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Surface electromyograms of agonist and antagonist muscles during force development of maximal isometric exercises – effects of instruction

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Abstract Surface integrated electromyograms (iEMG) of agonist and antagonist muscles were studied during the rising phase of maximal isometric efforts (elbow flexion, unilateral and bilateral leg extension) to explain the difference in maximal rate of force development (MRFD) with a *hard-and-fast* instruction (instruction I) and a *fast* instruction (instruction II). Force and EMG were simultaneously recorded in 24 athletes and iEMG were computed at MRFD and during different phases of force development (P_{0-25} , P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100}). A two-way ANOVA for repeated measures (muscle \times instruction) showed that the value of iEMG at MRFD was significantly higher with instruction II for elbow flexion, unilateral and bilateral leg press exercises ($F > 4.9$; $P < 0.04$). The effect of instruction upon iEMG of the agonist muscles corresponding to the different phases of the force development was significant for elbow flexion ($F = 4.2$; $P < 0.05$ unilateral ($F > 6.4$; $P < 0.02$) and bilateral leg extension ($F > 9$ and $P < 0.006$ for soleus and vastus lateralis; but $F = 3.2$ and $P = 0.08$ for vastus medialis). There was a significant interaction between instruction and phase of force development ($F > 2.6$; $P < 0.05$): iEMG was significantly higher with instruction II at the beginning of force development (P_{0-25}) for all the muscles (except the soleus muscle during the bilateral leg exercise) but not at higher force (P_{75-90} and P_{90-100}). The steeper force development with instruction II can be explained by the better activation

of the agonist muscles at the beginning of force development. A lower co-activation of the antagonist muscles does not explain the improvement in MRFD as the iEMG of the antagonist muscles was not lower with instruction II but was proportional to the activation level of the agonist muscle.

Keywords Isometric contraction · Electromyography · Muscle physiology

Introduction

Several studies have shown the importance of the instruction on the measurements of maximal isometric voluntary force (MVF) and the rate of force development. First, the effect of instruction has been studied for small muscle groups with a large cortical representation (somatotopic map) and involved in precise voluntary movements (Bemben et al. 1990; isometric hand-grip exercises). The maximal rate of force development (MRFD) was significantly slower when the subjects were instructed to produce their maximal peak force as fast as possible (*hard-and-fast* instructions) than when they were instructed to focus on the MRFD without any concern for the peak force (*fast* instruction). Christ et al. (1993) confirmed these results for different small-muscle groups of the upper limbs (finger flexors, thumb extensors, elbow extensors and flexors) and the lower limbs (ankle dorsi-flexors and plantar flexors). A recent study (Sahaly et al. 2001) indicates that the effect of the instruction upon MRFD is similar for muscle groups with different volumes (elbow flexors, one or both legs), cortical representations (arms and legs) and uses (take-off and lead legs, unilateral and bilateral leg extension).

Rate of force development should depend on nervous factors as MRFD is lower during voluntary contractions than during electrical stimulations (Kots 1986; Koryak 1998). Since the pioneering study by Adrian and Bronk

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(1929), it is known that the gradation of muscle force is the result of an increasing firing rate and additional motor unit recruitment. Small distal muscle groups mainly rely on an increase in firing rate for high force development whereas additional motor unit recruitment could be the main factor explaining the production of high force level in proximal muscle groups (Kukulka and Clamann 1981).

The effect of instruction upon MRFD is likely to be the expression of differences in muscle activation pattern and several explanations can be proposed. A higher rate of force development could be the result of a lower activation of the antagonist muscles in addition to a stronger activation of the agonist muscles. Indeed, co-activation of antagonist muscles is often observed even during isometric exercises. However, the magnitude of this co-activation can be modified, for example, after a strength training programme (Carolan and Cafarelli 1992) and, consequently, could be sensitive to instruction.

