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1 **Selective Muscle Contraction during Plantarflexion is**
2 **Incompatible with Maximal Voluntary Torque Assessment**

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4 **Nicolas A. Turpin, Antony Costes, David Villegier and Bruno Watier**

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19 **Abstract**

20 *Objective.* Large variations in maximal voluntary torque are reported in the literature during
21 isometric plantarflexion contractions. We propose that these differences, which could reach
22 40% across similar studies, could be explained by differences in the instructions provided, and
23 notably by instructions as to favoring or not multi-joint contractions.

24 *Method.* Sixteen participants were placed on an isokinetic ergometer in 3 different positions,
25 supine, prone and seated, with the ankle in the neutral position, and instructed to create maximal
26 force on the footplate by conforming with instructions that favored either isolated (ISOL) or
27 multi-joint (ALL) isometric contractions. Torque, foot kinematics and the electromyographic
28 activity of seven muscles of the lower limb have been recorded.

29 *Results.* Joint torques were greater in ALL compared to ISOL ($p<.05$) with gains of 43.5 [25.4
30 170.6]%, 42.5 [1.4 194.6]% and 15.3 [9.3 71.9]% in the supine, prone and seated position,
31 respectively (values are given as median [range]). The results suggested that forces created by
32 muscles that do not span over the ankle joint significantly influenced the measured joint torque,
33 notably in the seated position. Nevertheless, the observed gains in torque were associated with
34 greater plantarflexor muscles activation, showing that the ISOL condition may have induced a
35 form of inhibition of these muscles.

36 *Conclusions.* The results of this study suggest that using isolated contractions, hence
37 constrained testing protocols, cannot provide optimal conditions for MVC testing, notably for
38 plantarflexor muscles, which seem to be extremely sensitive to such constrained conditions.

39 **Keywords.** EMG, maximal voluntary contraction; plantarflexion; multi-joint contraction;
40 concurrent activation

list of abbreviations

ALL: multi-joint contractions condition

ANOVA: analysis of variance

CR: center of rotation

EMG: electromyographic signal

EMGmax: maximal electromyographic (EMG) value obtained over all conditions

GM: *gastrocnemius medialis*

Gmax: *gluteus maximus*

ISOL: isolated contractions condition

MVC: Maximal voluntary contraction

RF: *rectus femoris*

SCoRE: Symmetrical Centre of Rotation Estimation method

SCS: segment coordinate system

SD: standard deviation

Sol: *soleus*

ST: *semi tendinosus*

TA: *tibialis anterior*

VL: *vastus lateralis*

41 **Introduction**

42 Maximal voluntary contraction (MVC) torque is an important measure to evaluate
43 mechanical properties of the muscle and their progress with physical training (Klass et al. 2008;
44 Van Cutsem et al. 1998) or in rehabilitation, to assess the evolution of musculoskeletal diseases
45 and to quantify the beneficial effects of different therapeutic strategies (Moraux et al. 2013;
46 McNeil et al. 2007). MVC at the ankle joint is especially critical to consider due to the important
47 role of the plantarflexor and dorsiflexor muscles in maintaining balance and avoiding fall
48 (Horak et al. 1989). Still, MVCs evaluation requires several precautions to be taken, because
49 mechanical and neural factors could greatly influence torque output. Therefore, the present
50 study will focus on isometric plantarflexion MVCs.

51 Regarding mechanical factors, even though ergometers have proven to be reliable
52 instrument *per se* (Drouin et al. 2004), many biases are known to affect measurements, such as,
53 (i) gravitational effects, (ii) inertial effects, (iii) compliance of the ergometer moment arm or
54 deformation of the footplate and fasteners compliance, or (iv) misalignments between the axis
55 of rotation of the ergometer relative to that of the joint (Arampatzis et al. 2007; Herzog 1988;
56 Deslandes et al. 2008), that, moreover, represents only an approximation of the actual functional
57 axis of rotation of the joints (Ramos and Knapik 1978; Hicks 1953). In the isometric case,
58 gravitational effects are easily eliminated and the inertial effects are supposed to be negligible
59 (Deslandes et al. 2008). Compliance involves movement of the segment relative to the moment
60 arm of the ergometer, and implies that muscles MVCs cannot be evaluated at the exact intended
61 position. Adjustments can nevertheless be easily performed to correct positional changes
62 observed when the muscles go from the passive to the active state (De Ruyter et al. 2008).
63 Misalignment, on the other hand, is particularly critical for the evaluation of plantarflexion as
64 compared to other group of muscles.

65 With some simplifications, torque at the ankle can be written (Arampatzis et al. 2007) as:

66
$$\tau_{ankle} = \frac{r_{ankle}}{r_{dynamometer}} \tau_{dynamometer} \quad (\text{equation \#1})$$

67 with τ , the torque at either the ankle or the dynamometer axis, and r , the moment arm of the
68 reaction force to either the ankle or the dynamometer. This relation could be rewritten as:

69
$$\tau_{ankle} = \left(1 + \frac{\Delta r}{r_{dynamometer}} \right) \tau_{dynamometer}; \Delta r = r_{ankle} - r_{dynamometer} \quad (\text{equation \#2})$$

70 highlighting that, for a given misalignment Δr (order of magnitude = 1 cm), the bias is lower
71 for knee extension testing (with large $r_{dynamometer}$ relative to Δr ; $r_{dynamometer} \approx 30\text{-}40\text{cm}$,
72 (Arampatzis et al. 2004; Deslandes et al. 2008) than for plantarflexion testing ($r_{dynamometer} \approx$
73 17cm, assuming that the forces on the footplate act at the level of the metatarsophalangeal joint
74 of the big toe, Van Cutsem et al. 1998). In addition, with misalignment, a moment arm is created
75 between the ankle joint and the axis of rotation of the ergometer, and the reactions forces at the
76 level of the ankle joint can thus create a torque on the footplate without any torque on the foot.
77 Moreover, these forces can be easily manipulated by the participant using forces created by
78 muscles not crossing the ankle joint (e.g., knee or hip extensors), and these accessory muscles
79 can then have a mechanical influence on the measured joint torque.

