

## Effects of sex and joint action on voluntary activation

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The current study tested the hypothesis that a sex and joint-action interaction exists in the voluntary activation during maximal voluntary contraction (MVC). Twenty-eight healthy adults (14 of each sex) performed knee extensor MVC and plantar flexor MVC at extended and flexed knee positions. Voluntary activation during MVC was assessed using a twitch interpolation technique. A two-way analysis of variance demonstrated a significant interaction of sex and joint action. The voluntary activation during plantar flexor MVC at the extended knee position was significantly lower in women ( $88.3\% \pm 10.0\%$ ) than in men ( $96.2\% \pm 6.6\%$ ). In contrast, no significant sex differences were shown in the voluntary activation during knee extensor MVC and during plantar flexor MVC at the flexed knee position. The voluntary activation during knee extensor MVC was significantly higher than that during plantar flexor MVC at the extended knee position in women, whereas the corresponding difference was not observed in men. The results revealed that the sex difference in the voluntary activation during MVC depends on joint action.

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**12 Abstract**

13 The current study tested the hypothesis that a sex and joint-action interaction exists in the  
14 voluntary activation during maximal voluntary contraction (MVC). Twenty-eight healthy adults  
15 (14 of each sex) performed knee extensor MVC and plantar flexor MVC at extended and flexed  
16 knee positions. Voluntary activation during MVC was assessed using a twitch interpolation  
17 technique. A two-way analysis of variance demonstrated a significant interaction of sex and joint  
18 action. The voluntary activation during plantar flexor MVC at the extended knee position was  
19 significantly lower in women ( $88.3\% \pm 10.0\%$ ) than in men ( $96.2\% \pm 6.6\%$ ). In contrast, no  
20 significant sex differences were shown in the voluntary activation during knee extensor MVC  
21 and during plantar flexor MVC at the flexed knee position. The voluntary activation during knee  
22 extensor MVC was significantly higher than that during plantar flexor MVC at the extended knee  
23 position in women, whereas the corresponding difference was not observed in men. The results  
24 revealed that the sex difference in the voluntary activation during MVC depends on joint action.

## 25 **Introduction**

26 The magnitude of muscle activation during maximal voluntary isometric contractions (MVCs) is  
27 the major determinant of generated muscular force. Voluntary activation (VA%), determined by  
28 the twitch interpolation technique (Shield & Zhou, 2004), is an index often used to represent the  
29 magnitude of muscle activation.

30 It has been shown that the magnitude of VA% depends on joint action. For example,  
31 male participants demonstrated a lower VA% during knee extensor MVC than during plantar  
32 flexor MVC (Behm et al., 2002). As a possible reason for the difference, Behm et al. (2002)  
33 proposed the difference in the muscle fiber type compositions of agonist muscle groups, i.e., a  
34 difficulty in full recruitment of motor units during knee extensor MVC due to the relatively  
35 higher proportion of type II fibers of the quadriceps femoris compared with the triceps surae. The  
36 proportion of type II fibers of the vastus lateralis, the largest muscle among the quadriceps  
37 femoris in both sexes (Ema et al., 2017), is lower in women than in men (Hunter, 2014). If the  
38 proposal by Behm et al. (2002) is correct, women may show a higher magnitude of VA% during  
39 knee extensor MVC than men. In contrast, the soleus, which has the largest physiological cross-  
40 sectional area among the triceps surae (Fukunaga et al., 1992), comprises mainly type I fibers  
41 even in men (Johnson et al., 1973), suggesting that any possible sex difference of the soleus fiber  
42 type composition will be small. Moreover, given that knee flexion reduces the neural and  
43 mechanical contribution of the gastrocnemius to plantar flexion strength (Wakahara et al., 2007),  
44 it can be assumed that the sex difference in VA% during plantar flexor MVC, if any, will be  
45 small, especially at a flexed knee position. A training program induced a similar extent of  
46 strength gains between sexes despite a smaller magnitude of muscle hypertrophy in women  
47 (Lemmer et al., 2000; Melnyk et al., 2009), which may indicate greater neural adaptation by the

48 training in women than in men. Considering that the magnitude of VA% before training  
49 intervention (Gondin et al., 2005) and its training-induced change (Ema et al., 2018) were related  
50 to strength gain, an investigation of the above notions should promote better understanding of the  
51 sex dependency in training adaptation.

52 To the best of our knowledge, no studies have investigated the effects of sex and joint  
53 action on VA% during MVC simultaneously. In the current study, we determined VA% during  
54 knee extensor MVC and plantar flexor MVC at extended and flexed knee positions in both sexes.  
55 We tested the hypothesis that a sex and joint-action interaction exists in VA% during MVC.

