610 extension, we still cannot completely exclude a possibility that these slight ES activations could
611 have affected the profiles of remote effect facilitation of RA and TA muscles, in additions to
612 wrist flexion and extension contractions.

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728

729 **Figure caption**

730 **Figure 1:** (A) Experimental setup showing the hand posture of participants during the
731 experiment. During the experiment, participants were asked to match the isometric wrist flexion
732 and wrist extension force 0 to 50% of maximum voluntary contraction effort using their right
733 arm with real-time visual feedback of force displayed on a monitor. (B) Experiment consisted of
734 wrist flexion and wrist extension conditions, which were randomized between participants and
735 separated by 5 min rest. Each condition consisted of 11 blocks and each target force [0 (Rest), 5,
736 10, ..., 45, or 50% MVC] was randomly set to each block with at least 3 min rest between blocks.
737 Each block consisted of eight trials.

738

739 **Figure 2:**

740 Group data for background electromyographic (EMG) activity of the: (A) erector spinae (ES);
741 (B) rectus abdominis (RA); and (C) tibialis anterior (TA) muscles during 0 (Rest) to 50% of
742 maximum voluntary contraction (MVC) effort of wrist flexion and wrist extension. The lines and
743 cross marks in the box plots indicate median and mean values, respectively. The ends of the
744 boxes represent the 25th and 75th percentiles. The whiskers on the boxplot illustrate the
745 minimum and maximum values. Asterisks indicate significant differences compared to 0% MVC
746 (Rest). Legend: n.s. non-significant; * $p < 0.05$; ** $p < 0.01$.

747

748 **Figure 3:**

749 (A), (B), and (C) Wrist flexion condition: Averaged motor evoked potentials (MEPs) in the
750 erector spinae (ES), rectus abdominis (RA), and tibialis anterior (TA) muscles of one
751 representative subject during 0% MVC (Rest: gray traces) and 5-25% MVC (remote effect: blue
752 traces). Box plots show group data for MEPs elicited in the ES, RA, and TA muscles.

753 (D), (E), and (F) Wrist extension condition: Averaged MEPs in the ES, RA, and TA muscles of
754 one representative subject during 0% MVC (Rest: gray traces) and 5-25% MVC (remote effect:
755 red traces). Box plots show group data for MEPs elicited in the ES, RA, and TA muscles.

756 All MEP amplitudes were normalized with respect to the MEP amplitude at 0% MVC (Rest) for
757 each participant. The lines and cross marks in the box plots indicate median and mean values,
758 respectively. The ends of the boxes represent the 25th and 75th percentiles. The whiskers on the
759 boxplot illustrate the minimum and maximum values. Asterisks indicate significant differences

760 compared to 0% MVC (Rest). Hashtags indicate differences between 5-25% MVC of wrist
761 extension. Legend: * $p<0.05$, ** $p<0.01$; # and dashed line $p<0.10$, # and solid line $p<0.05$.

762

763 **Figure 4:**

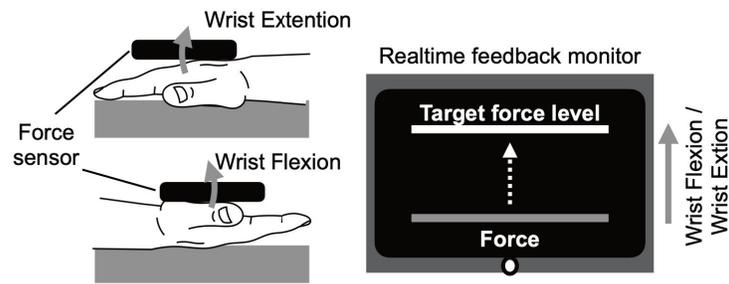
764 (A) and (B) Wrist flexion condition: Averaged motor evoked potentials (MEPs) in the rectus
765 abdominis (RA) and tibialis anterior (TA) muscles of one representative subject during 0% MVC
766 (Rest: gray traces) and 30-50% MVC (remote effect: blue traces). Box plots show group data for
767 MEPs elicited in the RA and TA muscles.

768 (C) and (D) Wrist extension condition: Averaged MEPs in the RA and TA muscles of one
769 representative subject during 0% MVC (Rest: gray traces) and 5-25% MVC (remote effect: red
770 traces). Box plots show group data for MEPs elicited in the RA and TA muscles.