80 At least two neural factors should be considered in this juncture: motivation and
81 *concurrent activation potentiation* (Ebben et al. 2008a; Ebben et al. 2010), also referred to as
82 *remote voluntary contraction* (Cherry et al. 2010; Ebben et al. 2008b). Motivation is a well-
83 known confound variable influencing performance which can be controlled following several
84 recommendations (see Gandevia (2001) notably for a review). *Concurrent activation*
85 *potentiation* is much less considered and captures the fact that contraction of accessory muscles

86 (remote contraction) may increase the maximal activation level of primary movers (Ebben et
87 al. 2008b). This phenomenon is commonly attributed to motor irradiation and/or to an increase
88 in spinal excitability (Ebben 2006). Jaw clenching, Valsalva maneuver and hand gripping have
89 been particularly investigated (see Ebben et al. (2008b) for a review), but muscles from adjacent
90 sites also proves to interact with the primary movers (Barry et al. 2008; Devanne et al. 2002;
91 Kouchtir-Devanne et al. 2012). It is therefore likely that muscles that do not span over the ankle
92 joint have also a neural influence on plantarflexor activity and hence on plantarflexion torque.

93 Since accessory muscles may come into play at both the neural and the mechanical level,
94 the aim of this study was to test the maximal torque produced in plantarflexion using two
95 modalities of instructions aimed at manipulating the degree of involvement of muscles not
96 crossing the ankle joint. Furthermore, the various positioning used in the literature, notably the
97 seated (Moraux et al. 2013; Simoneau et al. 2009), prone (Cresswell et al. 1995; Maganaris
98 2003) and supine positions (Danneskiold-Samsøe et al. 2009; Simoneau et al. 2007) are likely
99 to favour specific patterns of muscle activity, and thus to influence the results in a different
100 way. Therefore, in this study these three positions have been tested. Offset of the rotation axes,
101 ankle angle deviations and muscle activity have been recorded in order to set apart the neural
102 and mechanical influences of the accessory muscles.

103 **Materials and methods**

104 *Participants*

105 16 healthy males participated to the study (mass= 76.8 ± 8.5 kg, range =[68-92];
106 height= 1.77 ± 0.07 m, range=[1.62-1.87]; age= 26.9 ± 6.4 years, range=[20-41]). All of them
107 were informed of the experimental procedures prior to giving their written consent to
108 participate. The experimental design of the study was approved by the local ethical committee
109 and the experiments were conducted in accordance with the Declaration of Helsinki (last
110 modified in 2004).

111 *General procedure*

112 Ankle torque measurements were performed using an isokinetic dynamometer (Biodex
113 III, Shirley Corporation, NY, USA). The right leg was evaluated in all participants. Participants
114 were equipped of the reflective markers used for kinematic analysis and of the recording
115 electromyographic (EMG) surface electrodes at their arrival at the laboratory (see details in
116 sections *Kinematics* and *Electromyographic acquisition*). We first estimated the position of the
117 real center of rotation of the ankle by moving passively the ankle on the dynamometer footplate
118 in a procedure described in section *Estimation of the ankle rotation axis and center of rotation*.
119 Afterward, participants performed a warm up lasting 5 minutes which consisted of submaximal
120 isometric plantarflexor contractions while seated on the ergometer. Participants were then
121 successively placed in the PRONE, SUPINE or SEATED position in a random order to assess
122 their isometric MVCs. For each of these positions two modalities of instruction were randomly
123 given to the participants. These constitute a total of $3 \times 2 = 6$ randomized conditions and for each
124 of them 3 tries were given to the participant, resulting in a total of 18 MVCs.

125 *Kinematics*

126 A motion analysis system (Vicon Motion System, Lake Forest, CA) equipped with 11
127 infrared cameras recorded the 3-dimensional position of 11 reflexive markers stuck on the
128 participant and on the dynamometer. Markers were positioned on the right side of the body at
129 the level of the external and internal *maleolli*, *calcaneous* (posterior point of the heel), 1st and
130 5th Metatarsal Head, fibula's head and tibia's tuberosity. 4 reflexives markers were placed on
131 the dynamometer such that the mid distance between two of the markers corresponds to the
132 position of the dynamometer axis of rotation and that the two others, placed in a more backward
133 position, allowed to recover the direction of this axis. Kinematic data were recorded at a
134 sampling frequency of 200 Hz. Ankle angle represents the angle between the vector going from
135 the *calcaneous* to the midpoint between 1st and 5th Metatarsal Head, and the vector going from
136 the midpoint between fibula's head and tibia's tuberosity to the midpoint between the two
137 *maleolli* (see Figure 1).

138 *Electromyographic acquisition*

139 Surface EMG was recorded from 7 muscles located on the right side of the body, namely,
140 *tibialis anterior* (TA), *soleus* (Sol), *gastrocnemius medialis* (GM), *vastus lateralis* (VL), *rectus*
141 *femoris* (RF), *semi tendinosus* (ST) and *gluteus maximus* (Gmax). Prior to electrode application,
142 the skin was shaved and cleaned with alcohol to minimize impedance. Pairs of Ag-AgCl disk
143 electrodes of 8mm diameter with inter electrode-distances of 2cm were placed longitudinally
144 with respect to the underlying muscle fibers arrangement according to the recommendations of
145 Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) (Hermens et al. 2000). The
146 references electrode was placed at the level of the great trochanter. EMG signals were amplified
147 ($\times 1000$), digitized (6-400 Hz bandwidth) at a sampling rate of 1kHz (Biopac System Inc.
148 Goleta, USA), recorded and synchronized using the motion analysis system.

149 *Conditions of MVC testing and recording*

150 The ankle joint torque was acquired with the isokinetic dynamometer and digitally
151 synchronized at a sample rate of 1 kHz using the motion analysis system. During MVCs,
152 participants were positioned on the ergometer and securely stabilized by using two crossover
153 shoulder harnesses and a belt across the abdomen. The right foot was strapped securely to the
154 footplate with the ankle fixed at an angle of 90° i.e., at the neutral position with the sole of the
155 foot perpendicular to the shank, and held in place by a heel block. The axis of the dynamometer
156 was aligned with the anatomical ankle flexion-extension axis, estimated as the line passing
157 through the tips of the *malleoli* (Wu et al. 2002; Lundberg et al. 1989). A clear start and stop
158 signals were given. Each voluntary contraction lasted approximately 3-4 s and 1 minute of rest
159 were given between each contraction (Todd et al. 2004). Participants received no feedback of
160 their performances during the tests.

