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During Slow Wrist Movements, Distance Covered Affects EMG at a Given External Force

Tom G. Welter and Maarten F. Bobbert

This study investigates the hypothesis that EMG measured from a muscle at a given force, length, and low-shortening velocity depends on the contraction history, specifically the distance over which the muscle has shortened. Slow linear horizontal wrist movements (3 cm/s) involving shoulder and elbow rotations towards a test position of 90° elbow flexion were performed. REMG was measured at the test position after wrist displacements over 6.5 and 13 cm. Muscle contraction speed was below 1% of maximum. A constant force (25 N) causing flexion torque in the elbow was exerted by the wrist. Inertial load was minimal. Two main elbow flexors (biceps caput longum and breve) showed significantly higher (14 and 24%) concentric REMG after 13-cm wrist movement than after 6.5-cm. Eccentric EMG did not differ between the 6.5- and 13-cm conditions. It is concluded that adaptation of muscle activation is required to counteract the effects of contraction history on the force producing capacity of the muscle.

Key Words: wrist movement, flexion torque, contraction

Introduction

The human arm is a redundant system, and an infinite number of muscle activation patterns could lead to the same movement outcome. By measuring muscle activation during movement, it is possible to study the choice that the nervous system has made in mastering these degrees of freedom with the ultimate purpose of revealing control strategies. By *control strategy* we mean the method of selecting muscle activation based on some kind of criterion. Examples are strategies that minimize muscle fatigue (Dul, Johnson, Shiavi, & Townsend, 1984) or movement jerk (Hogan, 1984), or a control strategy that selects muscle activation depending on the movement and force direction (van Ingen Schenau, Pratt, & Macpherson, 1994).

Recently, Bolhuis et al. (van Bolhuis, Gielen, & van Ingen Schenau, 1998) measured electromyograms (EMG) of muscles spanning the elbow joint during

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slow linear wrist movements at constant velocity (1.5 cm/s). They observed that mono-articular muscles displayed their largest rectified EMG (REMG) amplitude for wrist movements in a specific direction, which they called the "preferred movement direction." It seemed that this preferred movement direction corresponded to the movement directions that resulted in the highest muscle shortening velocity. How should these findings be interpreted? Van Bolhuis et al. (1998) argued that because of their experimental design, muscle contractile properties could not have been the reason for such large REMG amplitude variations. Consequently, they interpreted the preferred movement direction as a reflection of a control strategy used by the nervous system, preferentially selecting muscles that show the highest muscle shortening velocity.

Before the activation changes observed in the study by Van Bolhuis et al. (1998) can be interpreted as a reflection of control strategies, we must be sure that they cannot be interpreted otherwise—for instance, as compensation for the effects of movement direction on force producing capacity of the muscles. This possibility was further investigated by Welter et al. (Welter et al., 2000). Using a 3D shoulder-arm model for the calculation of muscle contraction velocities and a muscle model for the calculation of the corresponding muscle maximum forces, it was shown that (a) the preferred movement direction did indeed coincide significantly with the movement direction that resulted in the largest muscle shortening, and (b) in line with the assumption of Van Bolhuis et al. (1998), the force velocity relationship could not account for the relatively large REMG changes as a function of movement direction because the effect of differences in contraction velocities on force producing capacities were too small. This would justify the interpretation that the preferred movement direction results from a control strategy. However, Welter et al. (2000) argued that when REMG at a given force and length is correlated to muscle shortening velocity, it might just as well be related to the distance of muscle shortening covered before reaching the test position. In other words, REMG changes could also have been an adaptation to history dependence of muscle force.