56

## 57 **Methods**

### 58 *Participants*

59 A sample size estimation (G\*Power 3.1.7, Kiel University, Germany) was performed to detect a  
60 within-between interaction for VA%. The expected effect size,  $\alpha$ , power, and correlation among  
61 repeated measures were set at 0.25, 0.05, 0.80, and 0.5, respectively. The estimation showed that  
62 28 participants are required. It was proposed that physical activity and the existence of practice  
63 for strength testing affect the magnitude of VA% (Hunter et al., 2016). Therefore, we recruited  
64 untrained healthy young adults, and all participants visited our laboratory in advance for  
65 familiarization and practice in performing MVCs with the experimental setting for the right leg.  
66 A total of 28 adults (14 of each sex) with no habitual resistance exercises, knee or ankle injuries  
67 participated in the study (Table 1). We confirmed no significant sex difference in the magnitude  
68 of habitual physical activity, assessed with the long version of the International Physical Activity  
69 Questionnaire (Craig et al., 2003). The strength testing for knee extension and plantar flexion  
70 was performed on different days in random order among the participants. This study was

71 approved by the Ethics Committee of the Shibaura Institute of Technology (Acceptance number:  
72 16-008). All participants were informed of potential risks and the study's purpose, and they  
73 provided written informed consent before participation.

74

#### 75 *Evoked twitch responses*

76 To provide insights into the effects of muscle fiber type composition on VA%, we investigated  
77 the twitch contractile properties, because the properties have been reported to be associated with  
78 the composition (Harridge et al., 1996; Hamada et al., 2000). Participants sat (for knee  
79 extensions) or lay supine (for plantar flexions) on the bench of an isokinetic dynamometer  
80 (CON-TREX MJ, PHYSIOMED, Germany) while being secured at the pelvis and torso to the  
81 dynamometer with nonelastic straps. The knee and hip joint angles were set at 90° and 80°,  
82 respectively, for knee extension (anatomical position = 0°). For plantar flexion, the knee joint  
83 angle was 0° (K0) or 90° (K90) and the ankle joint angle was 0° (Kennedy & Cresswell, 2001).  
84 The centers of rotation of the dynamometer and the right knee/ankle joints were visually adjusted.  
85 Using a constant current variable voltage stimulator (DS7A, Digitimer Ltd, UK), the quadriceps  
86 femoris and triceps surae twitch responses were obtained with rectangular pulses of 1 ms. For the  
87 quadriceps femoris, to percutaneously stimulate the femoral nerve, a cathode (2 × 2 cm) was  
88 placed in the femoral triangle, and an anode (4 × 5 cm) was placed in midway between the  
89 superior aspect of the greater trochanter and the inferior border of the iliac crest. For the triceps  
90 surae, the tibial nerve was stimulated percutaneously in the popliteal fossa with the cathode and  
91 over the ventral aspect of the thigh with the anode. The supramaximal stimulus intensity was  
92 determined by increasing the current intensity until plateaus in the twitch torque occurred.  
93 Thereafter, five supramaximal twitch responses at a higher current ( $\geq 20\%$ ) were obtained every

94 10 seconds. Torque signals were recorded at 4 kHz and stored in a personal computer after A/D  
95 conversion (PowerLab16/35, ADInstruments, Australia). After low-pass filtering the signal at  
96 500 Hz, contraction onset was manually identified as described previously (Ema et al., 2018). A  
97 previous study used the time to peak twitch torque (TPT), i.e., the duration from torque onset to  
98 peak twitch torque, as an index of estimated muscle fiber type composition (Kubo & Ikebukuro,  
99 2010). Moreover, TPT was associated with muscle fiber type composition (Hamada et al., 2000).  
100 However, TPT is possible to depend on the magnitude of the peak value of twitch torque, making  
101 it unsuitable for comparisons between sexes and between different joint actions. Therefore, we  
102 determined the twitch torque at 50 ms from torque onset relative to the peak value of twitch  
103 torque (normalized  $\text{Twitch}_{0-50}$ ) (Balshaw et al., 2016), and used this metric as the index of  
104 estimated muscle fiber type composition. The data were averaged across five contractions.

105

#### 106 *VA% evaluations*

107 After several warm-up contractions involving two maximal MVCs, participants performed knee  
108 extensor/plantar flexor MVCs two times. Verbal encouragement was provided during the  
109 contractions. Supramaximal triplet stimulations at 100 Hz were interpolated during and after  
110 MVC. If the difference in the peak value of torque before stimulation was above 10%, an  
111 additional contraction was requested with sufficient rest between contractions. The VA% was  
112 calculated as follows:  $(1 - [\text{superimposed triplet torque}/\text{potentiated resting triplet torque}]) \times 100$   
113 (Miyamoto et al., 2012). The mean of the two trials was used for subsequent analyses.