161 *Positions*

162 Three positions were tested, PRONE, SUPINE and SEATED. For PRONE and SUPINE
163 positions the participants were lying on the dynamometer chair with the hip and the knee fixed
164 at an angle of 0° (=full extension for both). In these positions the thigh was stabilized using a
165 belt. For the SEATED position, the chair was lifted up at an angle of 90° from the horizontal
166 and the knee and hip joints were both placed at an angle of 90°.

167 *Instructions*

168 For each position, MVCs were performed with two different modalities of instructions
169 named ISOL and ALL. In the isolation condition (ISOL), participants were required to produce
170 a force by rotating the footplate as hard as possible and to handle the shoulder harnesses. In this
171 condition, they were invited to use only their calf muscles. In a second condition (ALL), the

172 participants were invited to grip the ergometer handle and to use all the possible means to create
173 forces against the footplate.

174 *Estimation of the ankle joint rotation center*

175 The ankle joint rotation center was estimated using the Symmetrical Centre of Rotation
176 Estimation (SCoRE) method (Ehrig et al. 2006). Briefly, the position of the center of rotation
177 (CR) between two segments is determined by assuming a constant contact point between each
178 and use the relation

$$179 \quad CR = \mathbf{o}_1 + \mathbf{R}_1 \mathbf{u} = \mathbf{o}_2 + \mathbf{R}_2 \mathbf{v} \quad (\text{equation \#3})$$

180 where \mathbf{o}_1 and \mathbf{o}_2 are arbitrary points on segments #1 (the foot) and #2 (the leg), \mathbf{R}_1 and \mathbf{R}_2
181 are the rotation matrix transforming the segment coordinate system (SCS) to the global
182 coordinate system and \mathbf{u} and \mathbf{v} are the vector linking respectively \mathbf{o}_1 and \mathbf{o}_2 to CR in the foot
183 and leg coordinate system respectively. The SCSs were defined according to Wu et al. (2002).
184 For the estimation of the CR position, participants were seated on the ergometer chair with
185 solely their right foot strapped on the footplate connected to the moment arm of the
186 dynamometer and the ankle joint was moved passively at full but comfortable range of motion
187 for about 10 flexion-extension cycles in order to localize an accurate joint center. The values of
188 \mathbf{u} and \mathbf{v} were then used to estimate the position of the CR relative to the SCSs (foot and leg)
189 in all experimental conditions.

190 *Data analysis*

191 EMG signals were filtered with a bandpass filter (4th order Butterworth) between 20 and
192 400 Hz. Linear envelopes for each muscle were obtained by low-pass filtering the fully rectified
193 raw EMG signals with a 9 Hz low-pass filter (2nd order Butterworth, zero lag, (Shiavi et al.
194 1998). For each condition, the averaged value between -150 ms and 150 ms around the peak

195 torque event was extracted (Figure 2) and then normalized by the maximal value obtained over
196 all conditions (=EMG_{max}). These calculations were performed for each muscle and each
197 participant independently.

198 Joint torque and kinematic data were filtered by a 15 Hz low pass filter (2nd order
199 Butterworth filter (Winter 1990)). Joint torque was corrected for gravity by subtracting the
200 baseline, and for each condition the maximal value reached over the three tries given to the
201 participant was extracted for analysis (Figure 2).

202 *Statistics*

203 Normality of the data has been checked using Shapiro-Wilk's tests. For normally
204 distributed data two-way repeated measure ANOVAs (instruction=ALL and ISOL ×
205 position=SUPINE, PRONE and SEATED) were performed after checking for violations of
206 sphericity using Mauchly's test. Post-hoc analyses were then performed using Bonferroni
207 method (Maxwell 1980). For non-normal distribution non parametric Friedman ANOVAs (one-
208 way repeated measures ANOVA on ranks) was chosen. Wilcoxon rank sum tests associated
209 with Bonferroni-Dunn corrections were used when the null hypothesis was rejected.

210 The different biases mentioned in the introduction were rallied in kinematic deviations.
211 They include i) the ankle angle changes (in degrees) during the test due to the compliance of
212 the ergometer moment arm, deformation of the footplate and fasteners compliance; ii) the
213 alignment errors (in mm) between the axis of the dynamometer and the functional ankle joint
214 centre of rotation in horizontal and vertical axis during the rest and the MVC. Kinematic
215 deviations were compared to the reference using one-sample Student's t-tests (reference
216 value=0). A description of the axes is given in Figure 1.

217 We assessed the relationships between torque and other variables (i.e., kinematic
218 deviations and EMG activity) using Pearson's correlation coefficient (r). For these analyses,
219 values of each variable and for each participant were converted to z-scores, calculated by
220 subtracting the average (over all conditions) and dividing the result by the SD. Because
221 correlation analysis is very sensitive to the presence of outliers in the data (Chatterjee and Hadi
222 1986), normality of each variable was checked and values of $|z\text{-score}| > 2.58$ (corresponding to
223 the 99th percentile of the distribution) were discarded from the analysis (Burke 2001). All
224 available data were used (3 tries x 3 positions x 2 instructions x 16 subjects).

225 All statistical analyses were performed with the Statistica® software (Statistica®V6,
226 Statsoft, Maison-Alfort, France). Values are reported as mean \pm SD for normally distributed
227 data and as median [range] instead. A p -value below .05 was considered statistically significant.

228 **Results**

229 *Torque*

230 The results showed that MVCs were significantly affected by the positions ($F(2,30)=13.2$,
231 $p<.001$, $\eta_p^2=.60$) and the instructions provided ($F(1,15)=54.7$, $p<.001$, $\eta_p^2=.80$; Figure 3). Post-
232 hoc analyses showed that MVCs were significantly greater in the SUPINE and PRONE
233 positions compared to the SEATED position (pooled data: SUPINE= 146.0 ± 40.5 N.m and
234 PRONE= 145.7 ± 38.9 N.m vs. SEATED= 118.5 ± 31.2 N.m, $p<.001$). Torque was greater in the
235 ALL condition compared to the ISOL condition for each position ($p<.001$), corresponding to
236 gains of 43.5 [25.4 170.6]%, 42.5 [1.4 194.6]% and 15.3 [9.3 71.9]% for the SUPINE, PRONE
237 and SEATED position respectively. Gains were significantly lower in SEATED compared to
238 SUPINE ($Z=3.15$, $p<.001$) and PRONE ($Z=2.43$, $p=.015$) but were similar between SUPINE
239 and PRONE ($Z=1.55$, $p=.121$).