The phenomenon of history dependence of muscle force has been demonstrated with direct measurements of force of electrically stimulated muscles in vitro (Abbott & Aubert, 1952; Herzog, Leonard, & Wu, 1998) or in situ (de Ruiter, de Haan, Jones, & Sargeant, 1998). By history dependence, we refer to the experimentally observed phenomenon of decreased force generating capacity of muscles after different amounts of muscle shortening, and increased capacity after lengthening (Herzog, 1998). It has been suggested in literature that the effect of history dependence on muscle force is large enough to be of significance in naturally occurring muscle contractions (Edman, 1988). This suggestion was investigated only once in maximal voluntary contractions of the quadriceps, and it was confirmed that force could indeed be depressed after shortening (Lee, Suter, & Herzog, 2000). It is not known, however, whether force depression also occurs during voluntary submaximal contractions. For instance, the influence of history dependence may be limited because a short interruption of 200 ms of the maximal electrical stimulation of muscles was shown to abolish the history dependence effects completely (de Ruiter et al., 1998). In voluntary submaximal activation, individual muscle fibers may be switched on and off, causing a "reset" of the force generating capacity of these muscle fibers.

The purpose of this study was to investigate whether changes in REMG in the experimental set-up used by van Bolhuis et al. (1998) and Welter et al. (2000)

can be interpreted as compensations for the history dependence of the force generating capacity of muscles. The following hypotheses will be tested: (a) Concentric contractions over longer distances reveal higher REMG than concentric contractions over shorter distances; (b) eccentric contractions over shorter distances reveal higher REMG than eccentric contractions over longer distances. To test these hypotheses, the activity of arm flexor muscles was measured at constant external force, muscle length, and contraction speed, after contractions over small and larger shortening and lengthening distances in a set-up that was identical to that of Welter et al. (2000).

Methods

Outline of the Experimental Set-Up

Ten healthy subjects (2 female, 8 male, aged 23 to 34) with no known neurological disorder participated in the experiments after giving informed consent. The experimental set-up was the same as in our previous study (Welter et al., 2000). Subjects were seated at a table with the arm abducted 90° (upper arm in line with the shoulders) and the elbow flexed 90° in the horizontal plane (Figure 1). The forearm was in a position approximately halfway between full supination and full pronation. This was the reference position at which all measurements were made. To avoid fatigue, the forearm was suspended from the ceiling. The shoulder was prevented from moving back and forth by a brace mounted on the back of the chair. A horizontal force (20 N for female subjects and 25 N for male subjects) extending the arm was applied using a rope attached to a bracelet on the subject's wrist (see Figure 1). Very slow wrist displacements, involving shoulder and elbow rotations, were made in a straight line at a speed of 3 cm/s. This low constant movement velocity abolished the inertial load of the arm during the trials. The wrist movements toward the reference position were made in two opposite directions and over two distances, resulting in four movement conditions (see Figure 1):

SF: Elbow flexion with wrist movement over a small distance (6.5 cm) towards the shoulder (SF: small amplitude of flexion).

SE: Elbow extension with wrist movement over this small distance away from the shoulder (SE: small extension).

LF: Elbow flexion over a larger distance of 13 cm (LF: large flexion).

LE: Elbow extension over this larger distance (LE: large extension).

These movement directions corresponded roughly to the movement directions from Welter et al. (2000) that yielded the highest muscle shortening and lengthening velocities (according to a 3D arm model simulation) of the muscles of interest. EMG was recorded from the mono-articular elbow flexor brachioradialis (BRD), and two bi-articular elbow flexors, biceps caput breve (BIB), and biceps caput longum (BLO). Additionally, the activity of one mono-articular elbow extensor muscle, triceps caput laterale (TLA), was recorded to investigate the possible presence of co-contractions (see below). In the movement trials, the REMG was averaged over 2 s, during which the arm passed through the reference position. It was then scaled to the mean REMG for that muscle over all trials in the experiment.

Figure 1 — Schematic representation of the experimental set-up seen from the top. The subject is sitting with his elbow 90° flexed in the horizontal plane. This was the reference position at which all measurements were done. A force is applied at the wrist with a mass that is hanging from a rope running over a pulley. BRD, BIB, BLO, and TLA schematically indicate the muscles from which EMG was recorded. The arrows originating from LF, SF, SE, and LE indicate movement directions and distances of wrist movement. Movements were started from the positions indicated with the black dots and proceeded along the dashed line. F: Arrow indicating the force exerted by the subject.