At the start of a maximal isometric effort, intramuscular recording of isolated single motor units shows that firing rate was sometimes higher than the frequency necessary for a fused tetanus (Marsden et al. 1971; Grimby et al. 1981), which was assumed to improve the rate of force development by a faster rise in cytosolic calcium without increasing peak force. In this case, surface integrated electromyograms (iEMG) could be maximal at the beginning of the rising phase of a maximal isometric effort. In theory, the improvement in MRFD with a *fast* instruction could be the result of a level of activation higher than the level corresponding to MVF.

In the present investigation, we studied EMG during the rising phase of maximal isometric efforts to explain the effect of instruction (*hard-and-fast* instruction versus *fast* instruction) upon MRFD. As activation processes (recruitment and firing rate) probably depend on muscles, we studied the instruction effect upon EMG during the rising phase of maximal isometric exercises for muscles groups which differ with regard to muscle mass (elbow flexor, unilateral and bilateral leg extensors), location (proximal or more distal muscles) and usage (arm versus leg). EMG of antagonist muscles were recorded in addition to EMG of agonist muscles as co-activation could modify the rate of force development.

Methods

Subjects

iEMG measurements were performed on 24 out of the 26 healthy young male volunteers of the national Tunisian athletic team (sprinters, middle-distance and long-distance runners; walkers; long, high and triple jumpers; pole vaulters; and decathletes) who participated in the study on the effects of instruction upon MRFD (Sahaly et al. 2001).

Materials

Leg extensors and elbow flexors forces were assessed with a device described in a previous paper (Sahaly et al. 2001). It consisted of a metallic frame which enabled the adjustment of the knee angle (120°) by means of a sliding seat and the harnessing of the trunk and the pelvis with low compliance straps. The leg press consisted of a foot-platform fixed on the frame by three strain-gauge transducers (FE MAG-35, 7,500 N). The foot-platform was placed at about the same level as the seat of the chair. Leg extension force was measured during bilateral and unilateral (left and right leg separately) maximal effort with a 120° knee extension and a 60° plantar flexion.

Maximal isometric elbow flexion of the right arm was measured with the subjects seated in the same position with the right arm secured by bands. The hand was kept in a position midway between pronation and supination and the elbow joint was flexed at 90°. Shoulder rise and antepulsion during right elbow flexion were restricted by a cup and a strap. A low compliance strap passing around the right wrist was linked by means of a toggle joint to a strain-gauge transducer (FE MAG-35, 1,000 N) screwed on the metallic frame.

EMG signals were collected by means of pairs of Ag–AgCl surface electrodes with approximately a 40-mm distance between the centres of the electrodes. EMG signals were amplified by means of an amplifier designed and made by the computer and electronics department of our university (six differential channels, 10⁹ Ω input impedance, 110 dB common-mode rejection, bandwidth 10–5,000 Hz). Electrodes were placed over the belly of the muscles along their longitudinal axis after skin preparation. The EMG activities were recorded simultaneously with the signal from the force transducer during elbow flexion [biceps brachii (BB), brachio radialis (BR) and triceps brachii (T)] and during unilateral and bilateral leg press [vastus lateralis (VL), vastus medialis (VM), soleus (S) and biceps femoris (BF), Fig. 1]. There were no EMG measurements of the left leg muscles.

All the iEMG records were collected with the same electrodes and the same amplifier gains during all the exercises. If one electrode came unstuck, all the EMG data collected on the subject were excluded. This procedure explains why the results of only 24 subjects were taken into account in the present study whereas the results of 26 athletes were presented in the paper on the effects of instruction upon MRFD (Sahaly et al. 2001).

Force and amplified EMG signals were digitised by two data acquisition cards (Candibus, Toulouse, France and Eurosmart, Marne-la-Vallée, France) with a sampling rate equal to 1,000 Hz for each data acquisition card, and data were stored on a PC. Calculations of MVF and MRFD, and digital rectification and integration of EMG data were performed with the same computer.