240 *Muscle activation*

241 EMG variables were not normally distributed. The activity level of TA was greater in ALL
242 compared to ISOL (pooled data: ALL= $89.6 [6.5 100]$ % vs. ISOL= $65.3 [2.7 100]$ %, $Z=3.21$,
243 $p=.001$) but this effect was present in the SUPINE and PRONE positions only ($Z=3.31$, $p<.001$,
244 and $Z=2.53$, $p=.011$ respectively). Analysis revealed no main effect of the position on the
245 activity of TA ($\chi^2= 4.75$, $p=.093$; Figure 4).

246 Overall positions, Sol activity was greater in ALL compared to ISOL (ALL= $85.7 [6.0 100]$ %)
247 vs. ISOL= $66.1 [0.7 100]$ %, $Z=2.84$, $p=.004$) but post-hoc analysis revealed significant
248 differences in the SUPINE position only ($Z=2.43$, $p=.015$). There was no main effect of the
249 position on the activity of SOL ($\chi^2= 2.25$, $p=.325$).

250 Activity of GM was greater in ALL compared to ISOL (i.e., pooled data: ALL=88.1 [15.8
251 100]% vs. ISOL=61.5 [1.9 98.2]%; $Z=4.24$, $p<.001$). These differences held for the SUPINE
252 and PRONE positions ($Z=2.84$, $p=.004$ and $Z=2.74$, $p=.006$ respectively) but no differences
253 were found in the SEATED position ($Z=1.76$, $p=.08$). Analysis revealed a main effect of the
254 position ($\chi^2=17.69$, $p<.001$) i.e., GM was significantly less activated in the SEATED position
255 (=49.9 [15.3 100]%,) compared to the PRONE (=79.4 [1.9 100]%, $Z=3.78$, $p<.001$) and
256 SUPINE (=83 [0.09 1]%, $Z=3.72$, $p<.001$) positions.

257 ST was maximally activated in the PRONE position in 10 out of 16 participants. The activity
258 of ST was significantly higher in ALL compared to ISOL in SUPINE ($Z=3.46$, $p<.001$) and
259 SEATED ($Z=3.00$, $p=.003$), but no differences were found in the PRONE position ($Z=0.67$,
260 $p=.502$). A main effect of the position was found ($\chi^2=6.94$ $p=.03116$) i.e., there was higher ST
261 activity in the PRONE position but differences were significant only when compared to the
262 SUPINE's (i.e., pooled data=74.6 [3.6 100]% vs. 8.0 [0.8 100]%, $Z=3.22$, $p=.001$).

263 VL, RF and Gmax activities possess the same patterns among the experimental conditions and
264 were maximally activated in the SEATED position in most participants i.e., in 15, 13 and 15
265 out-of 16 participants respectively (Figure 4). Friedman ANOVA confirmed the effect of
266 position on VL, RF and Gmax (VL: $\chi^2= 31.75$, $p<.001$; RF: $\chi^2= 17.44$, $p<.001$; Gmax: $\chi^2= 38.31$,
267 $p<.001$). These muscles were significantly more activated in the SEATED compared to the
268 SUPINE and PRONE positions (merged values in SEATED position: VL=97.1 [1.4 100]%,
269 RF=62.5 [0.6 100]% and Gmax=90.7 [1.3 100]%) vs. SUPINE + PRONE: VL=6.2 [0.3 90.5]%,
270 RF=6.8 [0.3 100]% and Gmax=5.1 [0.4 54.9]%, Wilcoxon Z-values ranged from 3.23 to 4.75,
271 $p<.001$). Analyses indicated that the activity of VL, RF and Gmax were greater in the ALL
272 compared to the ISOL condition in the 3 positions tested (Wilcoxon Z-values and p-values
273 ranged from $Z=2.84$, $p=.004$ to $Z=3.51$, $p<.001$; Figure 4).

274 *Kinematic deviations*

275 Kinematic results and statistics are summarized in Table 1. During MVCs the ankle joint angle
276 varied of $-9.73 \pm 4.15^\circ$ in average i.e., from $91.0 \pm 5.2^\circ$ to $81.3 \pm 4.9^\circ$ overall conditions. From
277 rest to MVC and overall conditions, the CR varied on \mathbf{e}_x of $\Delta X = +14.8 \pm 8.0\text{mm}$ (i.e., from
278 $X_{\text{rest}} = 9.7 \pm 22.1\text{mm}$ to $X_{\text{MVC}} = 24.7 \pm 24.6\text{mm}$) and of $\Delta Y = -0.71 \pm 9.6\text{mm}$ on \mathbf{e}_y (i.e., from
279 $Y_{\text{rest}} = 3.9 \pm 13.1\text{mm}$ to $Y_{\text{MVC}} = 3.0 \pm 15.0\text{mm}$).

280 *Correlations*

281 All the results on correlation analyses are summarized in Table 2 and indicated that torque was
282 significantly correlated with the activity of the plantar flexors in each position. VL, RF, ST and
283 kinematic variables (ΔY and the variation in joint angle, $\Delta\theta$) were found to be significantly
284 related to torque depending on the position and on the instruction (see Table 2).

285 **Discussion**

286 The aim of this study was to point out the differences in torque output during maximal voluntary
287 contraction (MVC) in isometric plantarflexion when activating either isolated or global muscle
288 (conditions named ISOL and ALL respectively). The ALL condition was associated with higher
289 EMG activities in most of the recorded muscles, notably in plantarflexor muscles, and was
290 associated with higher joint torque compared to ISOL.

291 Very large differences were observed between ALL and ISOL, with gains on joint torque
292 of about 40% in average (Figure 3). Lower torque in seated position could be attributable to
293 muscle mechanics, i.e., force-length relationships (Maganaris 2003), and to impairments in
294 motor units recruitment, as already reported for this particular joint angle configuration (i.e.,
295 knee and ankle joint angles set at 90° of flexion) (Cresswell et al. 1995; Kennedy and Cresswell
296 2001). In mine with our findings, a previous study showed that plantarflexion torque could be
297 significantly enhanced (~+26%) in multi-joint compared to isolated plantar flexion (Hahn et al.
298 2011). However, this study remained inconclusive regarding the differences in EMG activity
299 resulting from these two conditions and used different methodologies to assess joint torque in
300 the multi-joint and isolated contractions, i.e., they used inverse dynamic calculations and
301 ergometer measurements, that proved to provide different results (Herzog 1988; Kaufman et al.
302 1995; Arampatzis et al. 2004). Sasaki et al.(1998) observed an increase in plantarflexion torque
303 linked to jaw clenching, but the conclusions relied on integrated electromyographic activity per
304 unit of time rather than EMG level, and did not check for the influence of mechanical factors,
305 as they focused on jaw clenching only.

