

# Crossed Corticospinal Facilitation between Arm and Trunk Muscles in Humans

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1 Crossed Corticospinal Facilitation between Arm and Trunk Muscles in Humans

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## 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

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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.

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## 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.

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## Methods

*Subjects.* Sixteen healthy volunteers (8 female, 8 male; 1 left handed) with a mean ( $\pm$ SD) age of  $29.7\pm 10.9$  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).

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180 *TMS.* TMS pulses were delivered via a Magstim 200<sup>2</sup> 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).

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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.

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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.

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## 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.

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### 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<sub>adj</sub> 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 ( $F_{2,14}=2.07$ ;  $p=0.16$ ,  $n=8$ ).

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## Discussion

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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.

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### *Crossed facilitation of a trunk muscle during arm voluntary contraction*

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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.

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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 12<sup>th</sup> 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.

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Figure 1

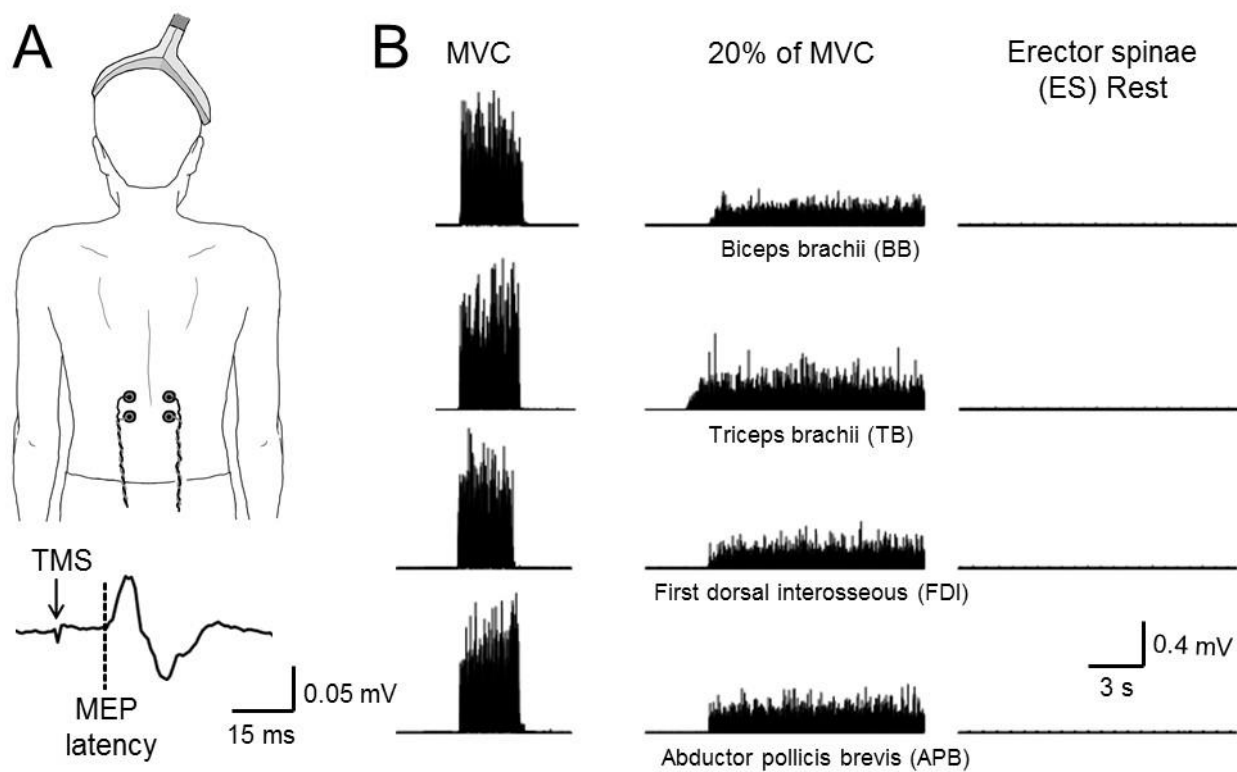


Figure 2

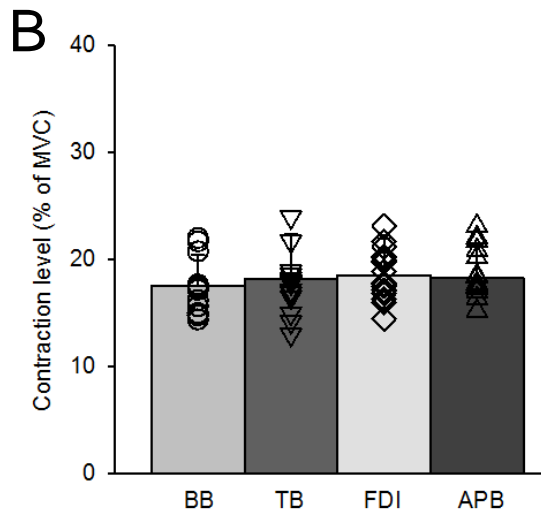
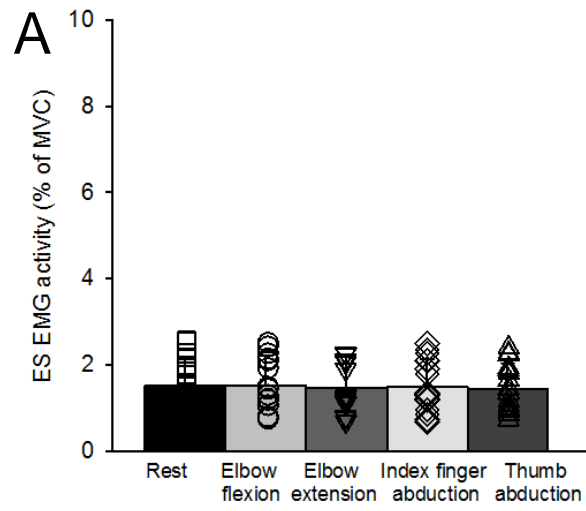


