

Crossed Corticospinal Facilitation between Arm and Trunk Muscles in Humans

Chiou, Shin-Yi; Strutton, Paul H; Perez, Monica A

DOI:

[10.1152/jn.00178.2018](https://doi.org/10.1152/jn.00178.2018)

License:

None: All rights reserved

Document Version

Peer reviewed version

Citation for published version (Harvard):

Chiou, S-Y, Strutton, PH & Perez, MA 2018, 'Crossed Corticospinal Facilitation between Arm and Trunk Muscles in Humans', *Journal of Neurophysiology*. <https://doi.org/10.1152/jn.00178.2018>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

Final version of record available at: <https://doi.org/10.1152/jn.00178.2018>. Published as above.

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

1 Crossed Corticospinal Facilitation between Arm and Trunk Muscles in Humans

2
3
4
5 Shin-Yi Chiou^{1,2}, Paul H. Strutton¹, Monica A. Perez^{2,3}

6
7 ¹The Nick Davey Laboratory, Division of Surgery, Department of Surgery and Cancer,
8 Faculty of Medicine, Imperial College London, UK. ²University of Pittsburgh, Department of
9 Physical Medicine and Rehabilitation, and Systems Neuroscience Institute, Pittsburgh, PA
10 15261. ³University of Miami, Department of Neurological Surgery, The Miami Project to
11 Cure Paralysis, Miami, FL 33136.
12
13
14
15
16

17 Section and Senior Editor:

18 Abbreviated title: Arm and trunk crossed facilitation

19 Number of figures: 5

20 Number of tables: 0

21 Number of pages: 29
22
23
24
25

26 Key words: Corticospinal pathway, intracortical inhibition, subcortical pathways, erector
27 spinae, motor evoked potentials, back muscles.
28
29
30
31
32
33
34

35 Correspondence to:

36 Monica A. Perez, Ph.D.

37 Department of Neurological Surgery

38 The Miami Project to Cure Paralysis

39 University of Miami

40 Bruce W. Carter Department of Veterans Affairs Medical Center

41 Phone: (305) 243-7119

42 E-mail: perezmo@miami.edu

43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62

Abstract

A voluntary contraction of muscles with one arm increases corticospinal excitability of projections to the contralateral resting arm, a phenomenon known as crossed facilitation. Although many motor tasks engage simultaneous activation of the arm and trunk, interactions between corticospinal projections targeting these segments remain largely unknown. Using transcranial magnetic stimulation over the trunk representation of the primary motor cortex we examined motor evoked potentials (MEPs) in the resting erector spinae (ES) muscle when the contralateral arm remained at rest or performed 20% of isometric maximal voluntary contraction (MVC) into index finger abduction, thumb abduction, elbow flexion and elbow extension. We found that MEP size in the ES increased during all voluntary contractions, with greater facilitation occurring during elbow flexion and index finger abduction. To further examine the origin of changes in MEP size we measured short-interval intracortical inhibition (SICI) and cervicomedullary MEPs (CMEPs) in the ES muscle during elbow flexion and index finger abduction and when the arm remained at rest. Notably, SICI decreased and CMEPs remained unchanged in the ES during both voluntary contractions compared with rest, suggesting a cortical origin for the effects. Our findings reveal crossed facilitatory interactions between trunk extensor and proximal and distal arm muscles, particularly for elbow flexor and index finger muscles, likely involving cortical mechanisms. These interactions might reflect the different role of these muscles during functionally relevant arm and trunk movements.

New and Noteworthy Section

63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87

Many of the tasks of daily life involve simultaneous activation of the arm and trunk. We found that responses in the erector spinae muscles evoked by motor cortical stimulation increased in size during elbow flexion and extension and during index finger abduction and thumb abduction. Crossed facilitation with the trunk was more pronounced during elbow flexion and index finger abduction. These results might reflect the different role of these muscles during arm and trunk movements.

88

Introduction

89 Interactions between arm and trunk muscles are evident in a number of activities of
90 daily living. For example, trunk muscles are activated prior to or concurrent with voluntary
91 arm movements (Hodges et al. 1992; Aruin and Latash 1995; Hodges and Richardson
92 1997a,b) and when individuals reach for objects beyond arm's length (Kaminski et al. 1995;
93 Levin 1996). Trunk muscles are involved in keeping the center of mass over the support
94 surface while arm muscles are more involved in countering reaction forces generated by limb
95 movement onset (van der Fits et al. 1998). Indeed, deficits in trunk control (Reft and Hasan
96 2002; Cacho et al. 2011) and afferent input from the trunk movement (Adamovich et al.
97 2001) can alter the trajectory of arm movements. Despite this evidence, the effect of
98 voluntary contraction of distal and proximal arm muscles on corticospinal projections
99 contributing to control trunk muscles, and its mechanisms of action, remains largely
100 unexplored.

101 Several lines of evidence suggest that physiological pathways controlling arm and
102 trunk muscles interact. Electrophysiological studies using transcranial magnetic stimulation
103 (TMS) over the primary motor cortex showed that the size of motor evoked potentials
104 (MEPs, reflecting changes in corticospinal excitability) in the erector spinae (ES) muscle
105 increases during contralateral shoulder abduction in standing and lying (Davey et al. 2002).
106 MEPs in the ES muscle also increase during a rapid shoulder flexion task that requires
107 postural control (Chiou et al. 2016). Note that the nature of these interactions can be
108 influenced by the task. For example, changes in dynamic elbow flexion but not elbow
109 extension changes MEP size in trunk muscles (Christmas et al. 2016). When muscles close to
110 the trunk play a postural role, corticospinal responses in a hand muscle increases when the
111 hand is involved in precise force control (Schieppatti et al. 1996). Furthermore, studies
112 showed that electromyographic (EMG) activity in the ES muscle increases according to

113 activation of different arm muscles during functional motor tasks involving the arm and trunk
114 (Marcolin et al. 2015). Even the onset of muscle activity in the ES has been shown to depend
115 on the direction of the arm movement (Hodges and Richardson 1997b). Crossed facilitatory
116 effects also differ when proximal and distal arm muscles are active. Evidence showed that
117 voluntary activation of elbow flexor muscles increased MEP size in hand muscles and that
118 contractions of hand muscles increased MEP size in homologous muscles on the contralateral
119 side (Bunday and Perez 2012; Bunday et al. 2013). Indeed, voluntary activation of elbow
120 flexors and extensor muscles has a different effect on pathways controlling contralateral
121 homologous and heteronymous muscles (Perez et al. 2014). Thus, we hypothesized that
122 voluntary activation of proximal and distal arm muscles would result in different
123 corticospinal facilitation in a trunk muscle. Evidence has shown that crossed corticospinal
124 facilitation can occur at the level of the primary motor cortex, spinal motoneurons, or at both
125 sites (Perez and Cohen 2008; Bunday et al. 2012). Therefore, we tested short-interval
126 intracortical inhibition (SICI) and motor evoked potentials (MEPs) elicited by TMS at the
127 primary motor cortex and cervicomedullary junction (CMEPs) respectively, to examine
128 cortical and subcortical mechanisms contributing to changes in MEP size in the ES muscle in
129 intact humans.

130

131

132

133

134

135

136

137

138
139
140
141
142
143
144
145
146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163

Methods

Subjects. Sixteen healthy volunteers (8 female, 8 male; 1 left handed) with a mean (\pm SD) age of 29.7 ± 10.9 years participated in the study. All subjects gave informed consent to the experimental procedures, which were approved by the local ethics committee at the University of Pittsburgh. The study was performed in accordance with the Declaration of Helsinki. Subjects were preselected out of a total of 25 subjects who were screened to ensure that they showed visible MEPs elicited by TMS in the ES muscle across conditions tested. All subjects confirmed that they were not taking any prescription drugs on a regular basis.