306 Interestingly, the value of 40% found in the present study fits well to differences with that
307 observed in similar studies examining ankle MVC, that is, values ranging from 134 up to 186

308 N.m, despite similar populations and protocols (Danneskiold-Samsøe et al. 2009; Cresswell et
309 al. 1995; Maganaris 2003). More precisely, considering isometric plantarflexion MVCs in the
310 supine and prone positions, and a population of young male adults, literature reports MVC
311 values ranging from ~134 N.m [e.g. 142 ± 42 , N=10 (Danneskiold-Samsøe et al. 2009) or 134
312 ± 23 N.m , N=10 (Cresswell et al. 1995)] up to ~186 N.m [e.g. 172 ± 15 , N=8 (Maganaris
313 2003) or 186 ± 28 N.m (N=9) (Hahn et al. 2011)]. These differences may pertain to differences
314 in the participants' fitness (i.e., more or less trained participants), but the results suggest that an
315 explanation also bears on the nature of the instructions (ALL vs. ISOL).

316 *Mechanical factors*

317 Misalignment has been shown to induce bias of ~10% in the estimation of joint torque
318 (Arampatzis et al. 2007; Deslandes et al. 2008), but this factor is not expected to create large
319 differences among studies, as the positioning of the foot is expected to be carefully executed

320 Given the equation #1, positive deviations of CR in the x-direction, that decreases $\frac{r_{ankle}}{r_{dynamometer}}$,
321 decreases the effectiveness of the ankle torque. The misalignments observed in this study on
322 the X-axis are positive and then, they are not likely to explain the gains in torque. Nevertheless,
323 misalignments may allow the auxiliary muscles, through joint reaction forces transmission, to
324 influence the ankle torque.

325 One can first observe that positioning have an effect on the activity of knee extensors, knee
326 flexors and hip extensors muscles (Figure 4). For example, the seated position was associated
327 with higher level of activity for VL, RF and Gmax and the prone position was associated with
328 higher ST activity (Figure 4) but the correlation values between these muscles and the torque
329 produced remained modest (Table 2), suggesting that the mechanical influence of these muscles
330 is small. Furthermore, despite the fact that differences were observed in ST activity between

331 PRONE and SUPINE, no differences were found in torque between these two positions.
332 Additionally, the large increase in Gmax, VL and RF activity (Figure 4) did not preclude to the
333 force deficit associated with the seated position (Figure 3). As a consequence, no major
334 mechanical influence of these muscles is expected on the produced torque. Notwithstanding, at
335 least two observations forbid ruling out the influence of such forces. Firstly, despite significant
336 and positive correlations of the activity of Sol and GM with torque in the seated position (Table
337 2), the increase in torque was not associated with significant increases in the activity of these
338 muscles i.e., SOL ($p=.255$) and GM ($p=.079$). And in this particular position, VL, RF and ST
339 were also correlated with torque (Table 2). These observations strongly suggest that the forces
340 created by muscles that do not span over the ankle joint significantly influenced the measured
341 joint torque, at least in the seated position. Secondly, provided that torque is mainly related to
342 plantarflexor activity, as the relation between EMG and torque tends to be convex toward
343 tension at high force levels (Perry and Bekey 1981; Lawrence and De Luca 1983), a given
344 increase in torque in this portion of the curve should have been associated with a larger increase
345 in EMG and not with a similar one (Figure 3 and Figure 4). Suggesting that even in the supine
346 and prone positions, plantarflexors are not the sole contributors of the increase in torque.

347 *Neural factors*

348 What can explain the higher muscle activity level in ALL compared to ISOL observed in this
349 study? First, motivation is not likely to explain the differences observed between ALL and
350 ISOL. Although motivation has not been explicitly assessed in this study, differences in
351 motivation are not expected, because the tests were randomized. Additionally, we found high
352 reliability between the 3 trials within all the conditions tested, with an average correlation
353 coefficient of .95 (range=[.90 .98]; model corresponding to case #1 in McGraw et al. (1996))
354 and an average coefficient of variation of 5.8% (range=[3.2 8.2]). These reliability values are

355 highly consistent with previous reports testing MVCs in plantarflexion (Webber and Porter
356 2010; Todd et al. 2004; Sleivert and Wenger 1994) and can be taken as evidences that MVC
357 testing conditions carried out here can be truly compared to those imposed in previous studies.
358 As a consequence, the lower values observed in ISOL are not likely to be due to a lack of
359 motivation from the participants.

360 In ALL, participants were allowed to grasp the ergometer, which is not generally allowed in
361 studies measuring ankle MVCs (cf. a representative setup in Figure #1 of Simoneau et al,
362 (2009), so that *concurrent activation potentiation* could be induced (Ebben et al. 2008a; Ebben
363 et al. 2010; Cherry et al. 2010; Ebben et al. 2008b). Jaw clenching or Valsalva maneuver have
364 been reported to improve the level of maximal activation of the contracting muscles (Ebben et
365 al. 2008b; Sasaki et al. 1998). However, most of these studies focused on the knee extensors
366 muscles (Ebben et al. 2008b; Ebben et al. 2010), and not on plantarflexors. Furthermore,
367 improvements in peak torque due to jaw clenching and Valsalva maneuver have been reported
368 to be of ~15% for the quadriceps muscles (Ebben et al. 2008b; Ebben et al. 2010), that is, far
369 less than the differences observed in the present study (i.e., ~40%). This may suggest a
370 particular sensitivity of the plantarflexors to the phenomenon. In fact, contrary to other muscles
371 such as elbow flexors (Herbert et al. 1998) or ankle dorsiflexors (Kent-Braun et al. 2002),
372 activation of plantarflexor muscles is rarely complete (Todd et al. 2004; Cresswell et al. 1995).
373 Without training or adequate testing conditions, plantarflexor muscles are not maximally
374 activated by volition, and only reach about 80-90% of voluntary activation (Cresswell et al.
375 1995; Maffiuletti et al. 2002). This is in line with the finding that the neural drive to these
376 muscles can be significantly improved by a strength training (Shield and Zhou 2004) or
377 imagined strength training (Zijdewind et al. 2003; Sidaway and Trzaska 2005), whereas such
378 is not the case for the elbow flexors, for example which possess a high initial level of voluntary