Exercise protocols

The subjects were carefully familiarised with test procedures of voluntary force production during several warm-up contractions, which preceded the execution of the tests. Each subject performed four exercises in the same session: elbow flexion of the right arm, right leg extension, left leg extension and bilateral leg extension. The order of the different exercises was randomised. As there were no EMG data for the left leg, iEMG results during unilateral and bilateral leg press exercises concerned the right leg only. Force data (MVF and MRFD) collected during left leg extension and the other exercises were presented in a previous paper (Sahaly et al. 2001).

In order to make the contraction as isometric as possible and to avoid the effect of a shock upon force measurement, the subjects were instructed to exert slight tension on the strap passing around the wrist (elbow flexion) or slight pressure on the foot-platform (leg press exercises, see Fig. 1) before they were instructed to exert a maximal effort. Otherwise, the subjects could slightly extend the elbow before flexing it (or slight traction of the leg before extending it for the leg press exercises) because harnessing of the body segments is never perfect. In this case, the force measured at the beginning of the maximal effort would not correspond to an isometric

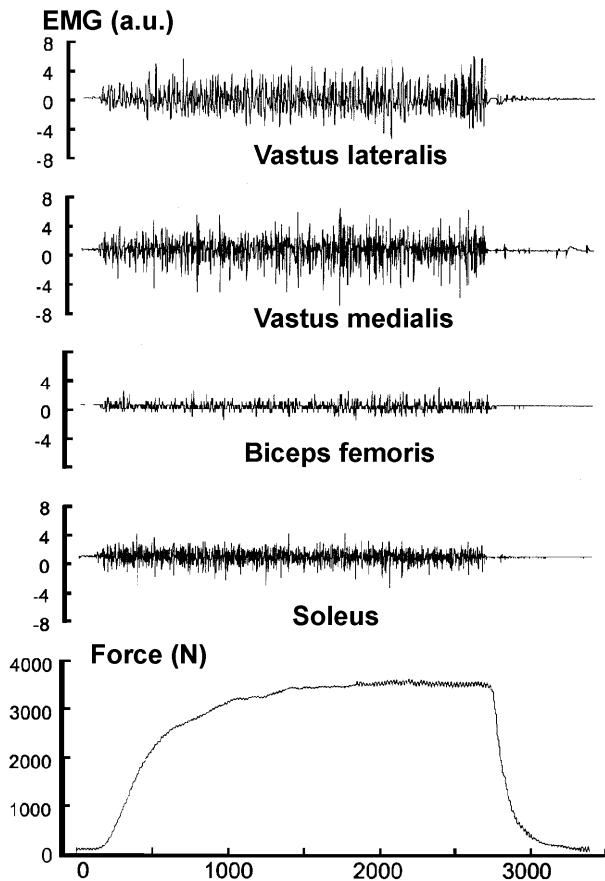


Fig. 1 Simultaneous recording of force and the surface electromyograms (EMG) of leg muscles during a maximal unilateral leg press exercise with instruction I (*hard-and-fast* instruction). Note that the subject exerts a small force on the foot-platform before maximal effort

contraction and would be altered by the transformation of a small amount of kinetic energy into an elastic potential energy as in a shock.

Two instructions were used for each exercise:

1. The “usual” *hard-and-fast* protocol (instruction I). In the first protocol, the subjects were instructed to produce their MVF as hard and fast as possible (instruction I).
2. protocol (instruction II). In the second protocol (instruction II), the subjects were instructed to provide the most “explosive” force, that is to concentrate on the fastest contraction without concern for achieving maximal force. However, after approximately 1 s of effort, they were encouraged to extend their effort and to reach maximal isometric strength before relaxing. The order of instructions I and II was randomised.

The subjects were not given any feedback on their performances but were verbally encouraged to produce their maximal effort during both instructions.

In both instructions, the subjects performed three trials for each exercise. The subjects recovered for 5 min between the trials, and 30 min between the different exercises (left leg, right leg, bilateral leg extension and elbow flexion).

Data analysis

The MVF corresponding to instructions I and II was defined as the highest peak force recorded during one trial with the same

instruction. The MRFD was equal to the steepest slope calculated in a 20-ms period.

