Relationship between Isometric Muscle Force and Surface EMG of Wrist Muscles at Different Shoulder and Elbow Angles

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Abstract: Purpose: The purpose of this study is to investigate the relationship between myoelectric activities of wrist flexors and extensors and hand grip strength at four different positions of shoulder and elbow joints. **Subjects**: Thirteen normal male university students volunteered to participate in this study. Their mean ages, weights and heights were 19.6 (± 1.06) years, 75.9 (± 7.51) Kg and 173.5 (± 4.67) cm respectively. **Method**: Four positions of shoulder (Sh) and elbow (El) joints were assumed during which both hand grip strength and EMG of wrist flexors and extensors were measured and correlated. The tested positions were (1) 0° Sh 90° El, (2) 90° Sh flexion 90° El flexion, (3) 90° Sh abduction 0° El, and (4) 90° Sh abduction 90° El flexion. Each subject was instructed to produce a powerful grip and maintain this grip force for 5 seconds during which the raw EMG signals were recorded. Three trials of recording of EMG and grip strength were collected with a rest period of 3 minutes between each trial to prevent fatigue **Analysis**: Pearson Product Moment Correlation Coefficient was conducted using StatGraphics plus with alpha level of significance set at 0.05. **Results**: Correlation between hand grip strength measured in kg and Root Mean Square (RMS) EMG of wrist flexors revealed significant positive correlation between both variables in positions (2), (3) and (4) (r = 0.38, 0.45, 0.48 respectively). Correlation between hand grip strength and RMS EMG of wrist extensors revealed significant positive correlation between both variables only in positions (2) and (3) (r = 0.48, 0.62 respectively). In positions (1) and (4) the (r) values were (r = 0.27, 0.30 respectively) which indicate non significant positive correlation. **Conclusion**: The findings of this indicated that abducted shoulder with extended elbow is the best position to produce hand grip strength with great correlation between hand grip strength and EMG activities of wrist flexors and extensors.

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1.Introduction

Surface electromyography (sEMG) is a useful method in ergonomics for task evaluation. Ergonomic research uses amplitude and frequency analyses of surface EMG to quantitatively understand body postures and workloads on physical comfort and discomfort (Kong *et al.,* 2010). It is a powerful tool for examining the biomechanics and motor control of the human body (Mogk and Keir, 2003 a). Physical therapists are among the most common users of EMG as a method of understanding function and dysfunction of the neuromuscular system (Soderberg and Knutson, 2000). The EMG signal reflects phenomena related to muscle contraction at the junction of neurons and muscle fibers (Liu and Bartuzi, 2013). Assessing the demands placed on a muscle is usually determined by the relative amplitude of the EMG signal. Greater amplitude of EMG is generally assumed to indicate greater intensity of muscle activation and in certain cases greater relative muscle force (Neumann, 2010).

Root Mean Squared (RMS) value is a method of representing the raw EMG amplitude over a period of time. This mathematic analysis involves squaring the signal (to ensure a completely positive signal), averaging, and then calculating the square root (Neumann, 2010). Given that there are many factors that influence the EMG signal, voltage recorded from a muscle is difficult to describe if there is no reference value to which it can be compared. Therefore, interpretation of the amplitude of the raw EMG signal is problematic unless some kind of normalization procedure is performed. Normalization refers to the conversion of the signal to a scale relative to a known and repeatable value. Normalization of EMG signals is usually performed by dividing the EMG signals during a task by a reference EMG value obtained from the same muscle (Hunter *et al.,* 2002). By normalizing to a reference EMG value collected using the same electrode configuration, factors that affect the EMG signals during the task and the reference contraction are the same. Therefore, one can validly obtain a relative measure of the activation compared to the reference value (Halaki and Ginn, 2012). One common method of normalizing EMG involves referencing the signal produced by an activated muscle to that produced by the same muscle during a maximal voluntary isometric contraction (MVIC). Comparisons can then be made on the relative amplitude or intensity of muscle activation across different subjects or days, expressed as a percent of MVIC (Hunter *et al.,* 2002).

Also, a muscle activation level can be referenced to some other meaningful reference task that does not involve maximal effort. EMG produced as subject performed certain task can be used as baseline value for comparison with other tasks by the same subject. Then other tasks are normalized to percentage of this EMG baseline value (%EMG) (Hunter *et al.,* 2002, Neumann 1999). The decision to normalize or not normalize is based on the type of descriptions or comparisons to be made. For example, if comparisons are made between subjects, days, muscles, or studies, the process is required. Conversely, if subjects serve as their own control and contrasts are made within a day and on the same muscle, with the electrode not being removed, normalization is not thought to be necessary. Authors advise normalizing EMG data, however, because this step is necessary if results are to be compared with similar data from other studies (Soderberg and Knutson, 2000).