EMG recordings. EMG was recorded bilaterally from the ES and unilaterally from the first dorsal interosseous (FDI), abductor pollicis brevis (APB), biceps (BB) and triceps (TB) brachii of the dominant arm (Fig. 1A) through surface electrodes (Ag-AgCl; 10 mm diameter) secured on the skin over the belly of each muscle. The signals were amplified ($\times 1000$), filtered (30–1000 Hz), and sampled at 2 kHz for off-line analysis (CED 1401 with Signal software, Cambridge Electronic Design, Cambridge, UK).

Experimental setup. Subjects were seated in an armchair with head supported by a headrest. At the beginning of the experiment, all subjects performed 2-3 unilateral isometric maximal voluntary contractions (MVCs) for 3-5 s into index finger and thumb abduction, and elbow flexion and extension, separated by 30 s of rest. During maximal contractions subjects received verbal encouragement to perform maximally. MVCs for the ES were collected in a prone position with subjects' pelvis and legs secured by the investigators. Testing was completed with the trunk resting on a chair (conditioned referred here as "rest") and when subjects performed index finger abduction, thumb abduction, elbow flexion, and elbow extension in a pseudo-randomized order. During index finger and thumb abduction, subjects were instructed to press with their index finger or thumb against a custom lever in the

164 abduction direction with the forearm pronated and the wrist restrained by straps. During
165 elbow flexion and extension testing, subjects were seated with both shoulders and elbows
166 flexed to 90° and the forearm supinated. Here, a custom-built arm device was used to
167 maintain the position of the arm. Since a voluntary contraction of arm muscles can generate
168 EMG activity in the ES, in a preliminary study (n=8) we tested the effects of 10, 20 and 30%
169 of MVC with all arm muscles tested on background EMG activity in the ES muscle. We
170 found that subjects were able to maintain 20% of MVC with each of the muscles tested
171 without eliciting voluntary activity in the ES muscle. Thus, testing was performed at rest and
172 when the contralateral arm remained at rest or when performing 20% of MVC into index
173 finger and thumb abduction and elbow flexion and extension. EMG activity in the ES and in
174 the arm muscle tested were continuously displayed on an oscilloscope and verbal feedback
175 was provided to subjects to ensure that physiological measurements were acquired at similar
176 levels of background EMG activity. A total of 3.4±2.0% trials in which mean rectified EMG
177 activity exceeded 2 SD of the mean average rectified EMG, measured 100 ms before the
178 stimulus artifact, were excluded from further analysis (Bunday et al. 2012, 2013).

179
180 *TMS.* TMS pulses were delivered via a Magstim 200² monophasic stimulator (Magstim
181 Company) through a bat-wing (loop diameter, 90 mm; handle pointing backward and 45°
182 away from the midline) or a double-cone coil (loop diameter, 110 mm; handle pointing
183 vertically upwards). In individuals in whom an MEP could not be elicited in the ES muscle
184 with a bat-wing coil the double-cone coil was used. We determined the optimal position for
185 eliciting a MEP in the ES muscle (hot spot) by moving the coil in small steps along the area
186 corresponding to the primary motor cortex. The hot spot was defined as the region where the
187 largest MEP in the ES could be evoked with the minimum intensity (Rothwell et al. 1999).
188 With this coil position the current flowed in a posterior-anterior direction and probably
189 produced D and early I wave activation (Sakai et al. 1997). The TMS coil was held to the

190 head of the subject with a custom coil holder, while the head was firmly secured to a headrest
191 by straps. TMS was used to elicit MEPs, resting motor threshold (RMT), and short-interval
192 intracortical inhibition (SICI).

193
194 *MEPs*. RMT [$78.8 \pm 18.2\%$ of the maximal stimulator output (MSO)] was defined as the
195 minimal stimulus intensity required to induce MEPs greater than $50 \mu\text{V}$ peak-to-peak
196 amplitude in at least 3/5 consecutive trials in the relaxed ES muscle (Rothwell et al. 1999).
197 Based on our previous results (Chiou et al. 2018), we used a stimulus intensity needed to
198 elicit an MEP with a peak-to-peak amplitude of $\sim 0.1 \text{ mV}$ ($89.7 \pm 12.7\%$ MSO) in the ES
199 muscle in order to elicit responses in most subjects. Single TMS pulses were delivered at 4 s
200 intervals in sets of 10 separated by rest periods as needed. Twenty MEPs were tested during
201 each voluntary contraction.

202
203 *SICI*. We observed that voluntary contraction into elbow flexion and index finger abduction
204 increased MEP size in the ES muscle to a larger extent than elbow extension and thumb
205 abduction. Therefore, we examined the contribution from the primary motor cortex to
206 changes in ES MEP size by testing SICI using a previously described method (Kujirai et al.
207 1993) at rest first and when subjects performed 20% of MVC into elbow flexion and index
208 finger abduction in a randomized order ($n=8$). A conditioning stimulus (CS) was set at an
209 intensity needed to elicit $\sim 50\%$ of SICI, which corresponded to $\sim 70\%$ of AMT ($55.2 \pm 13.1\%$
210 MSO). This low-intensity stimulus allowed us to assess SICI independently of the effects on
211 short-intracortical facilitation at low contraction levels (Ortu et al. 2008). The same stimulus
212 intensity was used for the CS across conditions. The test stimulus (TS) was set at an intensity
213 needed to elicit an MEP with a peak-to-peak amplitude of $\sim 0.1 \text{ mV}$ ($86.4 \pm 15.2\%$ MSO). The
214 CS was delivered 2.5 ms before the TS. Previous studies showed that the size of the test MEP
215 can influence the magnitude of SICI (Roshan et al. 2003). Since our results from the single-

216 pulse TMS showed that ES MEPs became larger during the elbow flexion and index finger
217 abduction compared with rest, we adjusted the size of the test MEP by decreasing the TMS
218 stimulus intensity to match the size of the test MEP at rest. SICI was also tested by adjusting
219 the size of the test MEP to match that of the resting test MEP. SICI was calculated by
220 expressing the size of the conditioned MEP as a percentage of the size of the test MEP.
221 Twenty test MEPs and 20 conditioned MEPs were tested in each condition.

222

223 *CMEPs*. Since voluntary contraction into elbow flexion and index finger abduction increased
224 MEP size in the ES muscle to a larger extent than elbow extension and thumb abduction we
225 examined subcortical contributions to changes in ES MEP size during elbow flexion and
226 index finger abduction by stimulating the corticospinal tract at the cervicomedullary junction
227 using a circular magnetic coil (diameter, 90 mm;) located over one side of the neck, lateral or
228 near the inion with current flowing downward in the coil (Bunday et al. 2014; Taylor and
229 Gandevia 2004; Chiou et al. 2018). The position of the coil was marked on the subjects using
230 a removable marker pen once the optimal coil position for evoking the largest CMEP was
231 identified. The coil was held firmly to the back of the neck of the subject by one of the
232 experimenters and, since our voluntary contractions were isometric, there was very little head
233 displacement observed during the contractions. The latency of CMEPs was also monitored
234 frame-by-frame to ensure that the stimulation was consistent and accurate across trials.
235 Cervical root activation was investigated by increasing the intensity until an abrupt decrement
236 in latency occurred, then decreasing the intensity and verifying that the response was
237 potentiated by a small background contraction (Taylor, 2006). The latency of CMEPs was
238 significantly shorter than MEPs elicited by TMS (CMEP=10.2±1.2 ms, MEP=16.7±1.9 ms;
239 $p<0.001$) indicating that the stimulation activated corticospinal axons directly. CMEPs were
240 tested at rest and during 20% of MVC into elbow flexion or index finger abduction with the

241 contralateral arm (n=8) using an intensity needed to elicit a CMEP with a peak-to-peak
242 amplitude of ~0.1 mV (intensity: $92.2 \pm 6.7\%$ MSO). Ten CMEPs were tested in each
243 condition.