Task

An almost constant external force on the wrist was generated by suspending a mass (2 kg for females, 2.5 kg for males) from a rope running over two pulleys. Friction in the pulleys caused force variations smaller than 5% depending on movement direction. Small variations (accelerations and decelerations) in movement speed caused force variations of 2.5%. Target position as a function of time was indicated to the subject by a cable with markers revolving about two small vertical axes (height 1 cm, diameter 0.5 cm) 45 cm apart. Subjects could match their wrist movement to the target movement by simply following it with a small antenna pointing downward from the wrist to one of the markers on the revolving cable.

Protocol

Each trial consisted of one wrist movement from start to end point. On command, the subject positioned the wrist at the starting position indicated in Figure 1. While the subject waited for the command to start moving along the indicated trajectory, the EMG recording was started, after which the weight was added over a period of 2–3 s. When the weight was fully supported by the subject, the command was given to start moving. Movements were made along a straight line in the short distance conditions from approximately 6.5 cm before to 6.5 cm past the reference position and, in the long distance conditions, from 13 cm before to 6.5 cm past the reference position. Subjects were instructed to make smooth movements without unnecessary co-contractions in elbow extensor muscles. To facilitate this, the velocity of movement (3 cm/s) was increased compared to the previous study (1.5 cm/s). In terms of muscle fiber contraction velocity, this change is comparable to an increase in peak velocity from 0.4% to 0.8% of the maximum contraction speed. These percentages are calculated as the ratio between the actual contraction velocity and the maximum contraction velocity $[(0.0374 \text{ fiber lengths/s}) / (10 \text{ fiber lengths/s}) \approx 0.4\%, 2 \times 0.4\% = 0.8\%$, see Welter et al. (2000), their Table 2 and Figure 3]. Although it might be speculated that contraction velocities for BLO and BIB differ considerably due to their different moment arms about the shoulder joint, calculations with a 3D shoulder-arm model (see Welter et al., 2000) showed that contraction velocities were almost the same. For each of the four conditions, 6 trials were performed, resulting in a total of 24 movement trials. To avoid systematic effects of fatigue on the results, the trials were performed in random order. After the movement trials, a static trial was performed to obtain a reference value for normalization of TLA REMG: EMG was recorded from TLA with a force direction 180° opposite to the force direction in the movement trials.

EMG

Surface EMG was recorded from four muscles (Figure 1). Electrodes (Ag/AgCl electrodes, Medi-Trace, Pellet 1801, diameter 1 cm, inter-electrode distance 2.5 cm) were placed on the muscle belly parallel to the direction of the muscle fibers. REMG values for each trial were obtained by averaging the rectified EMG signal over a period of 2 s, from 1 s before to 1 s after the wrist passed through the reference position. REMG for BRD, BIB, and BLO was then scaled to the mean activation level for each muscle over all trials in the experiment. Group mean REMG level for an experimental condition was obtained by averaging the mean values (from six trials) of the 10 subjects. Previous work (van Bolhuis et al., 1998; Welter et al., 2000) has shown that TLA and triceps caput longum show approximately the same variations in activation. For the force and movement directions used in the present study, activity of the extensor muscles was negligible. Therefore, TLA activity was taken to represent activity of all elbow extensors. Activity of TLA was scaled to the activity during the static trial.

Statistical Analysis

Differences in REMG between the four conditions were tested for statistical significance using a single factor ANOVA for repeated measurements, followed by a Newman-Keuls post hoc test (Winer, 1971).