379 activation (Herbert et al. 1998). The work of Devanne and collaborators (Devanne et al. 2002;
380 Kouchtir-Devanne et al. 2012) is particularly interesting in this respect. They observed that the
381 excitability of the cortical neurons associated with the *first dorsal interosseus* was lower during
382 isolated (contraction of *first dorsal interosseus* only) vs. global muscle contractions (precision
383 grip implying the thumb and the finger). This indicates that the cortical excitability of a given
384 muscle depends on its functional interconnections at the cortical level. These findings support
385 the idea that isolated contractions, which explicitly or implicitly (through instructions) require
386 a selection of the contracting muscles, may induce inhibition, incompatible with the objectives
387 of MVC testing. Allowing global muscle activation or not is then a critical aspect of the
388 instructions

389 *Conclusions*

390 This study reports that activation of plantarflexor muscles are superior during global muscle
391 activation compared to isolated joint contraction, entailing very large differences in motor-
392 output. It emphasizes the pertinence of using isolated vs. unconstrained MVC testing protocols,
393 notably for muscles that are not maximally activated by volition.

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524

525

	SUPINE		PRONE		SEATED	
	ALL	ISOL	ALL	ISOL	ALL	ISOL
X rest	22,5 ± 13,5	20,9 ± 14,6	-14,8 ± 11,3	-14,7 ± 16,0	20,0 ± 15,3	22,1 ± 16,4
Y rest	3,9 ± 9,7	4,4 ± 10,8	-5,2 ± 12,8	-6,0 ± 11,3	12,4 ± 10,4	15,4 ± 9,7
X MVC	39,3 ± 14,1	36,1 ± 13,0	-2,6 ± 13,6	-4,4 ± 17,0	41,0 ± 18,0	36,2 ± 15,4
Y MVC	-0,7 ± 10,3	11,6 ± 11,8	-12,5 ± 12,5	1,5 ± 10,1	1,9 ± 14,1	18,1 ± 12,1
ΔX	16,9 ± 5,8	15,2 ± 7,3	12,2 ± 12,7	9,8 ± 4,9	21,0 ± 5,3	14,1 ± 4,9
ΔY	-4,6 ± 4,7	7,3 ± 3,5	-7,1 ± 8,1	7,5 ± 7,5	-10,6 ± 9,3	2,7 ± 5,4
Δθ ankle	-6,71 ± 3,81	-7,70 ± 2,67	-9,51 ± 3,32	-9,63 ± 4,80	-14,29 ± 3,14	-10,70 ± 2,51

527 **Table 1. Kinematic variables.** X and Y are the position of the ankle joint (estimated by the
528 SCoRe method) relative to the axis of rotation of the dynamometer in the x-direction and y-
529 direction at rest (**X rest** and **Y rest**) and at the peak torque event (**X MVC** and **Y MVC**), given
530 in mm. ΔX = X MVC- X rest, and ΔY =Y MVC- Y rest. Δθ is the difference in joint angle in
531 degree between MVC and rest, in degree. Bolded values indicate a significant difference from
532 0 (t-test for single mean; $p < .05$). Values are given as mean ± SD.

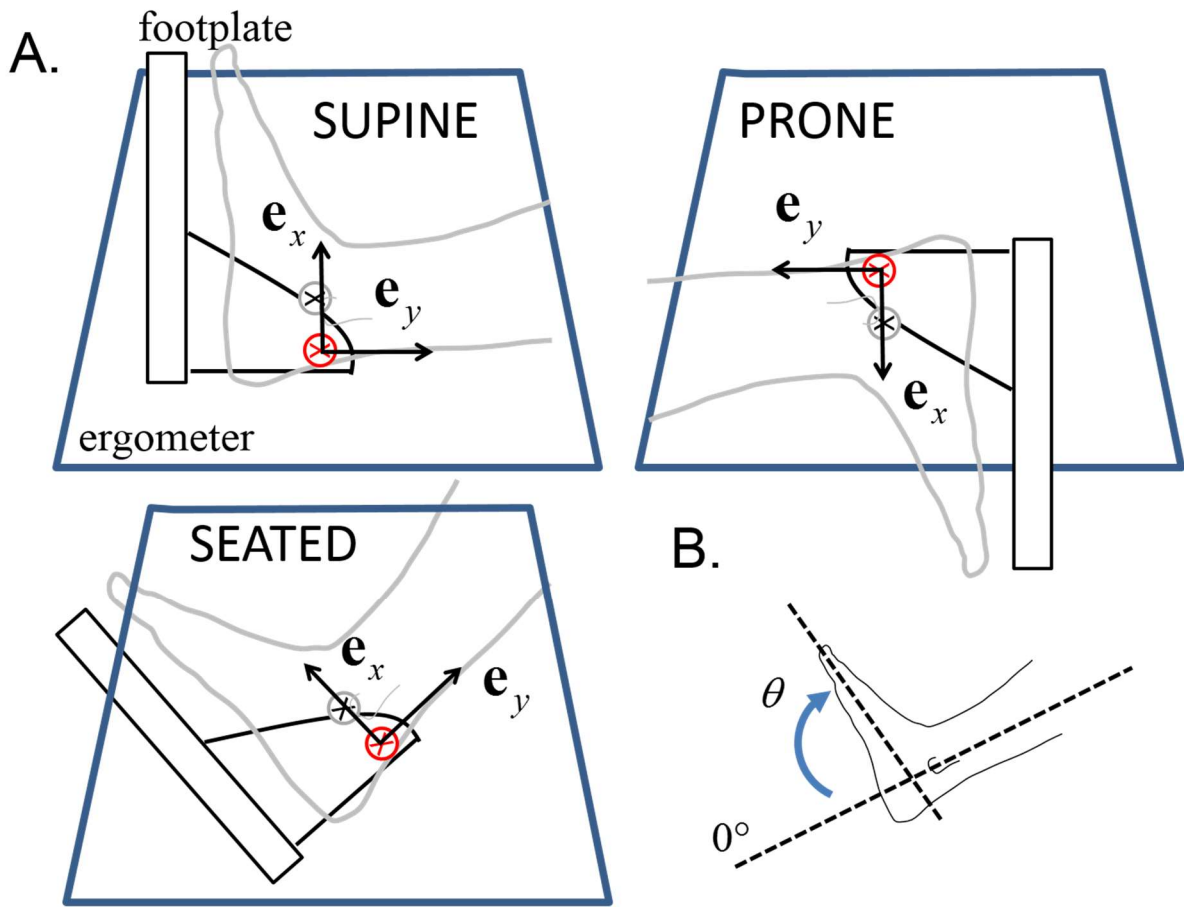
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<i>torque vs.</i>	SUPINE		PRONE		SEATED	
	ISOL	ALL	ISOL	ALL	ISOL	ALL
TA	0.10	0.55**	0.29	0.67**	0.29	0.10
Sol	-0.11	0.42**	0.41*	0.64**	0.59**	0.18
GM	0.40*	0.16	0.30	0.57**	0.42*	0.55**
VL	-0.28	-0.11	0.22	0.25	0.38*	0.35*
RF	-0.24	-0.10	0.19	0.34*	0.24	0.16
ST	0.31*	0.16	0.17	0.00	0.54**	0.27
Gmax	-0.29	-0.19	0.22	0.19	0.16	0.04
ΔX	0.17	0.01	0.23	0.03	0.27	0.24
ΔY	0.30*	-0.17	-0.08	-0.24	-0.06	-0.29
Δθ	-0.07	0.21	-0.28	-0.21	-0.26	-0.37*
N	46	47	36	37	42	37