For both instructions, EMG data processing was performed for the best trials only, which were chosen according to two criteria: either the higher MRFD or the higher MVF. However, the effects of instruction upon iEMG were similar with both criteria and only the results corresponding to the best MRFD are reported in the present paper.

EMG data were rectified and integrated during the corresponding phase and divided by the duration of the phase. Consequently, iEMG in the present study corresponded to average iEMG. Since all the iEMG were recorded with the same amplifier gain and the same electrodes in a single session, the effect of instruction on muscle activation was studied by comparing iEMG expressed as arbitrary units.

First, iEMG corresponding to MRFD (iEMG at MRFD) were computed by integrating EMG during a 128-ms window around MRFD (64 ms before and 64 ms after MRFD).

Second, force development was divided in different phases related to MVF: 0–25 (P_{0-25}), 25–50 (P_{25-50}), 50–75 (P_{50-75}), 75–90 (P_{75-90}) and 90–100% peak force (P_{90-100}). In contrast to MRFD, which was significantly steeper with instruction II, MVF was not significantly different with instructions I and II (Sahaly et al. 2001). Consequently, iEMG measured during P_{0-25} , P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100} corresponded to the same ranges of force for both instructions.

Statistics

Means, SD and SEM were computed according to conventional statistical methods. A two-way ANOVA (instruction \times muscle groups) for repeated measures and a post hoc test (Bonferonni’s test) were used to test for the effects of instruction and muscle and their interaction.

The relationship between activation pattern of the different muscles were studied by regressions of the iEMG corresponding to the different phases of force development (P_{0-25} , P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100}). Multiple linear regressions with a dummy variable corresponding to instruction were used for testing differences in these relationships with instructions I and II. For example, the relationship between iEMG of the VL and S muscles with instructions I and II was calculated as follows: $S = a + (b \times VL) + (c \times D)$, where D is a dummy variable, equal to 0 for instruction I and 1 for instruction II. Hence, if the Y -intercept is significantly different, the relationships would be: $S = a + (b \times VL)$, for instruction I and $S = (a + c) + (b \times VL)$, for instruction II.

Significance level was set at $P < 0.05$.

Results

iEMG at MRFD

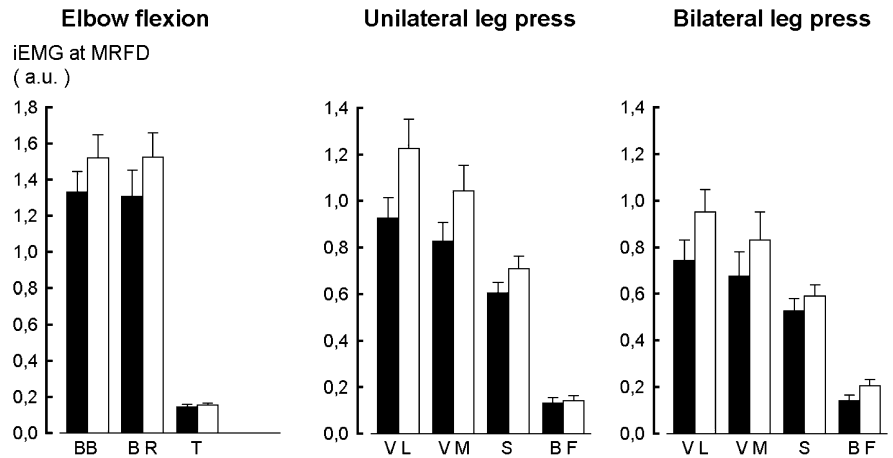
In all cases, MRFD was reached during P_{25-50} .

The value of iEMG at MRFD (Fig. 2) was significantly higher with instruction II for elbow flexion ($F = 4.9$, $P = 0.038$, Fig. 2), unilateral leg extension ($F = 14$, $P < 0.001$), and bilateral leg extension ($F = 6.1$, $P = 0.02$).

