Research Report

Relation between isometric muscle force and surface EMG in intrinsic hand muscles as function of the arm geometry

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ABSTRACT

Evidence exists that shoulder joint geometry influences recruitment efficiency and force-generating capacity of hand muscles [Ginanneschi, F., Del Santo, F., Dominici, F., Gelli, F., Mazzocchio, R., Rossi, A., 2005. Changes in corticomotor excitability of hand muscles in relation to static shoulder positions. Exp. Brain Res. 161 (3), 374–382; Dominici, F., Popa, T., Ginanneschi, F., Mazzocchio, R., Rossi, A., 2005. Cortico-motoneural output to intrinsic hand muscles is differentially influenced by static changes in shoulder positions. Exp. Brain Res. 164 (4), 500–504]. The present study was designed to examine the impact of changing shoulder joint position on the relation between surface EMG amplitude and isometric force production of the abductor digiti minimi muscle (ADM). EMG–force relation of ADM was examined in two shoulder positions: 30° adduction (ANT) and 30° abduction (POST) on the horizontal plane, i.e. under higher and lower force-generating capacity, respectively. The relation was studied over the full range isometric force (10–100% of maximum force in 10% increments, 3 s duration) by analysing root mean square (RMS), median frequency (MF) of the power spectrum and non-linear recurrence quantification analysis (percentage of determinism: %DET) of the surface EMG signals. We found that in POST, the slope of the RMS–force relation was significantly higher than in ANT, while its general shape (strictly linear) was preserved. Averaged MF of the EMG power spectrum was significantly higher in POST than in ANT, while no difference in %DET was observed between the two shoulder positions. The higher slope of the EMG–force relation in POST than in ANT is interpreted in terms of increased gain of the excitatory drive-firing rate relation. It is concluded that discharge from sensory receptors signalling shoulder position may act to regulate the gain of the excitatory drive-firing rate relation of motoneurones in order to compensate for reduced recruitment efficiency.

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1. Introduction

The surface electromyography (EMG) signal consists of the sum of motor unit action potentials (MUAP) from different motor units (MUs) within the recording range of the electrode. It is widely assumed that overall EMG is the outcome of a process of linear, indeed algebraic, summation of multiple action potentials trains that are generated by concurrently...
active MUs. A post-hoc validation of this concept has been obtained in the cat soleus muscle (Day and Hulliger, 2001; Perreault et al., 2003). The intensity of multiunit neurophysiological signals depends not only on the number of units that are active but also on discharge rates and the relative timing of the activity across the population.

The relation between isometric force and surface EMG amplitude has been the subject of extensive investigation (see also Basmajian and De Luca, 1985; Lawrence and De Luca, 1983; Milner-Brown and Stein, 1975; Moritani and deVries, 1978; Solomonow et al., 1990a,b; Woods and Bigland-Ritchie, 1983). For small muscles, with narrow motor unit recruitment range, such as intrinsic hand muscles, the observed relation between force and surface EMG is reported as being linear. For larger muscles, with wide motor unit recruitment ranges, such as proximal leg and arm muscles, the relation is reported to be non-linear (Woods and Bigland-Ritchie, 1983; Basmajian and De Luca, 1985; Solomonow et al., 1990a,b). MUAP-twitch relation, rate coding, grouping, muscle fibre conduction velocity, shape of the transmembrane potential, MU location within the muscle, muscle fibres arrangement and thickness of subcutaneous tissues, are all possible contributory factors in shaping the EMG amplitude-force relation (cf. Lowery and O’Malley, 2003; Zhou and Rymer, 2004).

We have recently demonstrated that shoulder position, possibly via afferent signals arising from peripheral receptors, influences the recruitment property of the motor-nuclei innervating forelimb and hand muscles (Ginanneschi et al., 2005, 2006, Dominici et al., 2005; Gelli et al., 2005). For example, the force-generating capacity of the abductor digiti minimi (ADM) is significantly lower in extended (POST) with respect to flexed (ANT) shoulder joint position in the horizontal plane (Dominici et al., 2005). In other terms, when the shoulder is placed at POST, the ADM motoneurones are less accessible to voluntary command (Dominici et al., 2005; Gelli et al., 2005).