534 **Table 2. Correlation coefficients.** N refers to the number of values used to compute the
535 Pearson's r. Bolded values indicate significant correlations (*: $p < .05$; **: $p < 0.001$).

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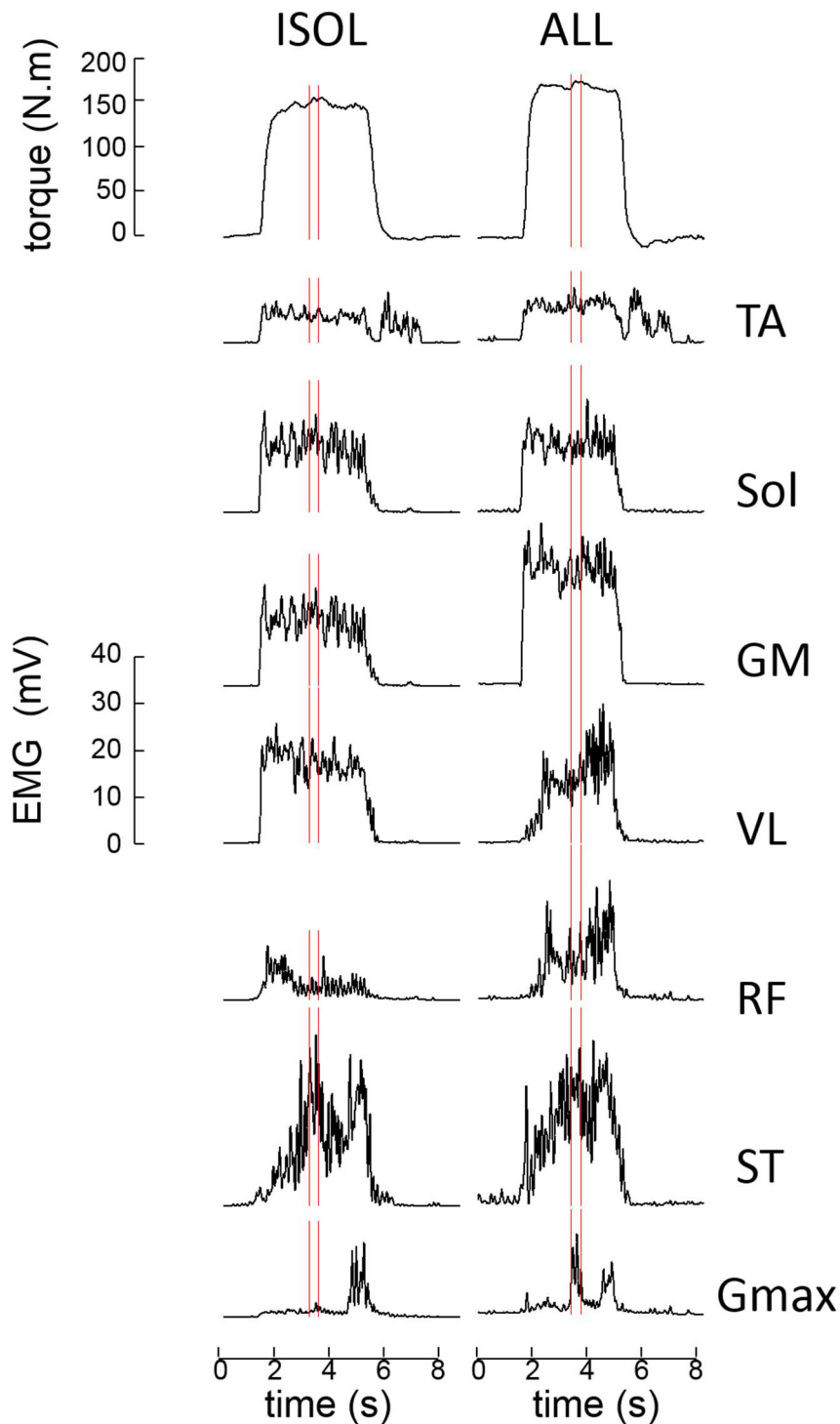
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540 **Figure 1.** Position of the foot relative to the ergometer. **A.** The circled red cross designs the
 541 ergometer axis of rotation and the circled black cross the ankle axis of rotation (=CR). In all
 542 positions, the X-axis associated with the vector e_x is the axis parallel to the footplate and
 543 pointing toward the participant toes and the Y-axis associated with the vector e_y is the axis
 544 orthogonal to it and pointing toward the participant leg. The origin is centered at the level of
 545 the ergometer axis of rotation. **B.** Definition of the ankle angle (θ).