The interaction between instruction and muscle was significant for unilateral leg extension ($F = 4.9$, $P < 0.004$). The effect of instruction upon iEMG at MRFD was significant ($P < 0.001$) for VL and VM but not for S ($P = 0.10$) and BF muscles ($P = 0.871$).

In contrast, the instruction \times muscle interaction was not significant for elbow flexion ($F = 1.7$, $P > 0.05$) and bilateral leg extension ($F = 1.95$, $P = 0.13$).

Fig. 2 Effect of instruction upon integrated electromyograms [*iEMG*; means and SEM in arbitrary units (*a.u.*)] corresponding to maximal rate of force development (*iEMG* at *MRFD*) for different muscles during elbow flexion [biceps brachii (*BB*), brachio-radialis (*BR*) and triceps brachii (*T*)], unilateral and bilateral leg press exercises [vastus lateralis (*VL*), vastus medialis (*VM*), soleus (*S*) and biceps femoris (*BF*)]. *Black and white vertical bars* correspond to instructions I and II, respectively



iEMG at P_{0-25} , P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100}

The values of *iEMG* corresponding to the different phases (P_{0-25} , P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100}) of the force development are presented in Fig. 3.

The effect of the phase of force development upon *iEMG* was significant for both instructions and all the muscles with the exception of the S muscle (see below).

The effect of instruction was significant for all the muscles and the different exercises with the exception of the BF during unilateral leg extension ($P=0.063$).

The interaction between instruction and phase of force development was significant for all the muscles and exercises with the exception of the VM during bilateral leg extension ($F=3.3$; $P=0.08$). The value of the *iEMG* was significantly higher with instruction II (Bonferonni's test, $P<0.05$) at P_{0-25} but not at higher forces (P_{50-75} ,

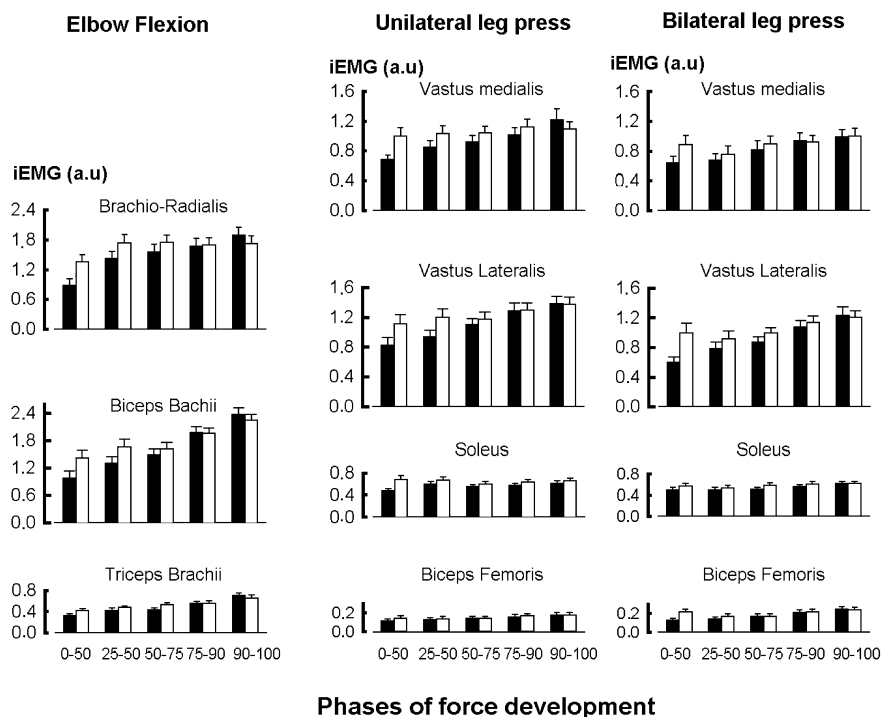
P_{75-90} and P_{90-100}) for all the muscles but the BF. The value of the *iEMG* at P_{0-25} was 10% higher with instruction II for the BF, but this difference was not significant.