The present study was specifically designed to examine the EMG-force relation in circumstances in which the force-generating capacity of the ADM was centrally modified by variation in shoulder joint position. Muscle force, EMG root mean square (RMS), median frequency (Mf) of the power spectrum and nonlinear recurrence quantification analysis percent of determinism (%DET) of the surface myoelectrical signals (EMG) were recorded during 10 steady levels of contraction of ADM.

2. Results

During 3 s isometric MVC of the ADM, the maximum absolute force values corresponded to 12.32 Newton (N)±1.12 S.E. and 8.76 N±1.56 S.E. in ANT and POST respectively (t=4.21, P<0.0001), i.e. the ability to generate maximum force in POST was 79% of ANT (Fig. 1A). Maximum RMS in each arm position was 0.36 mV2±0.0002 and 0.32 mV2±0.0005 in ANT and POST, respectively (t=2.21, P=0.0034) (Fig. 2B): maximum EMG amplitude was 12% lower in POST than in ANT.

Fig. 2A illustrates the relation between ADM isometric force and RMS with increasing force levels. Force values are expressed as Newton (N), while RMS amplitude was expressed in mV2. In both shoulder positions, the EMG-force relation was linear (r2 ANT=0.996; r2 POST=0.997). In POST, maximum RMS value was reached at force level 30% lower than in ANT. Slope of linear regressions fitted to experimental data were 0.95±0.02 and 1.29±0.05 in ANT and POST, respectively (t=13.12; P<0.0001) (Fig. 2C). The difference in EMG RMS amplitude between the two positions started to become significant at 20% MVC [2.46 N; t=3.24; P=0.041] for the experimental values. Mean RMS value for the range of contractions analyzed (10–70% MVC, data not shown) was 0.14 mV2±0.008 S.E. and 0.17 mV2±0.01 S.E. in ANT and POST, respectively (18% mean increment; t=3.84; P=0.0085).

Fig. 3B illustrates the relation between Mf and increasing force levels in the two arm positions. Mf values were 76.42 Hz±1.013 S.E. and 82.51 Hz±2.194 S.E. in ANT and POST, respectively: their differences were significant (t=2.699; P=0.016). By using the best-fitting equation (plateau—exponential decay, r2 ANT=0.99; r2 POST=0.99), two different phases were identified: an early plateau phase ending at 39.05% force±0.36 S.E. in ANT and at 59.36% force±0.29 S.E. in POST, followed by a decay. The slope of the linear equation of Mf plateau phases corresponded to 0.095±0.021 S.E. (ANT) and 0.131±0.021 S.E. (POST), respectively (t=3.84; P=0.0085).

Fig. 1 – (A) Grand mean value (±S.E.) of maximum voluntary force in ANT and POST. The insert shows the two different positions: 30° shoulder adduction (ANT) and 30° shoulder abduction (POST) (modified from Ginanneschi et al., 2005). (B) Schematic representation of the hand position and recording set-up.
Fig. 4A illustrates the relation between %DET and force levels. It was preliminarily verified (data not shown) that %DET within each single steady contraction did not change, indicating that no significant change in muscle conduction velocity or grouping occurred during the 3 s contraction. In both arm positions (ANT and POST) %DET exhibited a large rising phase with increasing force levels. Post-hoc analysis demonstrated that %DET increased significantly at force values above 30% MVC and end this phase at 50% MVC (\(F = 24.71, P < 0.0001\)). No significant difference (\(t = 0.1770, P = \text{ns}\)) was present between average %DET in ANT and in POST (46.38%±15.26 S.E. and 42.83%±13.02 S.E. respectively) (Fig. 4B).