244
245 *Data analysis.* Data were analyzed using SigmaPlot software (version 12.5, Systat Software,
246 Inc., San Jose California USA, 2011). Normal distribution and homogeneity of variances
247 were tested by the Shapiro-Wilk's test and by the Equal Variance test, respectively. If the data
248 failed the normality test ($p < 0.05$), non-parametric tests were used. Repeated-measures
249 analysis of variance (ANOVA) was performed to determine the effect of CONDITION (rest,
250 elbow flexion, elbow extension, index finger abduction, and thumb abduction) on MEP size
251 and mean rectified EMG in the ES muscle, and the effect of MUSCLE (BB, TB, FDI, and
252 APB) on the level of muscle activity. Repeated-measures ANOVA was also used to examine
253 the effect of SUBCONDITION (rest, elbow flexion, and index finger abduction) on SICI
254 adjusted and unadjusted and CMEPs in the ES muscle. Paired-t tests were employed to
255 compare the latencies of MEPs elicited by TMS over the primary motor cortex and the
256 cervicomedullary junction. Holm-Sidak *post hoc* test was used to test for significant
257 comparisons. Significance was set at $p < 0.05$. Group data are presented as the means \pm SD in
258 the text.

259

260

261

Results

262 **EMG**

263 Repeated measures ANOVA showed no effect of CONDITION ($F_{4,60} = 0.9$, $p = 0.47$,
264 $n = 16$; Fig. 2A) on mean rectified EMG activity in the contralateral ES muscle. This result
265 indicates that mean rectified ES EMG activity remains constant when the right arm was at

266 rest or performed 20% of MVC into index finger abduction, thumb abduction, elbow flexion
267 and elbow extension. We also found no effect of MUSCLE ($F_{3,45}=2.1$, $p=0.1$, $n=16$; Fig. 2B)
268 on the level of muscle contraction exerted by each muscle tested across conditions. Further,
269 repeated measures ANOVA showed no effect of CONDITION ($F_{4,60}=0.65$, $p=0.63$, $n=16$) on
270 mean rectified EMG activity in the ipsilateral ES muscle.

271

272

273 **MEPs**

274 Figure 3A illustrates traces of averaged MEPs elicited by TMS over the primary
275 motor cortex in the ES muscle from a representative subject. Note that the size of MEP in the
276 ES muscle increased during all voluntary contractions compared with rest but to a larger
277 extent during elbow flexion and index finger abduction.

278 Repeated-measures ANOVA revealed an effect of CONDITION ($F_{4,60}=11.29$;
279 $p<0.001$) on ES MEP size ($n=16$; Fig. 3B). *Post hoc* tests showed that ES MEP amplitude
280 increased during elbow flexion ($164.31\pm 48.58\%$, $p<0.001$; 16/16), elbow extension
281 ($128.07\pm 27.03\%$, $p=0.04$; 13/16), index finger abduction ($160.73\pm 51.39\%$, $p<0.001$; 15/16)
282 and thumb abduction ($130.36\pm 40.10\%$, $p=0.03$; 14/16) compared with rest. Note that changes
283 in MEP size in the ES muscle were also larger during elbow flexion compared with elbow
284 extension ($p=0.01$) and thumb abduction ($p=0.02$). In addition, changes in MEP size in the
285 ES muscle were larger during index finger abduction compared with elbow extension
286 ($p=0.02$) and thumb abduction ($p=0.04$). The majority of subjects showed larger ES MEP size
287 during elbow flexion (16/16) and during index finger flexion (15/16; Fig. 3C). No difference
288 was found in the amplitudes of the ES MEP between elbow flexion and index finger
289 abduction ($p=0.9$) or between elbow extension and thumb abduction ($p=0.8$).

290

291 **SICI**

292 Figure 4A illustrates averaged data from SICI measurements in a representative
293 subject. Note that the magnitude of SICI decreased during elbow flexion and index finger
294 abduction compared with rest. Repeated-measures ANOVA revealed an effect of
295 SUBCONDITIONS ($F_{2,14}=11.8$, $p<0.001$, $n=8$) on ES MEP size (Fig. 4B). *Post hoc* tests
296 showed that SICI in the ES decreased during the elbow flexion ($p=0.008$) and during the
297 index finger abduction ($p=0.001$; Fig 4B, left panel). Since MEP size increased during
298 voluntary contraction, SICI was also tested with an adjusted test stimulus intensity. Similarly,
299 there was a decrease in SICI_{adj} in the ES during elbow flexion ($p=0.002$) and during index
300 finger abduction ($p=0.005$) compared with rest (Fig. 4B, right panel). Note that SICI in the
301 ES was reduced in all participants (8/8) during elbow flexion and during index finger
302 abduction compared with rest (Fig. 4C). Mean background EMG in the ES was similar across
303 the conditions tested ($F_{2,14}=1.2$, $p=0.3$, $n=8$).

304 **CMEPs** 305

306 Figure 5A illustrates examples of averaged CMEPs in the ES muscle in a
307 representative subject. Note that ES CMEP size remained similar during contralateral elbow
308 flexion and index finger abduction compared with rest. Repeated-measures ANOVA revealed
309 no effect of SUBCONDITIONS ($F_{2,14}=2.36$; $p=0.13$, $n=8$) on ES CMEP size, suggesting that
310 the amplitude of CMEPs in the ES muscles remain the same at rest, during elbow flexion and
311 index finger abduction. Mean background EMG in the ES was similar across the conditions
312 tested ($F_{2,14}=2.07$; $p=0.16$, $n=8$).

313
314
315
316
317

318

Discussion

319

320

321

322

323

324

325

326

327

328

Our findings demonstrate that corticospinal excitability of projections to a trunk muscle increases during voluntary activation of proximal and distal arm muscles in intact humans. Specifically, we found that MEP size in the ES muscle increased during elbow flexion and extension and during index finger abduction and thumb abduction. Note that the ES MEP facilitation was greater during elbow flexion and index finger abduction compared with the other voluntary contractions. SICI decreased and CMEPs remain unchanged in the ES during elbow flexion and index finger abduction compared with rest, suggesting that crossed facilitatory interactions are mediated at the level of the motor cortex. We argue that these findings might reflect the role of proximal and distal arm muscles during functionally relevant arm and trunk movements.