Results

Figure 2 shows rectified and moving window (250 msec) averaged EMG traces of BIB for all concentric trials (LF, dotted lines, SF, solid lines) of 1 subject. EMG traces are aligned at the moment that the reference position was reached ($t = 0$). It can be seen that REMG was higher in the measurement period (to the right of the first vertical solid line) in LF than in SF. The duration of the trials differs in length due to different movement times and the “pre-movement” times between the start of the recording and the command to start moving. The initial build up of REMG (4–5 s) is due to the fact that the load is gradually increased while the subject kept his arm in a fixed position. Movement occurs in the last 3 s (SF) and 5 s (LF) of the curves. The traces are typical in the sense that all subjects had higher REMG in LF than in SF, starting from the onset muscle activity. However, the steepness and angle of the slope of the curves before and during the averaging period varied between subjects.

Figure 3 shows the mean REMG values ($\pm$ SEM, standard error of the mean) of each muscle in the four experimental conditions. Results of the statistical tests of differences between conditions are presented in Table 1.

Figure 2 — Rectified and moving window (250 msec) averaged REMG of BIB for all concentric trials (LF, dotted lines; SF, solid lines) of 1 subject. REMG traces are aligned at $t = 0$ (vertical line) the instant that the reference position was reached. Vertical axis: EMG in arbitrary units. Horizontal axis: time before reaching the reference position. REMG was averaged over 2 s from 1 s before the reference position was reached (left vertical line) to 1 s after the reference position was reached (right end of the graph). LF traces are longer than SF traces because the movement lasts longer. The traces for one condition do not have the same length because the time between the (manual) start of EMG recording to the start of the movement varied a little from trial to trial.

Figure 3 — Mean REMG levels for each muscle in the four movement conditions normalized to the mean activity over all conditions. Error bars indicate standard error of the mean. SF and LF: arm flexion (concentric contractions of elbow flexor muscles) over short (6.5 cm) and larger (13 cm) distances respectively. SE and LE: arm extension (eccentric contractions of elbow flexor muscles) over short and larger distances respectively. It can be seen that (a) concentric contractions (SF and LF) produce significantly higher EMG levels (marked with +) than the eccentric contractions (SE and LE), (b) flexion over larger distances (LF) produces significantly higher REMG values (marked with *) than flexion over short distances (SF), and (c) eccentric contractions do not reveal different REMG levels in the short and long distance conditions. The activity of elbow extensor TLA was negligible and may be due to cross talk from flexor muscles.

A clear difference was found between the flexor muscle REMGs in concentric and eccentric contractions. It can be seen in Figure 3 that for all flexor muscles, concentric REMG (SF and LF) is significantly higher (marked with +) than eccentric REMG (SE and LE). P values for these concentric-eccentric REMG differences are presented in Table 1, column 4. From Table 1, column 3, we can see that REMG was higher in SF than in SE, and higher in LF than in LE. Overall, the concentric contractions showed a 46% higher REMG than the eccentric contractions.

Figure 3 shows that the mean REMG in the concentric contractions is higher in LF than in SF for all muscles. However, the difference was only significant for BIB and BLO (Table 1, column 4) where REMG was 24% and 14% higher in LF, respectively (Table 1, column 3). These results confirm, for two muscles, the first hypothesis that in concentric contractions, REMG should increase with the shortening distance covered before reaching the reference position.

No statistically significant differences in REMG were found between short distance eccentric contractions (SE) and long distance eccentric contractions (LE,

Table 1 Significance of Selected Differences in Rectified EMG Level

Muscle	Cond.	%	<i>P</i> value
BRD	LF > SF	—	Ns
	SE > LE	—	Ns
	SF > SE	69.4	< .01
	LF > LE	77.2	< .01
BIB	LF > SF	24.1	< .05
	SE > LE	—	Ns
	SF > SE	32.5	< .05
	LF > LE	50.7	< .01
BLO	LF > SF	14.3	< .05
	SE > LE	—	Ns
	SF > SE	17.0	< .05
	LF > LE	27.8	< .01
TLA	LF > SF	—	Ns
	SE > LE	—	Ns
	SF > SE	53.7	< .05
	LF > LE	53.4	< .01

Note. Cond: This column indicates from which two conditions the difference is tested. For example, LF > SF means: test whether the REMG level is significantly higher in condition LF than in condition SF. %: The difference between the first and second condition expressed as percentage of the first. For example, row 3, column 3: BRD activity in condition SF is 69.4% higher than in condition SE. *P* value: Indicates the statistical significance of the tested difference. Ns: Not significant.

see Table 1, column 4). There seems to be no support for the second hypothesis: that in eccentric contractions REMG should increase with decreased shortening distance.