This interaction between phase and instruction was obvious for the S muscle during unilateral leg extension. Indeed, the value of S muscle *iEMG* with instruction II was even maximal at P_{0-25} and not significantly different from *iEMG* at P_{25-50} , P_{50-75} , P_{75-90} and P_{90-100} , whereas P_{0-25} with instruction I was significantly lower than P_{75-90} and P_{90-100} .

Co-ordination pattern between muscle groups

For bilateral leg extension, instruction did not influence the relationships between VL *iEMG*, and *iEMG* of VM,

Fig. 3 Effect of instruction upon *iEMG* (mean and SEM in *a.u.*) corresponding to the different phases of the force development (0–25 to 90–100 peak force) during elbow flexion, unilateral and bilateral leg press exercises. *Black and white vertical bars* correspond to instructions I and II, respectively



S and BF. The activation levels of VL and the other muscles were linearly related and the regression lines corresponding to instructions I and II were almost superimposed (Fig. 4) and not significantly different.

For the unilateral leg press, the regressions between the iEMG of VL and BF during force development with both instructions were almost superimposed. The difference in the relationships between VL and VM during force development with instructions I and II (Fig. 4) was not large enough to be significant ($P=0.35$). On the other hand, the regressions between iEMG of VL and S at the different phases of force development during unilateral leg press (Fig. 4) were significantly different ($P=0.025$) for instructions I and II:

- $S=0.43+0.11\text{ VL}$, for instruction I.
- $S=0.51+0.11\text{ VL}$, for instruction II.

For elbow flexion, the difference in the relationships between BB and BR during force development with instructions I and II (Fig. 4) was not large enough to be significant. The activation of the antagonist muscle (T) was linearly related ($r>0.94$) to the activation of the most proximal agonist muscles (BB) and was almost equal with both instructions:

- $T=0.0640+0.259\text{ BB}$ ($r=0.99$), for elbow flexion with instruction I.
- $T=0.0635+0.259\text{ BB}$ ($r=0.95$), for elbow flexion with instruction II.

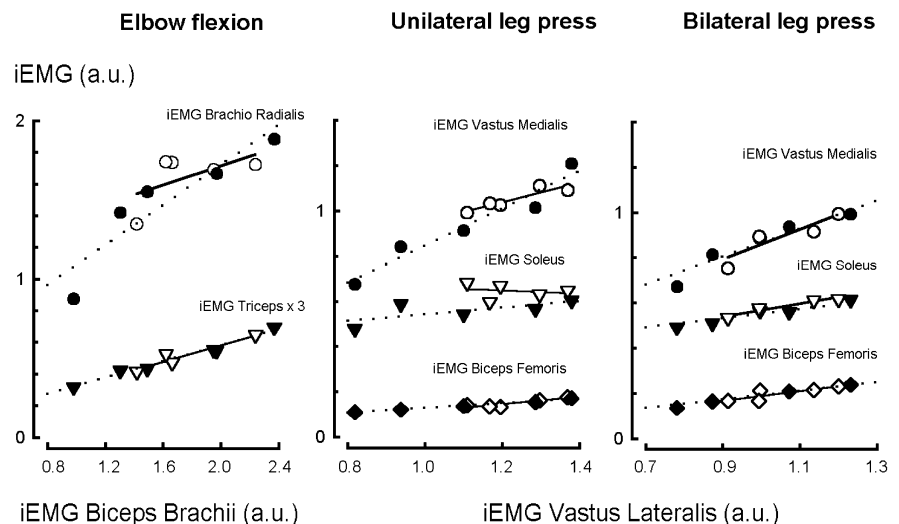
Discussion

The BF consists of two heads: a short mono-articular head (caput brevis) which is a knee flexor, and a long bi-articular head (caput longum). The bi-articular head of the BF muscle is an agonist of the quadriceps muscle in some exercises such as cycling and jumping. Nevertheless, it is likely that this muscle was a knee flexor in our leg-press protocol and consequently was an antagonist of the quadriceps muscle. The present study indicates

that the steeper force development with instruction II cannot be explained by a lower co-activation of the antagonist muscles. Indeed, the iEMG of the T and BF were even significantly higher with instruction II at MRFD during elbow flexion and knee extension, respectively.