329

330

Crossed facilitation of a trunk muscle during arm voluntary contraction

331

332

333

334

335

336

337

338

339

340

341

342

343

Our results agree with a previous study showing that MEP size of the voluntarily active ES muscle increases during strong levels of contralateral shoulder abduction when tested in standing and lying postures (Davey et al. 2002). We extended these results and for the first time examined crossed corticospinal facilitation between the trunk and different proximal and distal arm muscles and the mechanisms contributing to this effect. We found that MEPs in the ES muscle increased in size during elbow flexion and extension and during index finger abduction and thumb abduction, with greater facilitation observed during elbow flexion and index finger abduction. This agrees with topographical studies of the primary motor cortex showing that motor cortical zones controlling various forelimb segments are largely interconnected (Capaday et al. 1998; Huntley and Jones 1991). This is also consistent with evidence showing that crossed corticospinal facilitatory effects are present not only between contralateral homologous muscles but also between bilateral non-homologous muscles (Hortobagyi et al. 2003; Perez and Cohen 2008; Zijdwind and Kernell 2011; Chiou

344 et al. 2013). An intriguing question is why ES MEPs were more facilitated by elbow flexion
345 than elbow extension. If the primary motor cortex controls different forelimb segments as a
346 whole rather than individually (Devanne et al. 2002) one might expect that all proximal
347 muscles will exert similar facilitatory effects on the size of MEPs in the ES muscle. Although
348 the representations of elbow flexor and extensor muscles in the primary motor cortex are
349 close in monkeys (Kwan et al. 1978) and humans (Penfield and Boldrey 1937) some
350 differences exist in the neural control of these muscles. For example, the intrinsic properties
351 of human elbow flexor and extensor motor units differ (Wilson et al. 2015) and phase-
352 dependent modulation of MEPs is present in elbow flexors but not in elbow extensors during
353 arm cycling (Spence et al., 2016), supporting the view that both muscles are subject to
354 different motor control principles. In addition, evidence showed that ipsilateral MEPs tested
355 by TMS over the primary motor cortex are frequently elicited in elbow flexors while they are
356 not present in elbow extensors (Ziemann et al. 1999). Thus, it is possible that elbow flexors
357 might be better suited to contribute to the stronger interaction with the back extensors
358 observed in this study. This is also consistent with evidence showing that dynamic elbow
359 flexion but not elbow extension changes MEP size of the ES muscle (Christmas et al. 2016).
360 It is important to note that crossed facilitatory effects are more pronounced during strong
361 levels of voluntary activity (Muellbacher et al. 2000; Perez and Cohen 2008). However, it is
362 less likely that this factor contributed to our results since we found that the level of EMG
363 activity exerted during elbow flexion and extension was similar across voluntary
364 contractions.

365 A next important question is why ES MEPs were more facilitated by index finger
366 abduction compared with thumb abduction. Electrophysiological and biomechanical studies
367 suggest that the control of index finger and thumb muscles differ. In monkeys, a single
368 corticomotoneuronal cell does not facilitate the FDI and APB muscles simultaneously (Buy et

369 al. 1986), which might contribute to relatively independent movements of these digits. In
370 humans, the size of MEPs in the FDI increased in accordance with the posture of the hand
371 during grasping but it remained unchanged in the APB (Perez and Rothwell 2015). Hand
372 trajectory during pointing is affected during reaching movements involving the trunk
373 (Adamovich et al. 2001). During a postural task involving the whole arm, MEPs in the FDI
374 were greater when the task involved precise force control with the hand (Schieppatti et al.
375 1996). Biomechanical studies also showed that during grasping the APB has a more
376 stabilizing role (Chao et al. 1976) while the FDI contributes to the fine grading of forces
377 (Maier and Hepp-Reymond, 1995). Therefore, it is possible that these physiological and
378 biomechanical features make the FDI more suitable to have stronger facilitatory interactions
379 with the ES muscle during arm movements.

380 381 *Neuronal mechanisms*

382 We found a decrease in intracortical inhibition in the ES muscle during contralateral
383 elbow flexion and index finger abduction. These results agree with previous findings
384 suggesting that intracortical circuits contribute to modulate crossed corticospinal facilitation
385 between arm muscles (Perez and Cohen 2008; Chiou et al. 2013). This agrees with lesion
386 experiments and single-unit recordings in monkeys suggesting that the primary motor cortex
387 is involved in the coordination of limb segments (Kalaska and Drew 1993). Since ~50% of
388 corticospinal neurons project to both proximal and distal arm muscles (McKiernan et al.
389 1998) it is possible that extensive intraspinal branching of corticospinal axons might also
390 contribute to interactions found in our study. Indeed, it could be also argued that changes in
391 spinal excitability might contribute to crossed facilitation in the ES muscle, since subcortical
392 mechanisms have been shown to be involved in some crossed corticospinal facilitatory
393 effects in intact humans (Muellbacher et al. 2000; Stedman et al. 1998). Since we found no
394 changes in the size of CMEPs, it is less likely that our results reflect changes in corticospinal

395 transmission or motoneuron excitability (Ugawa et al. 1994; Taylor and Gandevia 2004).
396 However, others have shown that crossed facilitatory effects also involve changes in spinal
397 reflexes (Hortobayi et al. 2003); then, this possibility cannot be completely excluded. The
398 latencies of CMEPs in the ES muscle were shorter than the latency of MEPs elicited by TMS
399 over the primary motor cortex, supporting the view that corticospinal axons were stimulated
400 directly. In addition, the location of magnetic stimulation was distant from the root outflow
401 for the ES at vertebral level T12, thus it is unlikely that any direct stimulation of the relevant
402 ventral roots innervating ES T12 occurred. Our results are also consistent with a previous
403 study showing a lack of contribution of subcortical pathways to crossed facilitation when
404 similar low levels of voluntary contraction were performed (Stedman et al. 1998).

405
406 *Functional significance*

407 It is possible that the observed crossed facilitatory effects are relevant to limb and
408 trunk interactions during unimanual and bimanual actions (Carson et al. 2008; Lee et al.
409 2010). Functional interactions between the trunk and arm muscles are well recognized with
410 ample evidence showing that when the arms are moved, trunk muscle activity increases
411 concurrently (Aruin and Latash 1995; Benvenuti et al. 1997; Bouisset and Zattara 1987;
412 Hodges and Richardson 1997b). Studies showed greater activation of the ES muscle when
413 different arm muscles are active during functional motor tasks such as pushups (Marcolin et
414 al. 2015). Even the onset of muscle activity in the ES has been shown to depend on the
415 direction of the arm movement (Hodges and Richardson 1997b). The greater facilitation from
416 elbow flexors to the ES can be used to support postural perturbations since arm flexion
417 movements are likely to cause anterior displacement of the center of mass that required
418 activation of the trunk extensors (i.e. ES) to minimize the postural displacement (Aruin and
419 Latash 1995; Hodges and Richardson, 1997b). The more pronounced facilitatory effects of
420 the FDI to the ES can also be related to anticipatory postural adjustments needed to stabilize

421 the whole arm prior to upcoming finger activation (Caronni and Cavallari 2009). Indeed, the
422 earlier onset of anticipatory postural adjustments for proximal arm muscles has been
423 associated with higher precision of pointing movements (Bruttini et al. 2016). Altogether, our
424 findings support the view of strong interactions between the neural control of trunk and
425 proximal and distal hand muscles in intact humans.

426 These results may have clinical relevance since previous evidence suggests that
427 crossed corticospinal facilitatory effects might be beneficial in improving arm function in
428 patients with specific neurological disorders (Hamzei et al. 2012; Kowalczewski et al. 2011).
429 Since many patients with stroke (Verheyden et al. 2006) or spinal cord injury (Field-Fote and
430 Ray 2010) have reduced trunk control, the use of the arms to increase corticospinal
431 excitability of projections to trunk muscles may increase neural interactions, which could
432 contribute to improve functional outcomes. As such, crossed facilitation between arm and
433 trunk muscles might represent an opportunity for trunk rehabilitation and its effect on
434 functionally relevant motor tasks remain to be tested.