Figure 3

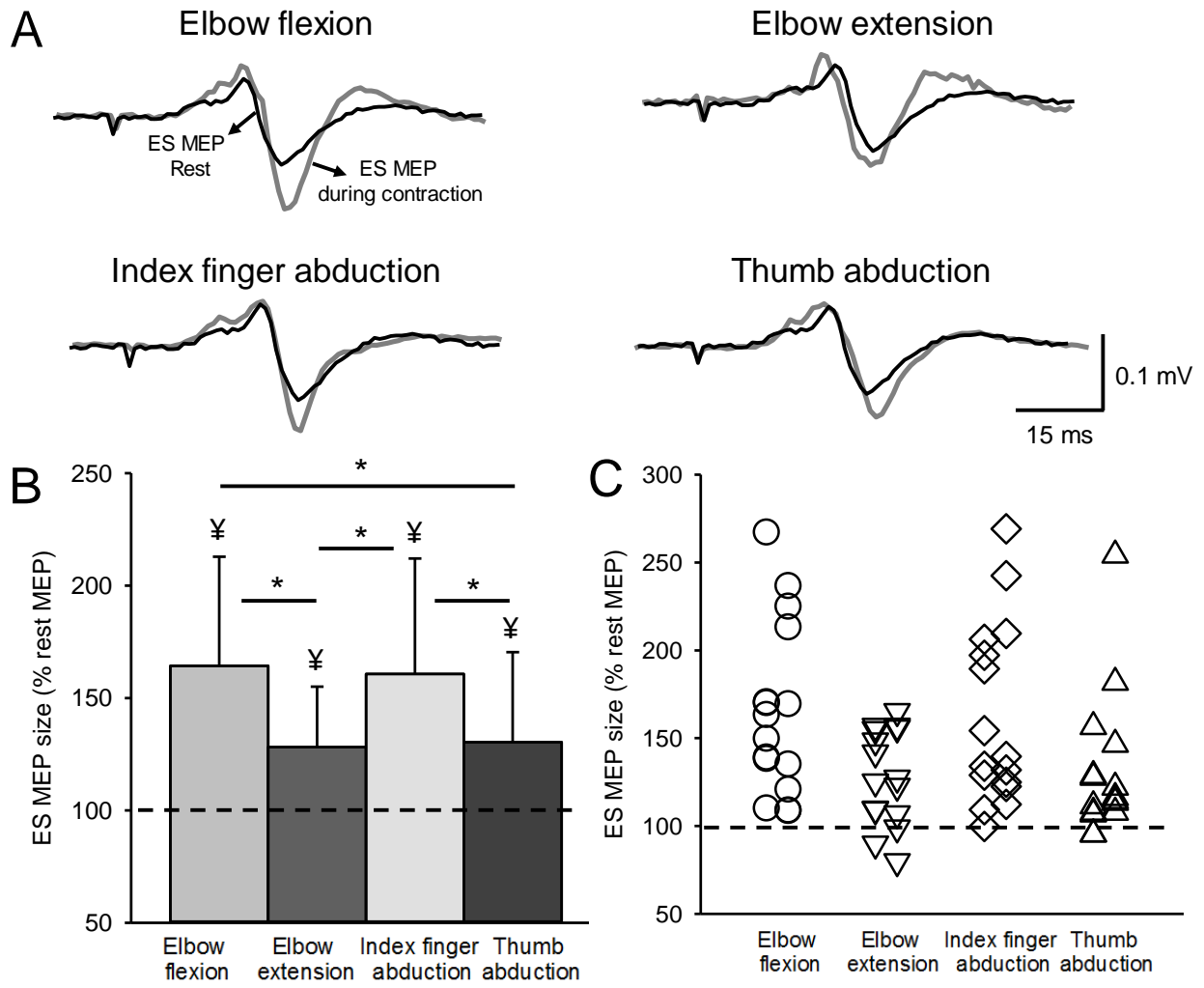