Needless to say, changes in agonist REMG can only be interpreted in terms of muscle contractile properties or muscle co-ordination strategies if they are not due merely to different levels of co-contraction of antagonistic muscles between the flexion and extension conditions. Two important features may be noted with respect to the measured REMG from TLA. First, the activity of TLA was low compared to the flexor muscle activity, between 5% and 10% of the activity during static arm extension against the external force (Figure 3). Second, the changes in TLA activity were much smaller than the changes in the flexor muscles. TLA changes were of the order of 5% and could never have caused the 46% overall change in flexor muscle REMG. The low REMG amplitude and the small concentric-eccentric EMG difference suggest that co-contraction of the flexor muscles with TLA activity must be ruled out as explanation for the observed REMG differences in flexor muscles between the flexor and extensor conditions. The small TLA REMG during the movement trials may represent cross talk from neighboring flexor muscles (m. brachialis) because the REMG changes in the conditions

are very similar to those of the flexor muscles (i.e., higher in SF and LF than in SE and LE).

Discussion

Van Bolhuis et al. (1998) demonstrated that during linear wrist movements at a fixed low speed, the REMG of mono-articular muscles at a given arm configuration and external force varied with the direction of wrist movement, and they introduced the concept of "preferred movement direction" of a muscle—the direction corresponding to the greatest REMG amplitude. Welter et al. (2000) obtained similar findings, not only for mono-articular but also for bi-articular muscles. The REMG-amplitude of a muscle during the movement was larger when the muscle acted concentrically during the movement than when it acted eccentrically, and the "preferred movement direction" of a muscle turned out to be the direction causing the largest shortening velocity of this muscle. At first sight, it may come as no surprise that eccentric contractions show lower REMG values than concentric contractions. These results seem to be predictable on the basis of the well known force velocity relationship. However, closer analyses showed that this explanation does not hold because the magnitudes of REMG changes were much larger than should be expected. Welter et al. (2000) showed that the maximum variations in REMG with movement direction were of the order of 20%, while the effects on muscle force producing capacity due to the corresponding variations in contraction velocity, calculated with a muscle model, were only about 5%. Consequently, they ruled out the possibility that the variations in REMG with movement direction were compensations for differences in this force producing capacity, caused by different muscle contraction velocities, which in turn were caused by the different directions of wrist movement. In other words, the force-velocity relationship did not offer an explanation for the variations in REMG with movement direction. The purpose of the present study was to investigate whether changes in REMG can be interpreted as compensations for the history dependence of the force generating capacity of muscles as suggested by Welter et al. (2000).

The present data confirm our earlier finding (Welter et al., 2000) that the force-velocity relationship cannot explain the relatively large variations in REMG with concentric and eccentric contraction. Additionally, the data partially support the hypothesis that history dependence might be an explanation for the observed REMG variations. These issues will be discussed in the next two paragraphs.

The activity of arm flexor muscles was measured at constant external force, muscle length, and contraction speed, after contractions over small distances (S, 6.5 cm) and large distances (L, 13 cm) of elbow flexion (F) and extension (E). As in the previous studies by Van Bolhuis et al. (1998) and Welter et al. (2000), we observed that REMG was greater when the muscles shortened than when they lengthened. The differences between SF-SE were 17%, 33%, and 69% for BLO, BIB, and BRD, respectively (Table 1). BLO was not included in the previous study. The SF-SE differences in the other two elbow flexors were larger than those reported by Welter et al. (Welter et al., 2000) for contractions over similar distances, but for wrist movements at half the speed used in the present study, suggesting that velocity of shortening does have an effect. However, using the models presented previously (Welter et al., 2000), it was estimated that in the present study, the differences in force generating capacity of the muscles caused by the differences

in contraction velocity were of the order of 10% (two times the 5% difference of Welter et al., 2000) which, although higher than in the previous study, still seems too low to interpret the observed REMG differences of 17% to 69% as compensatory adaptations for the effects of velocity on the force generating capacity.