Fig. 5 shows the relation between Mf and %DET. An inverse, significant correlation was present in both arm positions (Pearson \(r = -0.753, P = 0.012\) and \(-0.870, P = 0.005\) in ANT (A) and POST (B) respectively).

The EMG–force relationship in ADM was not influenced by weak voluntary contraction of the biceps muscle (data not illustrated). Difference point-to-point between EMG–force relationship in ADM with and without activation of the biceps muscle did not reached statistical significance (\(t = 0.007; P = 0.99\) and \(t = 0.006; P = 0.99\) in ANT and POST, respectively). No difference was also observed in the linear correlation between the two conditions (Pearson \(r = 0.99,\) ANT with biceps activation=0.99, ANT with biceps activation=0.99: \(t = 0.0034; P = 0.99\). Pearson \(r = 0.99,\) POST without biceps activation=0.99, POST with biceps activation=0.98: \(t = 0.0023; P = 0.97\)).

3. Discussion

In the present study we investigated the influence of different shoulder joint positions on the relationship between surface
EMG amplitude and isometric force of ADM. The main finding was that under reduced force-generating capacity of ADM, obtained by placing shoulder joint in POST, the slope of the RMS–force relation significantly increased. In the following discussion it is proposed that the change in the slope of the RMS–force relation reflects an increased gain of the excitatory drive-firing rate relation of motoneurones innervating the ADM.

3.1. EMG–force relationship

Motor commands are ultimately translated into skeletal muscle force, through two interrelated processes, 1) by varying the number of motor units that participate in a contraction (recruitment), and 2) by modulating the rate of action potentials driving active motor units (rate coding). It has been suggested that the relative contribution of rate coding and motor unit recruitment to force production is different in muscles of different fiber composition and function. In particular, rate coding appears to play a more important role in small muscles, such as intrinsic hand muscles (De Luca et al., 1982), while recruitment of additional MUs plays a more important role throughout the contractile force range in large muscles of mixed fiber composition such as biceps brachii (De Luca et al., 1982; Kukulka and Clamann, 1981). Two broadly different characteristic forms of the surface EMG amplitude-isometric force relation have been described for small and large muscles (Basmajian and De Luca, 1985; Lawrence and De Luca, 1983; Milner-Brown and Stein, 1975; Moritani and deVries, 1978; Solomonow et al., 1990a,b; Woods and Bigland-Ritchie, 1983). For intrinsic hand muscles, the relation is reported to be approximately linear, while for larger muscles, such as proximal leg or arm muscles, the relation is reported to be non-linear.

Similarly to what was found in the first dorsal interosseous and abductor pollicis muscles (Basmajian and De Luca, 1985; Lawrence and De Luca, 1983; Milner-Brown and Stein, 1975; Moritani and deVries, 1978; Solomonow et al., 1990a,b; Woods and Bigland-Ritchie, 1983), the relationship between surface EMG amplitude and isometric force in the ADM was strictly linear. The underlying mechanism for this linearity still needs to be clarified. Simulation studies suggest that the relation between electrical and mechanical properties at single MU level is the dominant factor in the relationship between surface EMG amplitude and isometric force (Zhou and Rymer, 2004). Since there is evidence that MUs from intrinsic hand muscles operate along a continuum of responses, which makes it hard to classify them into large/small or fast/slow (McNulty et al., 2000), summation of MUs with similar properties (in terms of relation between motor unit size/force output) could contribute to yield a linear EMG–force relationship.

Changes in arm geometry (i.e. ANT vs POST) did not modify the general shape of the EMG–force relationship, while they significantly affected the slope. In particular, the slope was higher in POST than in ANT, indicating that EMG signal in POST increased more than force. Changes in recruitment strategy, grouping and/or firing rate of activated MUs can be considered as putative factors affecting the slope of the EMG–force relation. Changes in recruitment strategy are unlikely to explain the increased slope in POST, since intrinsic hand muscles, such as the ADM, rely predominantly on rate coding to increase force and the EMG–force relation has been shown to be poorly sensitive to changes in motor unit firing rate strategies (Zhou and Rymer, 2004). These authors also observed that the level of motor unit synchrony exerts negligible effects on the overall EMG–force relation. We therefore propose that the higher slope in POST than in ANT was predominantly caused by an increased MU firing rate. Indeed, an increased gain of the excitatory drive-firing rate relation may compensate for the reduced force-generating capacity of the ADM in POST.