114

#### 115 *Statistical analyses*

116 Statistical analyses were performed using SPSS version 22 (IBM, USA). All data are shown as  
117 means  $\pm$  standard deviation. A two-way analysis of variance (ANOVA) with repeated measures  
118 was conducted to examine the effects of sex (men and women) and joint action (knee extension,  
119 plantar flexion in K0 and K90) on dependent variables. When a significant interaction was  
120 shown, follow-up ANOVAs with Bonferroni multiple-comparisons were used. Partial  $\eta^2$  was  
121 calculated as an index of effect size for ANOVA. The significance level was set at  $P < 0.05$ .

122

### 123 **Results**

124 Figure 1 shows VA% during MVC. There was a significant sex  $\times$  joint-action interaction (F [2,  
125 52] = 3.221,  $P = 0.048$ , partial  $\eta^2 = 0.110$ ) and significant main effect of sex (F [1, 26] = 4.27,  $P$   
126 = 0.049, partial  $\eta^2 = 0.141$ ) but not of joint action (F [2, 52] = 1.198,  $P = 0.310$ , partial  $\eta^2 =$   
127 0.044). Regarding the sex difference, VA% during plantar flexor MVC in K0 was significantly  
128 higher in men than in women ( $P = 0.020$ ), whereas no significant sex difference was found for  
129 VA% during knee extensor MVC ( $P = 0.501$ ) or plantar flexor MVC in K90 ( $P = 0.086$ ). For  
130 joint action dependency, VA% during knee extensor MVC was significantly higher than that  
131 during plantar flexor MVC in K0 in women ( $P = 0.001$ ) but not in men ( $P = 0.421$ ). No  
132 corresponding differences were shown between other joint actions in each sex ( $P = 0.152$ – $0.772$ ).

133 The normalized Twitch<sub>0-50</sub> results are described in Figure 2. A significant main effect of  
134 joint action (F [2, 52] = 90.321,  $P < 0.001$ , partial  $\eta^2 = 0.776$ ) without a main effect of sex (F [1,  
135 26] = 0.376,  $P = 0.545$ , partial  $\eta^2 = 0.014$ ) or an interaction of the two factors (F [2, 52] = 0.607,  
136  $P = 0.549$ , partial  $\eta^2 = 0.023$ ) was shown. The normalized Twitch<sub>0-50</sub> of knee extension was  
137 significantly greater than those of plantar flexions for both extended ( $P < 0.001$ ) and flexed knee  
138 positions ( $P < 0.001$ ).

139

140 **Discussion**

141 The main finding of the current study was that the sex difference in VA% was shown only  
142 during plantar flexor MVC at the extended knee position. Compared with men, women showed  
143 lower VA% during plantar flexor MVC at the extended knee position. In contrast, corresponding  
144 sex difference in VA% was not observed during knee extensor MVC or during plantar flexor  
145 MVC at the flexed knee position. In addition, in women but not in men, VA% during plantar  
146 flexor MVC at the extended knee position was significantly different from that during knee  
147 extensor MVC. These results indicate that the sex difference in VA% during MVC depended on  
148 joint action.

149 The only sex difference in VA% was shown during plantar flexor MVC in K0. The  
150 normalized Twitch<sub>0-50</sub> was not significantly different between sexes for any joint action (Figure  
151 2), suggesting that the muscle fiber type composition is not a major factor for the observed sex  
152 and joint-action dependency in VA%. Co-contraction of the antagonist tibialis anterior during  
153 plantar flexor MVC might be the explainable factor for the current result. Compared with males,  
154 females exhibited higher magnitude of the tibialis anterior activation relative to medial  
155 gastrocnemius activation during the push-off phase of countermovement jumping (Márquez et al.,  
156 2017). During countermovement jumping, just before take-off, the fascicles of the medial  
157 gastrocnemius contracted quasi-isometrically (Kurokawa et al., 2003); therefore, the contraction  
158 type of the triceps surae may be partly similar between the current (i.e., isometric contraction)  
159 and previous (Márquez et al., 2017) studies. Because of reciprocal inhibition (Crone et al., 1987),  
160 co-contraction of the tibialis anterior during plantar flexor MVC could diminish the magnitude of  
161 triceps surae activation during plantar flexion. In contrast, the absence of a sex difference in

162 VA% during knee extensor MVC (Figure 1) is in line with previous studies (Krishnan &  
163 Williams, 2009; Lee et al., 2017), and the magnitude of hamstring activation as antagonists  
164 during knee extensor MVC was not different between sexes (Krishnan & Williams, 2009). Such  
165 notions may be also related to the higher VA% during knee extensor MVC than during plantar  
166 flexor MVC in K0 only in women. Taken together, a possible sex difference in the antagonist  
167 activation may account for the current sex- and joint-action differences in VA%.