435 **References**

- 436 **Adamovich SV, Archambault PS, Ghafouri M, Levin MF, Poizner H, Feldman AG.**
437 Hand trajectory invariance in reaching movements involving the trunk. *Exp Brain Res* 138:
438 288–303, 2001.
- 439
440 **Aruin AS, and Latash ML.** Directional specificity of postural muscles in feed-forward
441 postural reactions during fast voluntary arm movements. *Exp Brain Res* 103: 323–332, 1995.
442
- 443 **Benvenuti F, Stanhope SJ, Thomas SL, Panzer VP, and Hallett M.** Flexibility of
444 anticipatory postural adjustments revealed by self-paced and reaction-time arm movements.
445 *Brain Res* 761: 59–70, 1997.
446
- 447 **Bouisset S, and Zattara M.** Biomechanical study of the programming of anticipatory
448 postural adjustments associated with voluntary movement. *Journal of biomechanics* 20: 735–
449 742, 1987.
- 450
451 **Bruttini C, Esposti R, Bolzoni F, and Cavallari P.** Higher Precision in Pointing
452 Movements of the Preferred vs. Non-Preferred Hand Is Associated with an Earlier
453 Occurrence of Anticipatory Postural Adjustments. *Front Hum Neurosci* 10: 365, 2016.
454
- 455 **Bunday KL, Oudega M, and Perez MA.** Aberrant crossed corticospinal facilitation in
456 muscles distant from a spinal cord injury. *PLoS One* 8: e76747, 2013.
457
- 458 **Bunday KL, Tazoe T, Rothwell JC, and Perez MA.** Subcortical control of precision grip
459 after human spinal cord injury. *J Neurosci* 34: 7341–7350, 2014.
460
- 461 **Buys EJ, Lemon RN, Mantel GW, Muir RB.** Selective facilitation of different hand
462 muscles by single corticospinal neurones in the conscious monkey. *J Physiol* 381: 529–549,
463 1986.
464
- 465 **Capaday C, Devanne H, Bertrand L, Lavoie BA.** Intracortical connections between motor
466 cortical zones controlling antagonistic muscles in the cat: a combined anatomical and
467 physiological study. *Exp Brain Res* 120: 223–232, 1998.
468
- 469 **Caronni A, and Cavallari P.** Anticipatory postural adjustments stabilise the whole upper-
470 limb prior to a gentle index finger tap. *Exp Brain Res* 194: 59–66, 2009.
471
- 472 **Carson RG, Kennedy NC, Linden MA, and Britton L.** Muscle-specific variations in use-
473 dependent crossed-facilitation of corticospinal pathways mediated by transcranial direct
474 current (DC) stimulation. *Neuroscience letters* 441: 153–157, 2008.
475
- 476 **Chao EY, Opgrande JD, and Axmear FE.** Three-dimensional force analysis of finger joints
477 in selected isometric hand functions. *J Biomech* 9: 387–396, 1976.
478
- 479 **Chiou SY, Gottardi SE, Hodges PW, and Strutton PH.** Corticospinal Excitability of Trunk
480 Muscles during Different Postural Tasks. *PloS one* 11: e0147650, 2016.
481
- 482 **Chiou SY, Hurry M, Reed T, Quek JX, and Strutton PH.** Cortical contributions to
483 anticipatory postural adjustments in the trunk. *J Physiol (in press)* 2018.

484
485 **Chiou SY, Wang RY, Liao KK, Wu YT, Lu CF, and Yang YR.** Co-activation of primary
486 motor cortex ipsilateral to muscles contracting in a unilateral motor task. *Clinical*
487 *neurophysiology : official journal of the International Federation of Clinical*
488 *Neurophysiology* 124: 1353–1363, 2013.
489
490 **Christmas D, Dave S, Chiou SY, and Strutton PH.** Effects of dynamic arm cycling on
491 crossed-corticospinal facilitation to trunk muscles. *The 46th annual meeting of the society for*
492 *neuroscience. San Diego, CA, USA.* 2016.
493
494 **Davey NJ, Lisle RM, Loxton-Edwards B, Nowicky AV, and McGregor AH.** Activation of
495 back muscles during voluntary abduction of the contralateral arm in humans. *Spine (Phila Pa*
496 *1976)* 27: 1355–1360, 2002.
497
498 **Devanne H, Cohen LG, Kouchtir-Devanne N, and Capaday C.** Integrated motor cortical
499 control of task-related muscles during pointing in humans. *J Neurophysiol* 87: 3006–3017,
500 2002.
501
502 **Dominici F, Popa T, Ginanneschi F, Mazzocchio R, and Rossi A.** Cortico-motoneuronal
503 output to intrinsic hand muscles is differentially influenced by static changes in shoulder
504 positions. *Exp Brain Res* 164: 500–504, 2005.
505
506 **Field-Fote EC, and Ray SS.** Seated reach distance and trunk excursion accurately reflect
507 dynamic postural control in individuals with motor-incomplete spinal cord injury. *Spinal*
508 *Cord* 48: 745–749, 2010.
509
510 **Hamzei F, Lappchen CH, Glauche V, Mader I, Rijntjes M, and Weiller C.** Functional
511 plasticity induced by mirror training: the mirror as the element connecting both hands to one
512 hemisphere. *Neurorehabil Neural Repair* 26: 484–496, 2012.
513
514 **Hess CW, Mills KR, and Murray NM.** Responses in small hand muscles from magnetic
515 stimulation of the human brain. *The Journal of physiology* 388: 397–419, 1987.
516
517 **Hodges PW, and Richardson CA.** Contraction of the abdominal muscles associated with
518 movement of the lower limb. *Physical therapy* 77: 132-142; discussion 142–134, 1997a.
519
520 **Hodges PW, and Richardson CA.** Feedforward contraction of transversus abdominis is not
521 influenced by the direction of arm movement. *Exp Brain Res* 114: 362–370, 1997b.
522
523 **Hortobagyi T, Taylor JL, Petersen NT, Russell G, and Gandevia SC.** Changes in
524 segmental and motor cortical output with contralateral muscle contractions and altered
525 sensory inputs in humans. *J Neurophysiol* 90: 2451–2459, 2003.
526
527 **Huntley GW, Jones EG.** Relationship of intrinsic connections to forelimb movement
528 representations in monkey motor cortex: a correlative anatomic and physiological study. *J*
529 *Neurophysiol* 66: 390–413, 1991.
530
531 **Kalaska JF, Drew T.** Motor cortex and visuomotor behavior. *Exerc Sport Sci Rev* 21:397-
532 436, 1993.
533