Can the REMG differences be interpreted as compensatory adaptations for the effect of the amplitude of muscle shortening or lengthening on the force generating capacity of muscles? The results of the present study seem to support this possibility. When the wrist movement amplitude was increased from 6.5 cm to 13 cm, the difference between REMG during shortening and lengthening at the same external force, muscle length, and contraction velocity, averaged over the flexors, increased by 12%. This was not due to a decrease in the REMG during the eccentric contractions (Table 1) but to an increase in REMG in the concentric contractions with wrist movement amplitude (Figure 3), albeit that the difference was only significant for BIB and BLO (Table 1, column 4). If we were to explain these findings with changes in muscle fiber recruitment, we would have to speculate that fiber recruitment not only differs between concentric and eccentric contractions (Nardone, Romano, & Schieppati, 1989) but also between concentric contractions over varying distances. This seems highly implausible. A more straightforward explanation is that REMG differences are compensatory adaptations for the effect of the amplitude of muscle shortening on the force generating capacity of muscles. The fact that REMG in eccentric contractions did not show history dependent effects may reflect, as proposed by Herzog (1998), that different mechanisms underlie the history dependent effects in concentric and eccentric contractions. The observation that the present results from voluntary contractions do not fully comply with results from electrically stimulated muscle preparations (where eccentric contractions did seem to increase force generating capacity) is in line with results from maximal voluntary contractions, where only a small force depression was found (Lee et al., 2000). Obviously, it is beyond the scope of this paper to speculate any further on these issues.

In addition to the discussion of the average REMG values, a remark can be made about the time course of REMG during the movements. De Ruiter et al. (1998) found a steady force decline during shortening contractions in electrically stimulated muscles *in vivo*. Assuming a similar force decline in the concentric contractions in our experiment, an increasing REMG should be expected when a constant force must be maintained. However, although Figure 2 shows a steadily increasing BIB REMG for SF in the last 2 s, the curves cannot be used as support for the hypothesis that history dependence influences REMG. First, contrary to expectations, no consistent increase is present in the last seconds of the LF traces of Figure 2. Moreover, the slope of the curves varied between subjects. Second, an unknown part of the increase may be due to the force-length relationship, since Murray et al. (Murray, Buchanan, & Delp, 2000) showed that at 90° elbow flexion, the arm flexor muscles operate on the ascending limb of the force-length curve. Third, the rate of REMG level change may be influenced by a progressing redistribution of the load between muscles as the movement proceeds. This obscures the contraction history dependent time course of REMG of a single muscle at constant force. In view of these considerations, it seems that the data are not sufficient to relate the time course of REMG to contraction history during movements in the same way, as the time course of force can be compared to contraction history in electrically stimulated muscles.

In this study, we found that when the distance covered by the wrist was increased from 6.5 cm to 13 cm, REMG amplitude of BIB and BLO at a given external force, muscle length, and shortening velocity increased by 14% and 24%, respectively. The changes are much larger than those expected based on the force-velocity relationship. Apparently, REMG amplitude measured during slow wrist movements depends on contraction history. This finding has nasty implications. It means, for instance, that differences among studies in the way in which the starting position for a movement was reached, or in the way external loads were applied, could affect the outcome of the studies. Perhaps this explains why Welter et al. (2000) obtained different results when trying to replicate the study by Van Bolhuis et al. (1998). In a more general sense, we feel that it makes the interpretation of REMG results obtained during slow movements in terms of control strategies a questionable enterprise.

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