168 Another possible factor for the joint-action dependency of sex difference in VA% is the  
169 corresponding differences in motor unit firing rates. It was shown that VA% during knee  
170 extensor MVC was associated with motor unit firing rates of the vastus lateralis (Knight &  
171 Kamen, 2008). A previous study failed to find a significant sex difference in the motor unit firing  
172 rates of the vastus medialis, one of the muscles of the quadriceps femoris (Tenan et al., 2013). In  
173 contrast, in an animal study, males showed more rapid firing rates than females (English &  
174 Widmer, 2003). Therefore, if the aforementioned findings are applicable to other quadriceps  
175 femoris muscles and human trieps surae, they may relate to the present VA% results.

176 The lack of significant difference in VA% between joint actions in male participants is  
177 not consistent with the previous finding of a higher value of VA% during plantar flexor MVC  
178 than during knee extensor MVC in men (Behm et al., 2002). This discrepancy may be related to  
179 the difference in participant backgrounds. We recruited untrained participants because resistance  
180 training can affect the magnitude of VA% (Ema et al., 2018). In contrast, Behm et al. (2002)  
181 examined subjects who participated in habitual resistance exercises or competitive sport  
182 activities. Although the kind of resistance training that the subjects had performed was not  
183 mentioned, it is possible that the effects of training on VA% during MVC differed between joint

184 actions, likely resulting in the higher VA% during plantar flexor MVC than during knee extensor  
185 MVC (Behm et al., 2002).

186 Previous studies demonstrated that greater muscle hypertrophy in men than in women  
187 after resistance training were accompanied by a lack of sex difference in knee extension strength  
188 gains (Lemmer et al., 2000; Melnyk et al., 2009). The previous results imply a greater neural  
189 adaptation in women than in men, because there was a negative correlation between VA% before  
190 training and the magnitude of strength improvement (Gondin et al., 2005). However, no  
191 significant sex difference in VA% during knee extensor MVC was found in the present study;  
192 therefore, it is difficult to explain the aforementioned results in terms of a sex difference in  
193 neural adaptations. In contrast, our data might suggest that the training-induced increase in  
194 plantar flexion strength can be expected to be greater in women than in men; future attempts are  
195 required to clarify this subject.

196

## 197 **Conclusion**

198 The significant sex difference in VA% was limited during plantar flexor MVC at the extended  
199 knee position, and only women showed joint action dependency in VA%. These results revealed  
200 that there is an interaction of sex and joint action for VA% during MVC.

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268 **Figure Captions**

269 **Figure 1**

270 Scatterplots showing individual data of voluntary activation (VA%) during maximal voluntary  
271 contractions of knee extension, plantar flexion at extended (K0) and at flexed (K90) knee  
272 positions. Solid line shows the mean value. \*Indicates a significant difference between joint  
273 actions. †Shows a significant difference between sexes.

274

275 **Figure 2**

276 Scatterplots showing individual data of rate of torque development of twitch torque ( $RTD_{\text{twitch}}$ )  
277 of knee extension, plantar flexion at extended (K0) and at flexed (K90) knee positions Solid line  
278 shows the mean value. \*Indicates a significant difference between joint actions.

**Table 1** (on next page)

Physical characteristics of participants.

MET, metabolic equivalent. Data are shown as mean  $\pm$  standard deviation.

Table 1 Physical characteristics of participants

□ □ □

□	□	Men (n = 14)	□	Women (n = 14)
Age	years	23 ± 4		22 ± 1
Height	cm	169.7 ± 4.4		157.6 ± 4.1
Body mass	kg	62.0 ± 6.2		51.5 ± 6.6
Physical activity	MET min/wk	3108 ± 2177	□	2836 ± 2542

MET, metabolic equivalent. Data are shown as mean ± standard deviation.



## Figure 2

Scatterplots showing individual data of rate of torque development of twitch torque ( $RTD_{\text{twitch}}$ ) of knee extension, plantar flexion at extended (K0) and at flexed (K90) knee positions.

Solid line shows the mean value. \*Indicates a significant difference between joint actions.