534 **Kaminski TR, Bock C, and Gentile AM.** The coordination between trunk and arm motion
535 during pointing movements. *Exp Brain Res* 106: 457–466, 1995.
536
537 **Kowalczewski J, Chong SL, Galea M, and Prochazka A.** In-home tele-rehabilitation
538 improves tetraplegic hand function. *Neurorehabil Neural Repair* 25: 412–422, 2011.
539 **Kujirai T, Caramia MD, Rothwell JC, Day BL, Thompson PD, Ferbert A, Wroe S,**
540 **Asselman P, and Marsden CD.** Corticocortical inhibition in human motor cortex. *J Physiol*
541 471: 501–519, 1993.
542
543 **Kwan HC, MacKay WA, Murphy JT, Wong YC.** Spatial organization of precentral cortex
544 in awake primates. II. Motor outputs. *J Neurophysiol* 41: 1120–1131, 1978.
545
546 **Lee M, Hinder MR, Gandevia SC, and Carroll TJ.** The ipsilateral motor cortex
547 contributes to cross-limb transfer of performance gains after ballistic motor practice. *J*
548 *Physiol* 588: 201–212, 2010.
549
550 **Levin MF.** Interjoint coordination during pointing movements is disrupted in spastic
551 hemiparesis. *Brain* 119 (Pt 1): 281–293, 1996.
552
553 **Maier MA, and Hepp-Reymond MC.** EMG activation patterns during force production in
554 precision grip. I. Contribution of 15 finger muscles to isometric force. *Exp Brain Res* 103:
555 108-122, 1995.
556
557 **McKiernan BJ, Marcario JK, Karrer JH, Cheney PD.** Corticomotoneuronal postspike
558 effects in shoulder, elbow, wrist, digit, and intrinsic hand muscles during a reach and
559 prehension task. *J Neuropysiol* 367:
560 1961–1980, 1998.
561
562 **Muellbacher W, Facchini S, Boroojerdi B, and Hallett M.** Changes in motor cortex
563 excitability during ipsilateral hand muscle activation in humans. *Clin Neurophysiol* 111: 344-
564 349, 2000.
565
566 **Penfield WG, Boldrey E.** Somatic motor and sensory representation in the cerebral cortex of
567 man as studied by electrical stimulation. *Brain* 60: 389–443, 1937.
568
569 **Perez MA, and Cohen LG.** Mechanisms underlying functional changes in the primary motor
570 cortex ipsilateral to an active hand. *J Neurosci* 28: 5631-5640, 2008.
571
572 **Perez MA, and Rothwell JC.** Distinct influence of hand posture on cortical activity during
573 human grasping. *J Neurosci* 35: 4882–4889, 2015.
574
575 **Perez MA, Butler JE, Taylor JL.** Modulation of transcallosal inhibition by bilateral
576 activation of agonist and antagonist proximal arm muscles. *J Neurophysiol* 111: 405–414,
577 2014.
578
579 **Roshan L, Paradiso GO, and Chen R.** Two phases of short- interval intracortical inhibition.
580 *Exp Brain Res* 151: 330–337, 2003.
581

- 582 **Rothwell JC, Hallett M, Berardelli A, Eisen A, Rossini P, and Paulus W.** Magnetic
583 stimulation: motor evoked potentials. The International Federation of Clinical
584 Neurophysiology. *Electroencephalogr Clin Neurophysiol Suppl* 52: 97–103, 1999.
585
- 586 **Sakai K, Ugawa Y, Terao Y, Hanajima R, Furubayashi T, and Kanazawa I.** Preferential
587 activation of different I waves by transcranial magnetic stimulation with a figure-of-eight-
588 shaped coil. *Exp Brain Res* 113: 24–32, 1997.
589
- 590 **Schiepatti M, Trompetto C, Abbruzzese G.** Selective facilitation of responses to cortical
591 stimulation of proximal and distal arm muscles by precision tasks in man. *J Physiol (Lond)*
592 491: 551–562, 1996.
593
- 594 **Spence AJ, Alcock LR, Lockyer EJ, Button DC, Power KE.** Phase- and Workload-
595 Dependent Changes in Corticospinal Excitability to the Biceps and Triceps Brachii during
596 Arm Cycling. *Brain Sci* 15;6(4). pii: E60, 2016.
597
- 598 **Stedman A, Davey NJ, and Ellaway PH.** Facilitation of human first dorsal interosseous
599 muscle responses to transcranial magnetic stimulation during voluntary contraction of the
600 contralateral homonymous muscle. *Muscle Nerve* 21: 1033–1039, 1998.
601
- 602 **Taylor JL, and Gandevia SC.** Noninvasive stimulation of the human corticospinal tract.
603 *Journal of applied physiology (Bethesda, Md: 1985)* 96: 1496–1503, 2004.
604
- 605 **Taylor JL.** Stimulation at the cervicomedullary junction in human subjects. *Journal of*
606 *Electromyography and Kinesiology* 16: 215–223, 2006.
607
- 608 **Ugawa Y, Uesaka Y, Terao Y, Hanajima R, and Kanazawa I.** Magnetic stimulation of
609 corticospinal pathways at the foramen magnum level in humans. *Ann Neurol* 36: 618–624,
610 1994.
611
- 612 **Verheyden G, Vereeck L, Truijen S, Troch M, Herregodts I, Lafosse C, Nieuwboer A,**
613 **De Weerd W.** Trunk performance after stroke and the relationship with balance, gait and
614 functional ability. *Clin Rehabil* 20: 451–458, 2016.
615
- 616 **Wilson JM, Thompson CK, Miller LC, and Heckman CJ.** Intrinsic excitability of human
617 motoneurons in biceps brachii versus triceps brachii. *J Neurophysiol* 113:3692-3699, 2015.
618
- 619 **Zijdewind I, Kernell D.** Bilateral interactions during contractions of intrinsic hand muscles.
620 *J Neurophysiol* 85: 1907–1913, 2001.
621

622 **Figure legends**

623 **Figure 1.** (A) Schematic illustration of the coil position (when the cone coil was used) and
624 the electrodes over the erector spinae (ES) muscle at the 12th thoracic vertebral level. Raw
625 motor evoked potential (MEP) trace elicited in the ES muscle by transcranial magnetic
626 stimulation (TMS) over the primary motor cortex from a representative subject (20 stimuli,
627 averaged unrectified). The arrow indicates the TMS pulse and the dotted line indicates the
628 onset of the MEP. (B) Raw rectified electromyographic (EMG) activity from each of the
629 muscles tested during 20% of maximal voluntary contraction (MVC) into elbow flexion
630 (recording from the biceps brachii, BB), elbow extension (recording from the triceps brachii,
631 TB), index finger abduction (recording from the first dorsal interosseous, FDI), and thumb
632 abduction (recording from the abductor pollicis brevis, APB).

633
634 **Figure 2. Electromyography (EMG).** (A) Group data showing background EMG in ES
635 across voluntary contractions (n=16). Testing was completed with the trunk resting on a chair
636 (conditioned referred here as “rest”) and when subjects performed index finger abduction,
637 thumb abduction, elbow flexion, and elbow extension in a pseudo-randomized order. The
638 abscissa shows the condition tested (rest, elbow flexion, elbow extension, index finger
639 abduction, and thumb abduction) and the ordinate shows the mean background EMG activity
640 in the ES muscle (as a % of MVC). (B) Group data showing the background EMG in each
641 muscle tested during 20% of MVC (n=16). The abscissa shows the muscle tested [biceps
642 brachii (BB), triceps brachii (TB), first dorsal interosseous (FDI) and abductor pollicis brevis
643 (APB)] and ordinate the contraction level (as a % of MVC). Note that individual data is
644 shown for each condition. Error bars indicate the SD *p<0.05.

645
646 **Figure 3. Motor evoked potentials (MEPs).** (A) MEPs traces recorded from the ES muscle
647 of a representative subject. Traces show the average of 20 MEPs in the ES muscle at rest

648 (black traces) and during 20% of MVC (grey traces). (B) Group data (n=16) showing MEPs
649 in ES across conditions. The abscissa shows the condition tested (elbow flexion, elbow
650 extension, index finger abduction, and thumb abduction) and the ordinate shows the size of
651 the ES MEP during 20% of MVC (as a % of the ES MEP obtained at rest). The horizontal
652 dashed line represents the size of the ES MEP at rest. Note that the amplitudes of MEP in the
653 ES muscle increased during all voluntary contractions, with greater facilitation observed
654 during elbow flexion and index finger abduction. (C) Note that that majority of participants
655 show increases in ES MEPs during all voluntary contractions compared with rest. Error bars
656 indicate the SD. * $p < 0.05$, comparison between voluntary contractions. $\text{¥}p < 0.05$, comparison
657 between rest and all voluntary contractions.