A supramaximal activation (an activation at a frequency higher than necessary for a fused tetanus) should improve the rate of force development. The higher rate of force development with instruction II cannot be explained by this mechanism because the iEMG was not maximal at the beginning of the force development (iEMG at P_{0-25}) for all the muscles except the S during unilateral leg press. This exception could be linked to the fact that the S was the most distal muscle. Tanji and Kato (1972) observed in man that firing rates of many single motor units of the abductor digiti minimi muscle rose to very high frequencies (70–90 Hz) and then fell rapidly to 10–20 Hz during maximal isometric effort when the force was developed as quickly as possible. This phenomenon was not observed and the firing rates rarely exceeded 40 Hz when the same subjects exerted maximal isometric efforts up to maximal force but with gradual increases in tension (Tanji and Kato 1972). Similarly, the short burst of high firing rate (150 Hz) at the start of voluntary isometric efforts “as powerful as the subject can make” (Marsden et al. 1971) has been observed in small and distal hand muscles such as the adductor pollicis. Moreover, high transitory firing rates at the very beginning of maximal voluntary effort (Grimby et al. 1981) have also been observed in single motor units of the tibialis anterior muscle, an antagonist of the S muscle. De Luca et al. (1982) observed bursts of increasing firing rate during long-lasting isometric contraction at a high percentage of MVF in the first dorsal interosseous muscle but not in the deltoid muscle. Consequently, the occurrence of short bursts of high firing rate at the beginning of an isometric exercise with instruction II is a possible interpretation of the difference in iEMG at the beginning of force development between instructions for the S muscle. But this explanation cannot be based on

Fig. 4 Relationships between iEMG of the biceps brachii muscle, brachio-radialis, and triceps brachii muscles during elbow flexion, and the vastus lateralis, vastus medialis, soleus, and biceps femoris during unilateral and bilateral leg press exercises. Black symbols and dotted lines correspond to instruction I. Open symbols and continuous lines correspond to instruction II. Each symbol corresponds to the mean of the iEMG measured during the different phases (P_{0-25} to P_{90-100}) of force development



surface EMG as in the present study. Moreover, the fact that soleus iEMG at P_{0-25} was higher than iEMG at P_{90-100} did not prove that iEMG at P_{0-25} was maximal and, even less, supramaximal.

The effect of instruction upon MRFD could be explained by a better activation at the beginning of force development as iEMG was higher at P_{0-25} with instruction II than with instruction I. These higher values of iEMG at the beginning of force development with instruction II do not mean that muscle activation was optimal for force development with this protocol. It would have been interesting to compare force development during electrical stimulations and MRFD with instructions I and II. Indeed, when compared with an electrical stimulation, MRFD during voluntary effort with a *hard-and-fast* instruction has been found to be submaximal (Kots 1986, Koryak 1998). It should be mentioned that the athletes of the present study were not habituated to isometric exercises and the effect of instructions upon iEMG during maximal force development might be less after specific training because it has been reported that explosive-type strength training improves MRFD (Häkkinen et al. 1985).

In conclusion, the present study shows that the steeper force development with a *fast* instruction (instruction II) compared with a *hard-and-fast* instruction (instruction I) cannot be explained by a lower co-activation of the antagonist muscles as the iEMG of the antagonist muscles were even higher with instruction II. A supramaximal activation could not explain a higher MRFD with instruction II because the iEMG was not maximal at the beginning of the force development. Moreover, the pattern of co-operation between the investigated muscles did not depend on instruction, with the possible exception of the S muscle. The higher value of MRFD could be explained by better activation of the agonist muscles at the beginning of force development as iEMG was higher with instruction II for all the muscles.

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