Figure 4

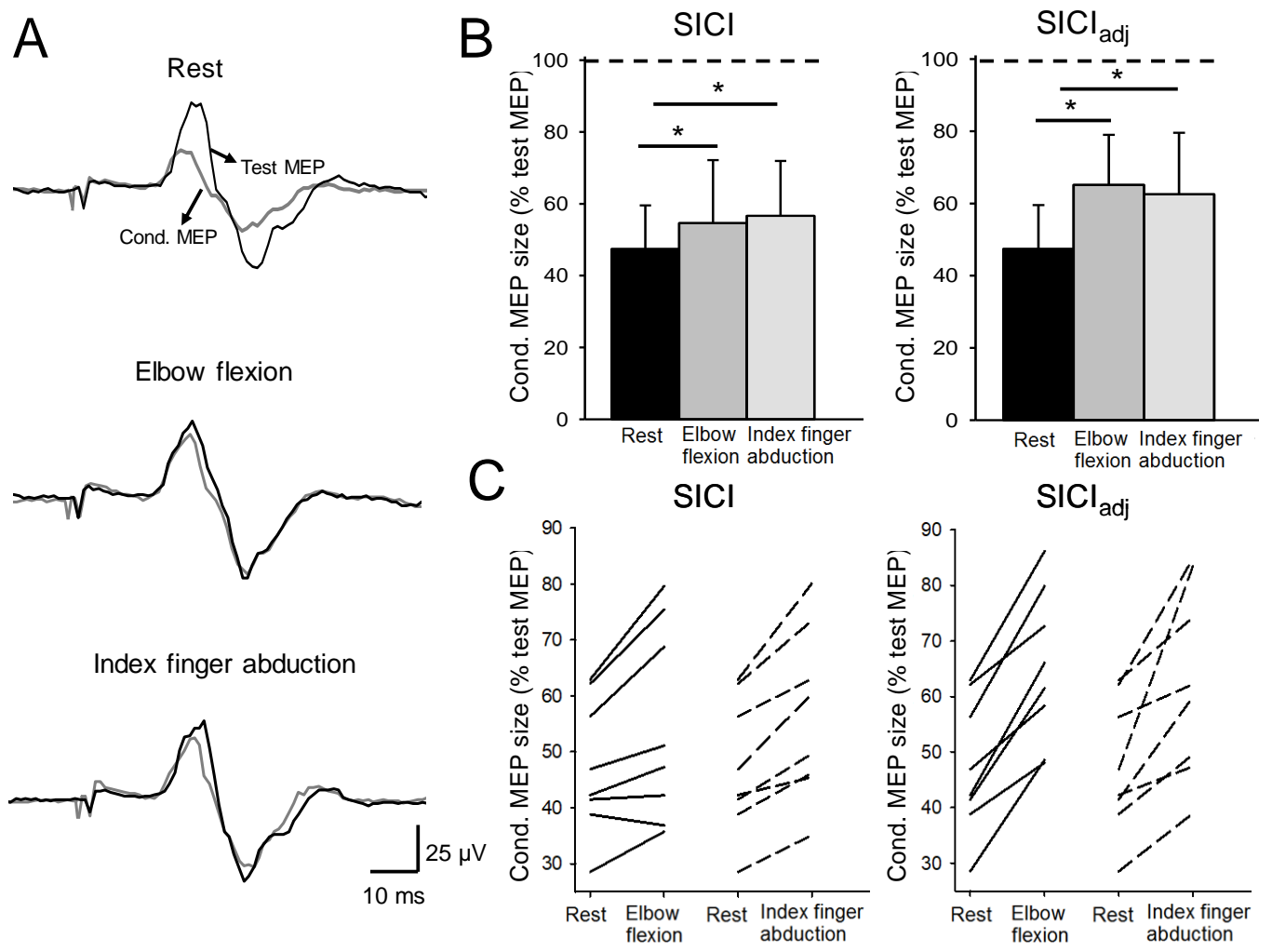


Figure 5