658

659 **Figure 4. Short-interval intracortical inhibition (SICI).** (A) SICI recorded from the ES
660 muscle of a representative subject. Traces show the average of 20 test MEPs (black traces)
661 and conditioned MEPs (Cond. MEP, grey traces) indicated by arrows. (B) Group data
662 showing SICI in the ES (n=8). The abscissa shows the subconditions tested in the unadjusted
663 (rest, elbow flexion and index finger abduction) and adjusted (rest, elbow flexion adj. and
664 index finger abduction adj.) conditions. The ordinate shows the size of the conditioned MEP
665 expressed as a % of the test MEP. The horizontal dotted line shows SICI at rest. Note that
666 SICI decreased (increased conditioned MEP size) during elbow flexion (grey bars) and index
667 finger abduction (grey bars) when SICI was tested with an adjusted and unadjusted test MEP
668 size. (C) Note that all participants show reduction in SICI during elbow flexion (solid lines)
669 and index finger abduction (dotted lines) compared with rest. Error bars indicate the SD.
670 * $p < 0.05$, comparison between subconditions.

671

672 **Figure 5. Cervicomedullary MEPs (CMEPs).** (A) CMEPs recorded from the ES muscle of
673 a representative subject. Traces show the average of 10 CMEPs. (B) Group data (n=8). The

674 abscissa shows the conditions tested (elbow flexion and index finger abduction). The ordinate
675 shows the size of the CMEPs (as a % of the test CMEP). The horizontal dashed line
676 represents the size of the CMEP at rest. Note that individual data is shown for each condition.
677 Error bars indicate the SD. * $p < 0.05$, comparison between subconditions.

678

679

680

681

682

683

684

685

686

687

688

689

690

691

692

693

694

695

696

697

698

Figure 1

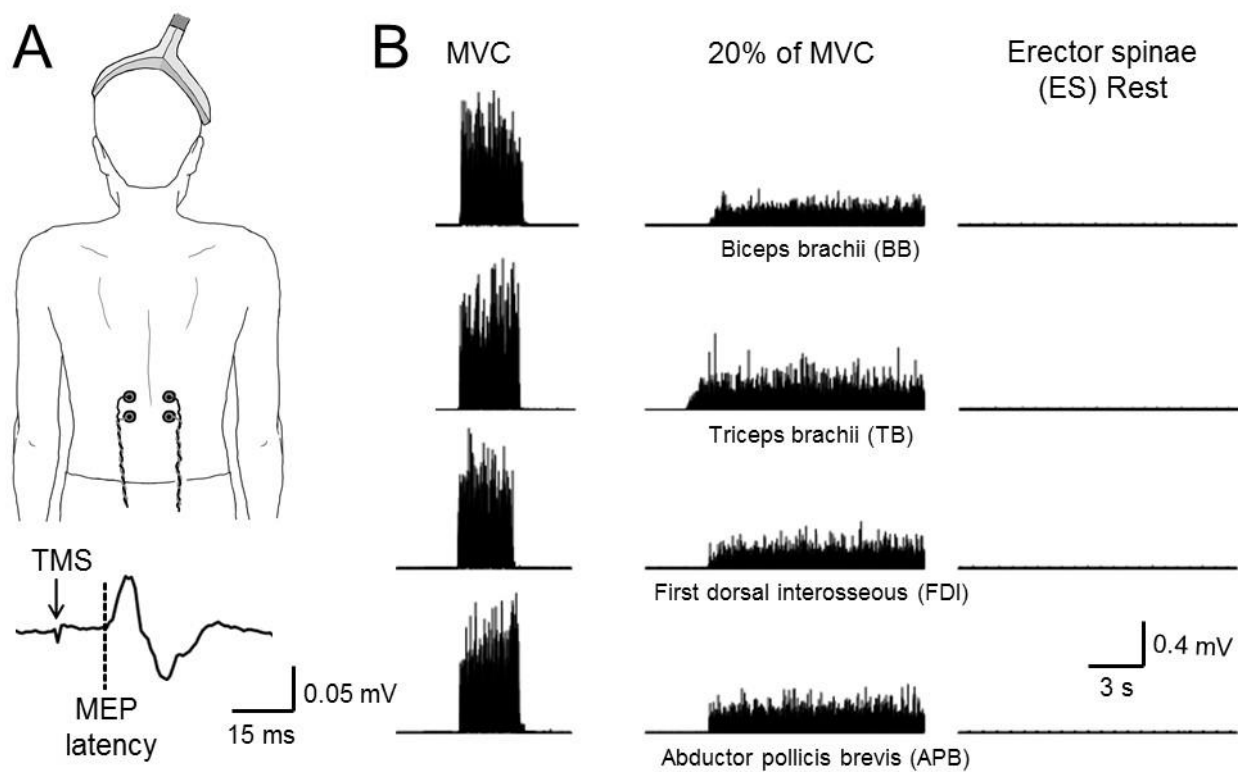


Figure 2

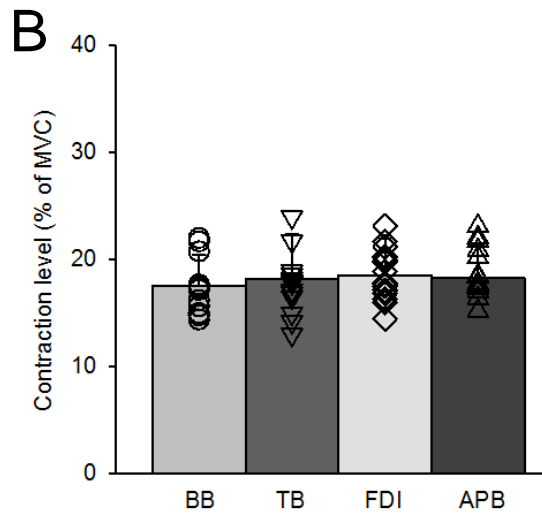
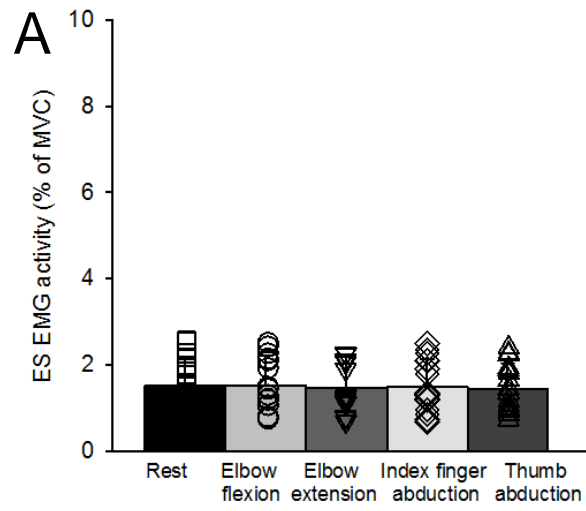