EMG signals are affected by changes in muscle force and muscle length and the relationship may be further complicated by changes in electrode-muscle configuration. (Mogk and Keir 2003 a). The length-contraction relationship is important for the upper limb, with its numerous degrees of freedom which make adopting variety of postures possible. The association between joint position and EMG signal characteristics has been studied in relation to elbow joint muscles, where changes in muscle length are evident during changes in the joint angle. Those studies examined the larger upper limb muscles, e.g. biceps brachii (Doheny *et al.,* 2008, and Cechetto *et al.,* 2001), triceps brachii or brachioradialis (Doheny *et al.,* 2008)

Accurate muscle force estimation using the surface EMG (sEMG) is required in a number of applications including control of prostheses, ergonomic analysis, sports medicine, and human–robot interaction (Staudenmann *et al.,* 2010). However, even for isometric contractions, the sEMG is affected by physiological and nonphysiological factors which impact the accuracy of sEMG amplitude estimation (Disselhorst-Klug *et al.,* 2009; Farina *et al.,* 2004). Also, errors introduced by the estimation of physiological and biomechanical parameters affect the accuracy of the sEMG–force relationship (Hashemi *et al.,* 2013).

Changing joint angle influences the estimation of both the sEMG amplitude and muscle biomechanical parameters by altering the muscle length, the muscle moment arm and the relative location of the innervation zone (IZ) with respect to the sEMG recording electrode (Farina *et al.,* 2001). Different modeling methods have been used to predict muscle force from sEMG. In general, the force–length relationship for a muscle *in vivo* is limited to a portion of the classic force–length relationship. Models have been developed to quantify the moment arms of the upper arm muscles with respect to joint angle (An *et al.,* 1984; Holzbaur *et al.,* 2005). Beck *et al.* (2008) studied the effects of the relative position of the electrode and IZ on the recorded sEMG. They noted that electrode placement has an effect on the sEMG amplitude and suggested that the effect of IZ shift on sEMG amplitude is reduced by normalization with respect to the highest recorded value for each subject Beck *et al.* (2008).

Many MVC normalization techniques assume that there is a linear relationship between force generated and EMG level (Marras and Davis, 2001). In other words, as force is uniformly increased, there is a corresponding linear response in the activity of the muscle up to the level of the maximum force exertion. Thus, the proportion of muscle activity for any force level below the MVC can then be represented as a percentage of the EMG level relative to the MVC. The linear assumption has been widely supported in the literature (Chaffin *et al.,* 1980, Hagberg (1981), Perry and Bekey (1981), Woods and Bigland-Ritchie (1983), Moritani *et al.* (1988)), although some researchers have found non-linear relationships (Lawrence and DeLuca (1983), Solomonow *et al.* (1986), Solomonow *et al.* (1987), , Solomonow *et al.* (1990)). The purpose of this study is to examine the correlation between wrist flexors and extensors EMG and force exerted by the muscles during gripping task.

2.Material and Methods

Subjects:

Thirty normal male university students volunteered to participate in this study. They were collected from the students of Faculty of Physical Therapy. Age ranged from 18-22 years, height ranged from 161-180, and weight ranged from 65-92 kg. The mean ± (SD) of their ages, weights and heights were 19.6 (± 1.06) years, 75.9 (± 7.51) Kg and 173.5 (± 4.67) cm respectively. All subjects were under normal condition with no pathology in their upper extremity. The dominant hand was the only tested hand.

Instrumentation:

Hand grip dynamometer (JAMAR, Sammons Preston, 452 N. Sangamon, Chicago, IL 60622 SN 30107301) was used to measure hand grip strength under different positions of shoulder and elbow joints synchoronously with the measurement of EMG activities of the wrist flexors and extensors. Hand grip strength was recorded with kg unit.

The Myomonitor EMG System (DELSYS INC., USA 2008, REF PM-E04, MAN-003-2-0) was used for measuring the myoelectric activities of wrist flexors and extensors. Parallel bar surface EMG sensors (active electrodes), and reference electrode were used for EMG recording. Data acquisition software was prepared so that the EMG gain is 1000, EMG signals were sampled at 1000 Hz and stored in a personal computer. The EMG signals were filtered with a bandwidth of 20-450 Hz. CMRR -92dB at 60 Hz, input impedance > 10^{15} Ω.