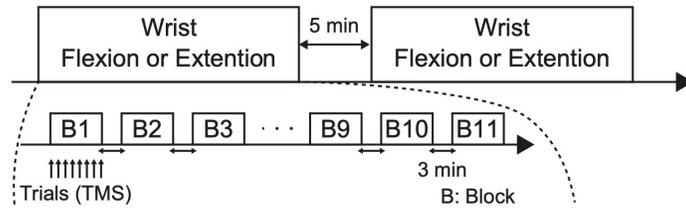
771 All MEP amplitudes were normalized with respect to the MEP amplitude at 0% MVC (Rest) for
772 each participant. The lines and cross marks in the box plots indicate median and mean values,
773 respectively. The ends of the boxes represent the 25th and 75th percentiles. The whiskers on the
774 boxplot illustrate the minimum and maximum values. Asterisks indicate significant differences
775 compared to 0% MVC (Rest). Hashtags indicate significant differences between 30-50% MVC
776 of wrist extension. Legend: * $p<0.05$, ** $p<0.01$; # and solid line $p<0.05$.

777

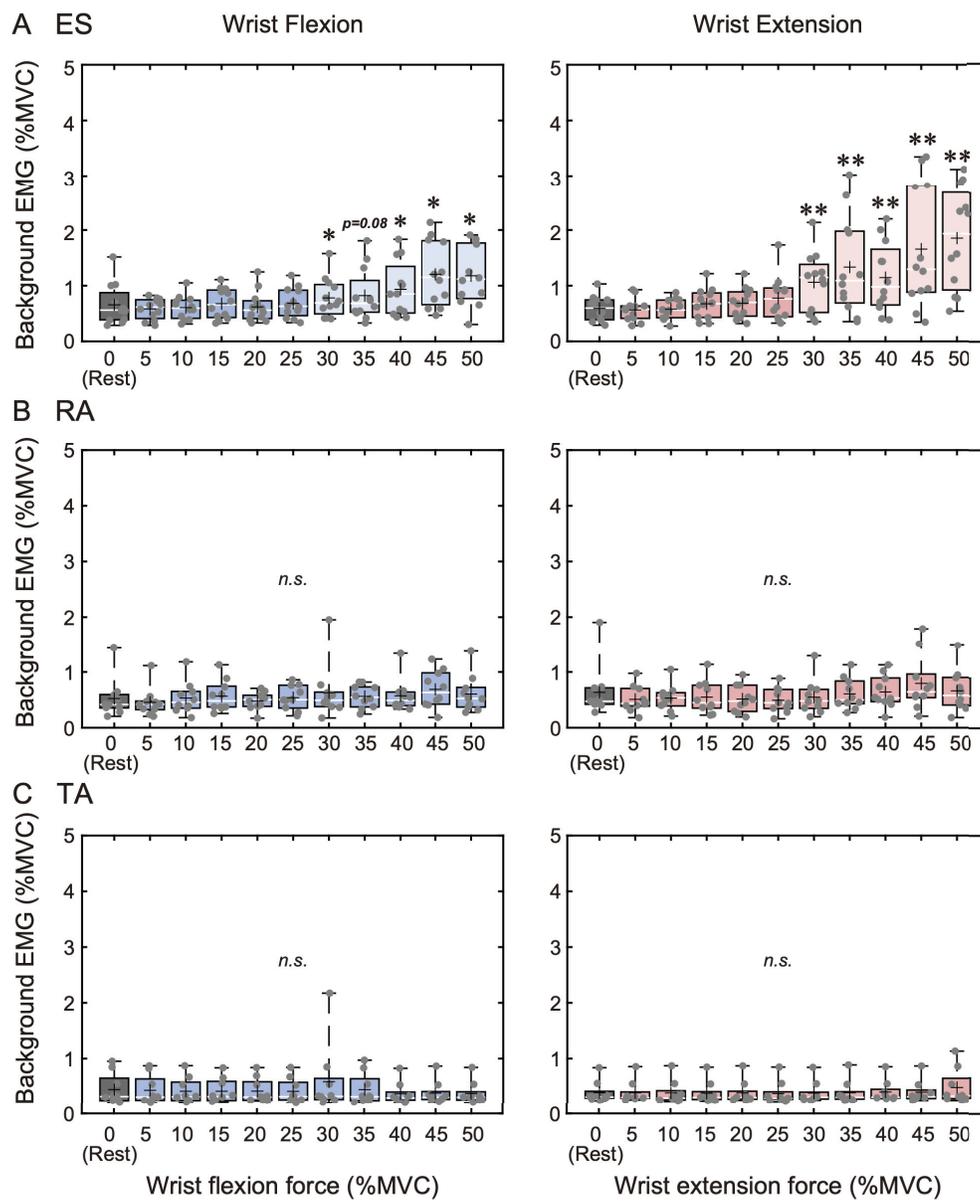
A Experimental setup



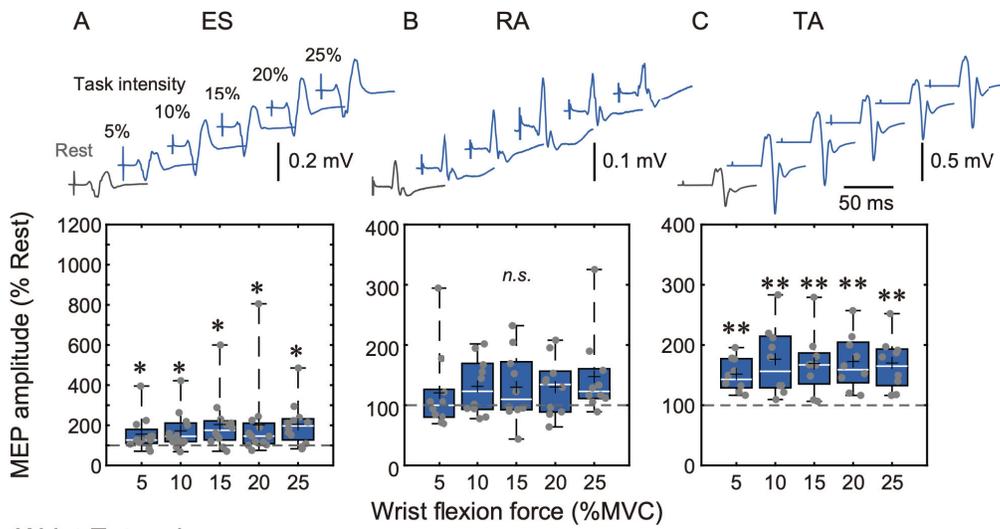
B Experimental protocol



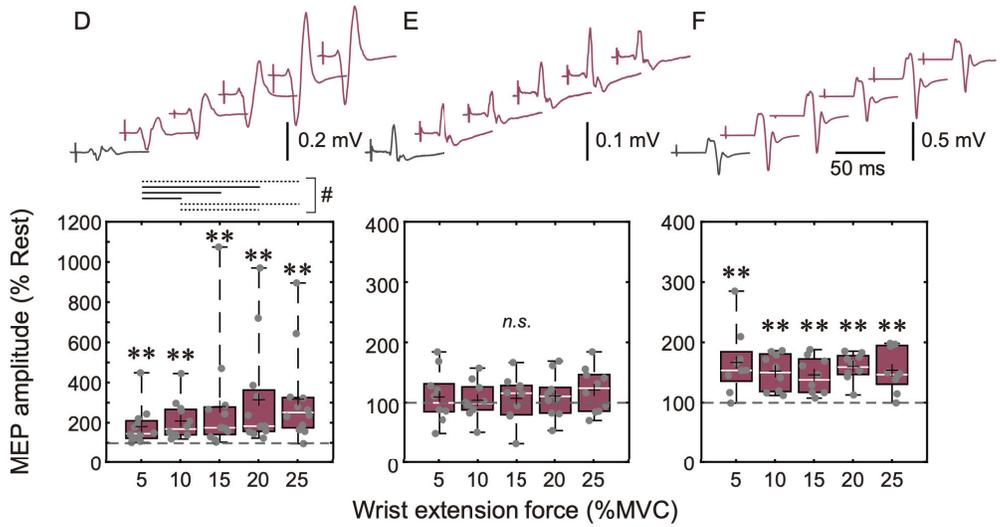
- 0 (Rest), 5, 10, ..., 45, or 50 %MVC target force levels were performed in B1, B2, B3, ..., B10, or B11 blocks.
- The order of the 11 target force levels was randomized across participants.



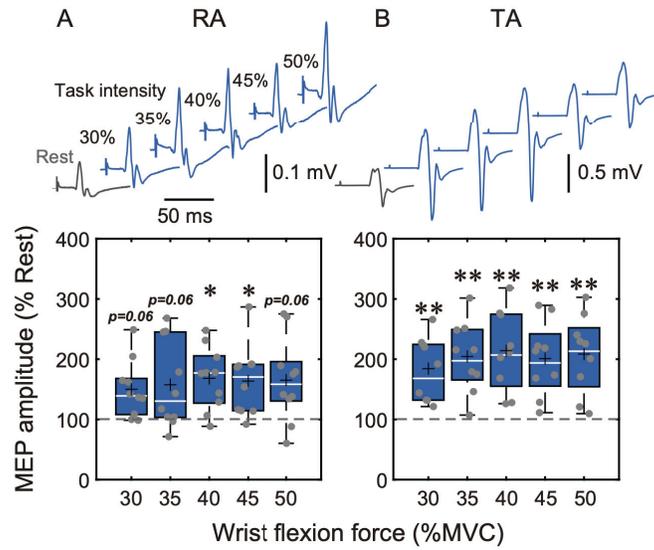
Wrist Flexion



Wrist Extension



Wrist Flexion



Wrist Extension