3.2. Mf–force relationship

The average frequency content of the EMG signal (Mf) was significantly higher in POST than in ANT. The most immediate interpretation is that MU firing rate increased in POST to compensate for the reduced motoneuron excitability. In other terms, to maintain the same level of force as in ANT, the CNS had to increase the firing rate in POST. However, in both shoulder positions, the Mf-force relation exhibited a biphasic
behaviour; an early plateau phase (between 10% and 50% of MVC) followed by an exponential decay phase. In animals Mf increases linearly with increasing average conduction velocity during orderly MU recruitment (Solomonow et al., 1990a,b). Although these results cannot be directly extended to surface recordings, there is evidence that Mf is still a good index of MUs recruitment in constant-torque contractions (Farina et al., 2002b). In addition, the Mf plateau phase ended around 50% MVC, a value very close to the upper recruitment limit already described in intrinsic hand muscles (Kukulka and Clamann, 1981; Milner-Brown et al., 1973). The rising phase of the Mf–force relation was followed by an exponential decay phase. There is evidence that during high contraction strength, due to the high firing rates, some motoneurones become effectively refractory as a result of the trajectory of their afterhyperpolarization (e.g. Matthews, 1996; Martin et al., 2006; Gelli et al., 2007). Indeed, the probability of eliciting a spike in motoneurones decreases as the time available for excitation is shorter: i.e. when the membrane potentials approaches threshold quickly as during high-frequency firing. Because high firing rate during strong voluntary contraction may prevent discharge of some motoneurones, the frequency content of the EMG signal is expected to decrease. However, the decrement of the Mf occurred at greater force level in POST than in ANT. This is apparently in contrast with the assumption that in POST the firing rate is higher than in ANT. Indeed, according to the abovementioned concept, the frequency content of the EMG signal in POST should decrease earlier (i.e. for lower force levels) than in ANT. Our explanation for this opposite behaviour is that, due to the reduced recruitment efficiency of motoneurones innervating the ADM in POST (Ginanneschi et al., 2005), the upper recruitment limit is delayed. This prolonged recruitment may “mask” the decrement in frequency content of the EMG signal (c.f. Farina et al., 2002b).

The Mf decay phase could also reflect increased MU grouping (i.e. the tendency of MUs to fire with dependent latencies relative to each other: cf. Mattei et al., 2003). Indeed, grouping (by reducing the number of independent MU) could cause a shift of the Mf to lower frequencies (Yao et al., 2000). In the present experiments we found that Mf was significantly and inversely related to %DET: the Mf decay phase associated with a steep raising phase of %DET. As already mentioned, increasing %DET is mainly expected to increase with increasing MU grouping (or MU superimposition) and/or muscle fatigue (Farina et al., 2002a,b). Since under our experimental condition muscle fatigue can be excluded (each steady contraction lasted no more than 3 s), the hypothesis that increasing %DET with decreasing Mf may be due, at least in part, to MU grouping should be considered. Therefore, we propose that the Mf decay phase observed above the recruitment limit of the ADM, can result from motoneuron refractoriness and MU superimposition.

3.3. Percent DET–force relation (recurrence quantification analysis)

There is some evidence that muscle fibre conduction velocity and MU grouping are the main factors at play which combine to condition %DET of the EMG signal (Del Santo et al., 2006; Farina et al., 2002a; Filligoi and Felici, 1999; Zbilut and Webber, 1992). In the present study, no significant difference in the average %DET was observed between ANT and POST, suggesting that the above variables were not influenced by shoulder position. In other terms, these variables were not responsible for the different slope of the EMG–force relationship observed in ANT and POST.