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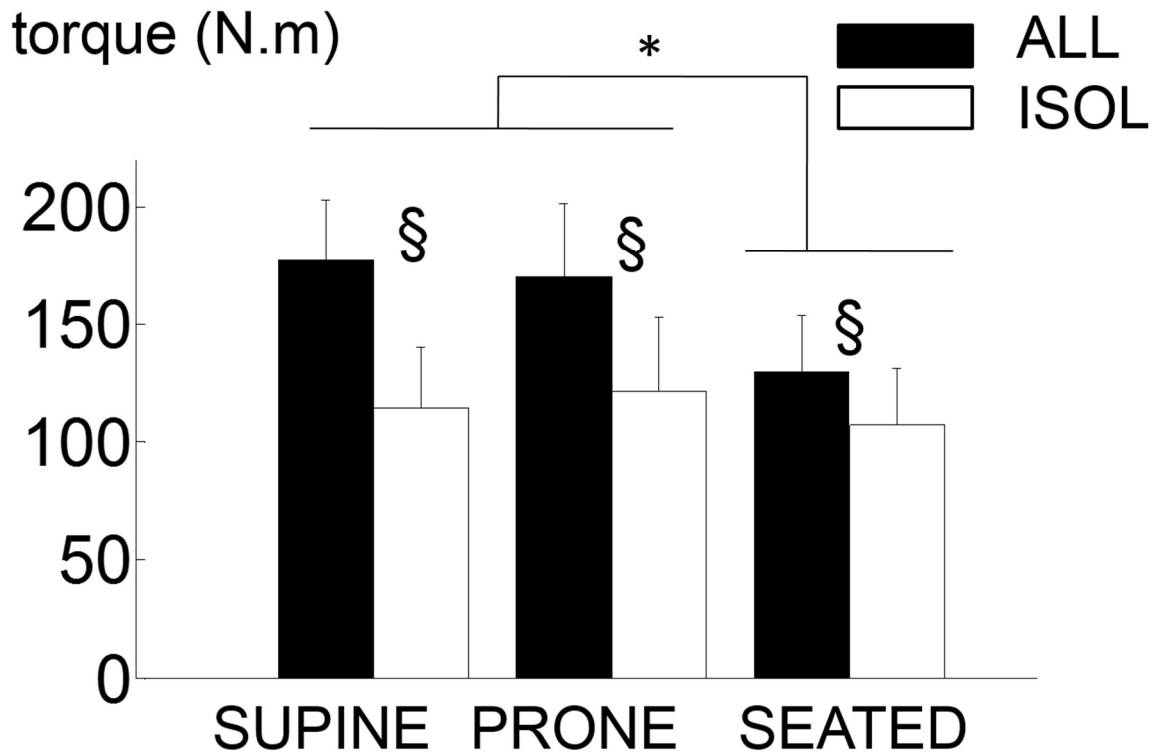
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550

551 **Figure 2. Example of torque and EMG data for a typical participant.** Condition = supine
 552 position. Smoothed torque and EMG envelope are processed as indicated in section *Data*
 553 *analysis*. Vertical lines indicate the region around peak torque used for analysis.: *tibialis*
 554 *anterior*. **SOL**: *soleus*. **GM**: *gastrocnemius medialis* **VL**: *vastus lateralis*. **RF**: *rectus femoris*.
 555 **ST**: *semi tendinosus*. **Gmax**: *gluteus maximus*.

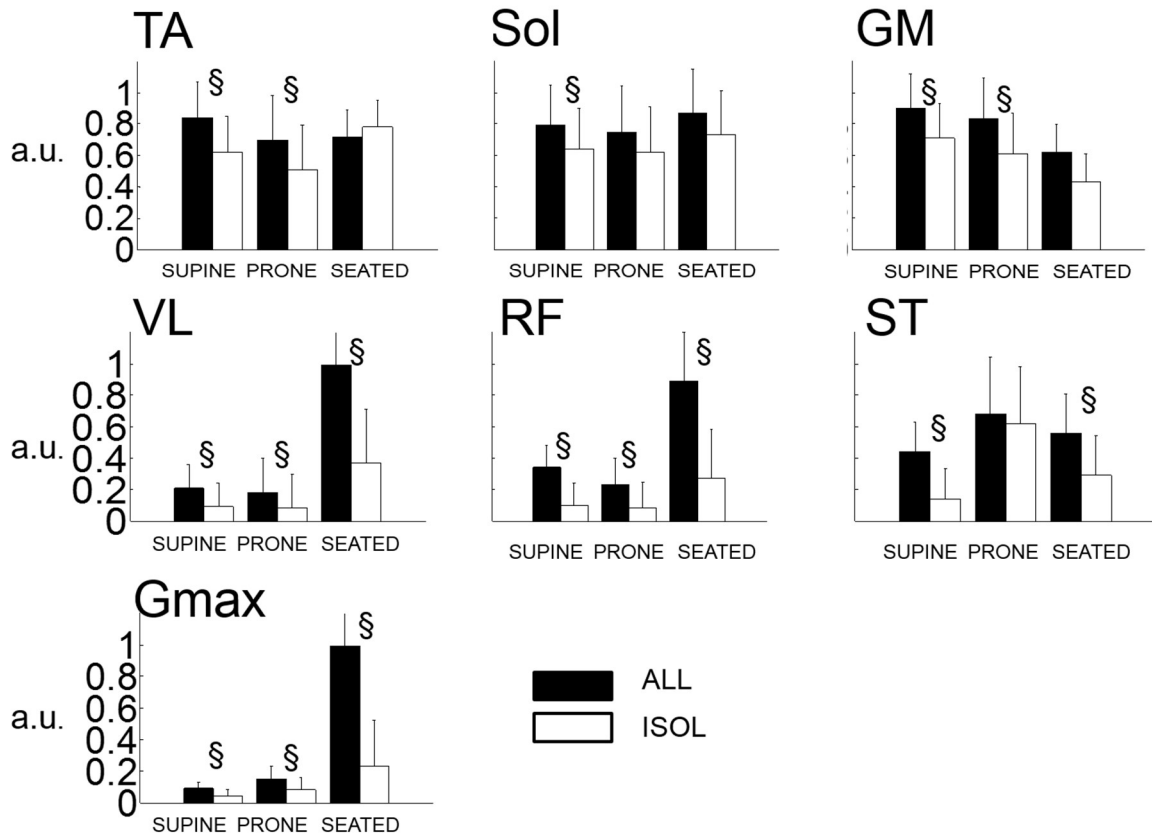


556

557 **Figure 3. Torque data.** Bars represent the mean and error-bars one SD. § indicates a significant
 558 difference ($p < .05$) between ALL and ISOL. * indicates a significant difference between
 559 [SUPINE and PRONE] vs. SEATED ($p < .05$). See section RESULTS for details.

560

561



562

563 **Figure 4. Normalized EMG activities.** Bars represent the mean and error-bars one SD. §
 564 indicates a significant difference ($p < .05$) between ALL and ISOL.

565