Figure 3

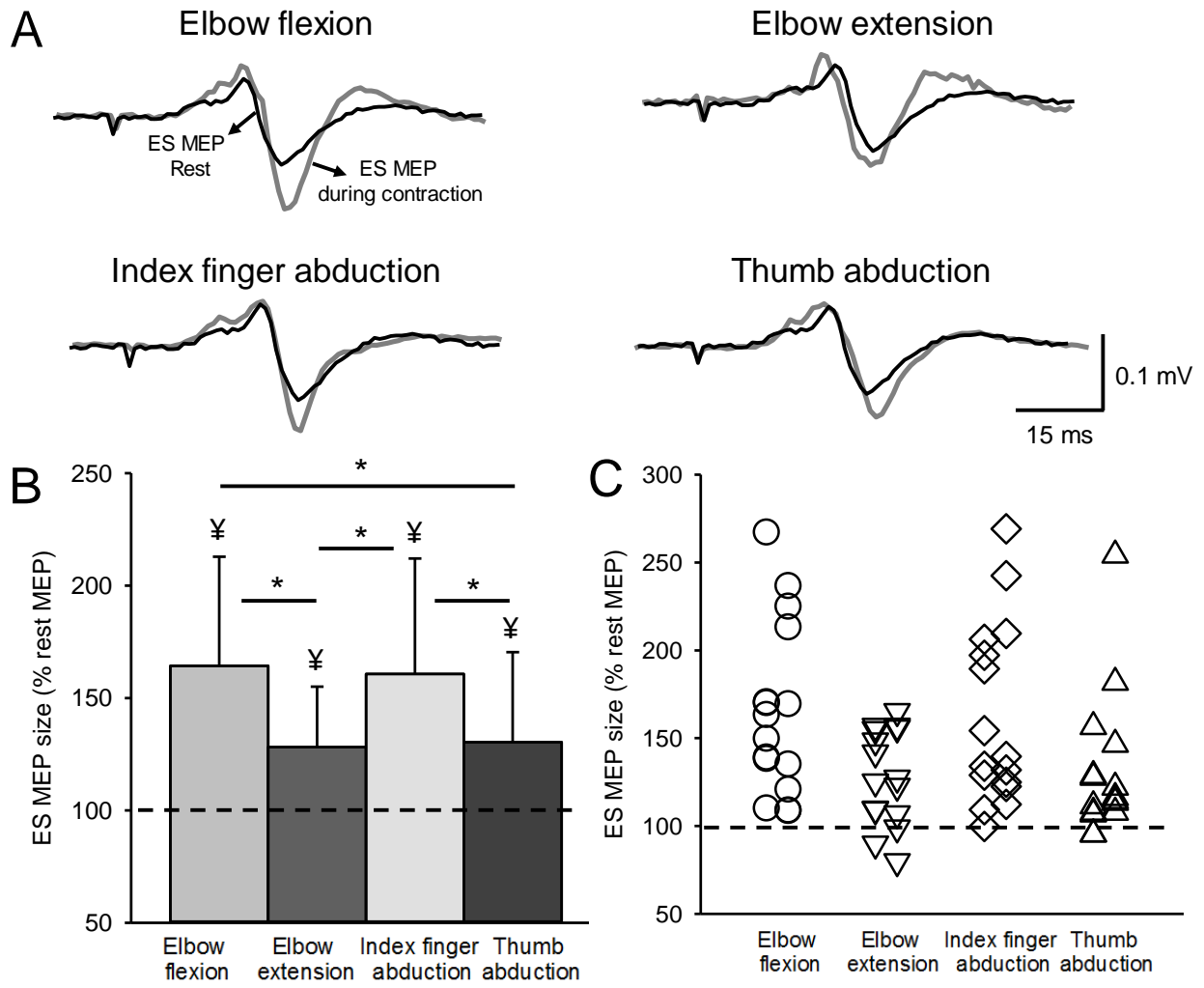


Figure 4

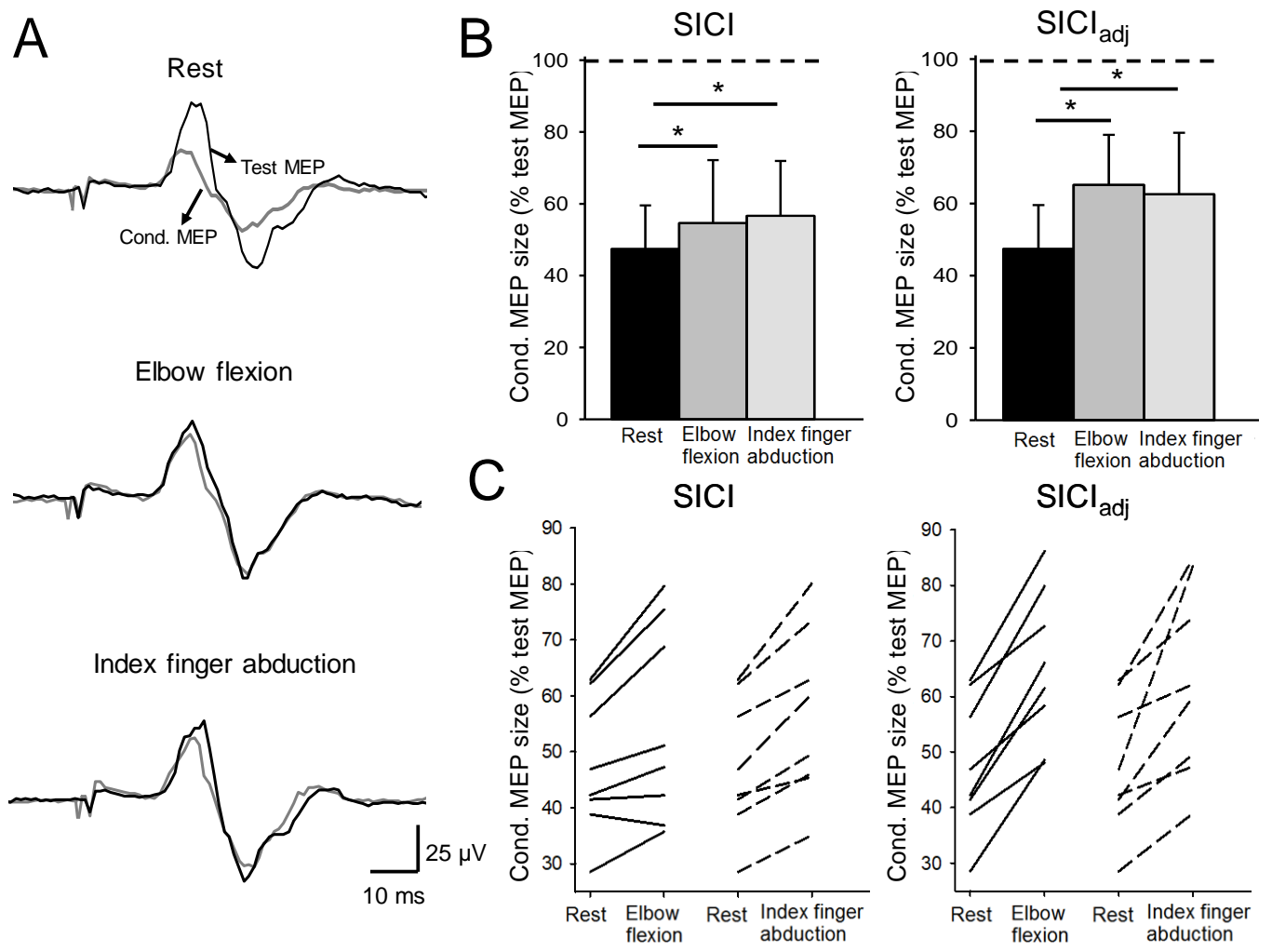


Figure 5