3.4. Conclusions

In the present study we explored the impact of the shoulder joint geometry on the slope of the EMG–force relation in ADM. We found that under reduced force-generating capacity of ADM obtained by changing shoulder position from ANT to POST, the slope of the EMG–force relation significantly increased. Combined analysis of non-linear recurrence and power spectrum median frequency of the EMG signal, suggests that the increased slope was mainly caused by an increased MU firing rate. This may be important to maintain willed muscle contraction under reduced motoneuron recruitment efficiency.

As proposed in a previous paper (Ginanneschi et al., 2006) the proximal–distal interactions described in the present paper could be placed in a broader theoretical framework based on the reference body configuration hypothesis (St-Onge and Feldman, 2004). The reference body configuration is a virtual, geometric image of the body with which actual body configuration is compared. It has been suggested that the nervous system may specify a referent configuration determined by a set of the threshold joint angles at which muscles are silent. Muscle activity and movement may emerge following the natural system’s dynamical reactions to the deflection of the body from the referent configuration.

Accordingly, the effects of changing shoulder joint position, as observed in the present study, could be interpreted in terms of mismatching between the referent and actual arm configuration, thus generating excitability changes involving multiple muscles.

4. Experimental procedures

4.1. Subjects

Nine (3 female, 6 male) right-handed subjects volunteered for the study (mean age 29.5±6.8 years, range 25–52). Informed consent was obtained from all subjects before testing and ethical approval for the study was obtained from the University of Siena Human Subjects Ethics Committee in accordance with the declaration of Helsinki. All subjects were trained to control ADM contractions relevant to the study.

4.2. Experimental setting

The subjects sat in a reclining armchair with their right arm on a horizontal plane and the shoulder at 90° abduction on vertical plane. Right arm and forearm were inserted and secured in arm pieces that fixed the elbow joint at 90° and the wrist joint in neutral position as shown in Fig. 1A (insert). The hand and first four fingers were secured in a rigid piece as illustrated in Fig. 1B. The fifth finger was placed at about 10° horizontal abduction and secured to a device equipped with a stiff force transducer.
Determinism (%DET), as measured by RQA, is not affected by different force levels (Filligoi and Felici, 1999). Optimal embedding dimensions, obtained with false nearest neighbours algorithm, was fixed to 15; the time delay value was calculated with minimal mutual information algorithm (Zbilut and Webber, 1992). Radius values were calculated with Euclidean distance metric to be smaller than 10% of maximum normalized distance for each spatial vector (Zbilut and Webber, 1992; Farina et al., 2002a), normalizing energy for each contraction (Farina et al., 2002a) and after phase randomisation (Filligoi and Felici, 1999). For each subject, %DET was extracted in contiguous non-overlapping epochs, chosen accordingly with spectral analysis parameters (see below). In addition, %DET was determined for each contraction in each arm position in order to determine its variations under the contraction time; its behaviour was tested with linear correlation %DET/Time for each contraction.

4.5. Spectral parameters and statistical analysis

Fast Fourier Transform was applied to data segmented in 4096 points non-overlapping windows (Spike 2.0 software, version 4.01, Cambridge Electronic Design, UK). $M_f$ of the EMG power spectrum was computed for each level of contraction using the mathematical definition of median.

Results were then averaged and tested for their normality (Kolmogorov–Smirnov distance method). Force values were compared between the two arm positions in order to perform exactly the same absolute force output in the two positions at each level of contraction. Level of EMG activity, %DET, $M_f$ and force were compared between the two shoulder positions using paired Student’s t-test, after pairing verification (correlation coefficient method). The statistical power of %DET differences between ANT and POST was confirmed with Bonferroni post-hoc tests. Correlation coefficient between %DET and $M_f$ values was calculated using parametric Pearson r. Statistical significance was assumed if $P < 0.05$. Results were expressed as mean value and standard error (S.E.).

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References