Experimental Preparation

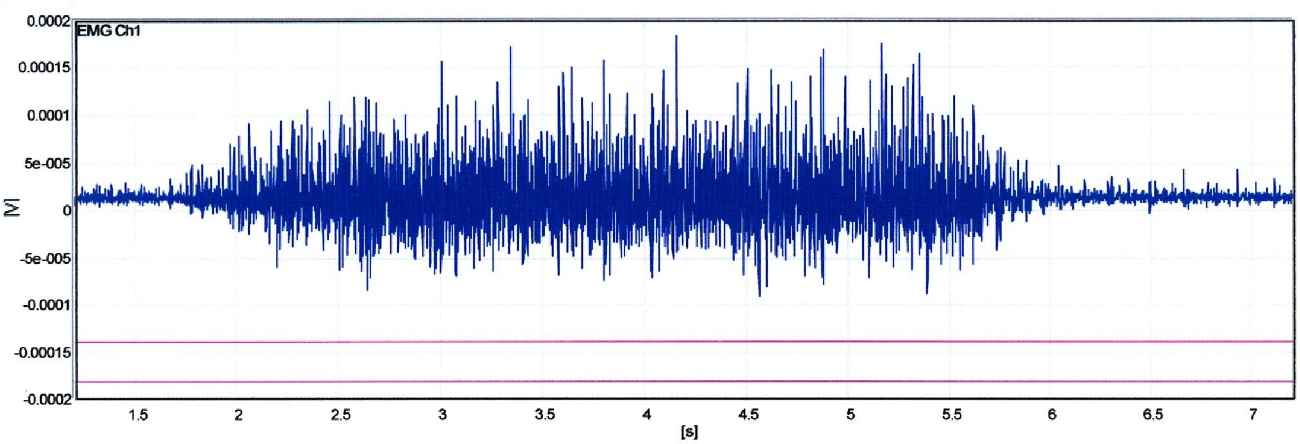
Each subject was informed about the nature of the study. The skin over the site of wrist flexors and extensors muscles at the forearm was cleaned with alcohol to reduce skin resistance. The two parallel bar surface EMG electrodes were applied over the muscles belly of wrist flexors and wrist extensors. Wrist flexors EMG electrode position was determined on a line between the origin and insertion of the muscle in the supinated hand, parallel to the direction of muscle fibers using anatomical atlas and manual palpation and following the placement recommendations of Perotto (2005) and SENIAM (Hermens *et al.,* 1999). The electrode was placed ulnarly in the line between the medial epicondyle of humerus and the pisiform.

Wrist extensors EMG electrode position was determined on a line between the origin and insertion of the muscle in the pronated hand, parallel to the direction of muscle fibers. The electrode was placed radially in the line between the lateral epicondyle of humerus to the base of the metacarpal bone of thumb. Detection of the proper site of EMG recording electrodes was performed by palpating the muscle belly while the subject was performing maximum isometric contraction of wrist flexors and wrist extensors against resistance. The parallel bar surface electrodes were secured with double-sided tape over the muscular belly. The reference self adhesive (ground) electrode was applied over the dorsal surface of the hand. The crosstalk among forearm muscles was larger than leg muscles as the muscles run across the forearm within a relatively confined space (Kong *et al.,* 2010). So it was decided to pick up EMG activities of whole forearm muscles and not the individual muscles.

Procedure

The subject assumed sitting position and the EMG electrodes were applied over the wrist flexors and extensors. Each subject was asked to grasp the handle of the hand grip dynamometer with the dominant hand while the radioulnar joint is in the midway between supination and pronation and the wrist joint is neutral. The subject was instructed to build up his maximum strength to produce a powerful grip and maintain this grip force for 5 seconds during which the raw EMG signals (Fig 1a) of wrist flexors and extensors were recorded. The Root Means Square (RMS) (Fig 1b) value was taken to quantify the muscle activity for statistical analysis. Three trials of recording of EMG and grip strength were collected with a rest period of 3 minutes between each trial to prevent fatigue. The subject repeated the same procedure in four different positions. The four positions were: 1) 0° shoulder motion with 90° elbow flexion, 2) 90° shoulder flexion with 90° elbow flexion, 3) 90° shoulder abduction with 0° elbow flexion, 4) 90° shoulder abduction with 90° elbow flexion. Random assignment of the position was followed to avoid test-retest effect.

a:



b:

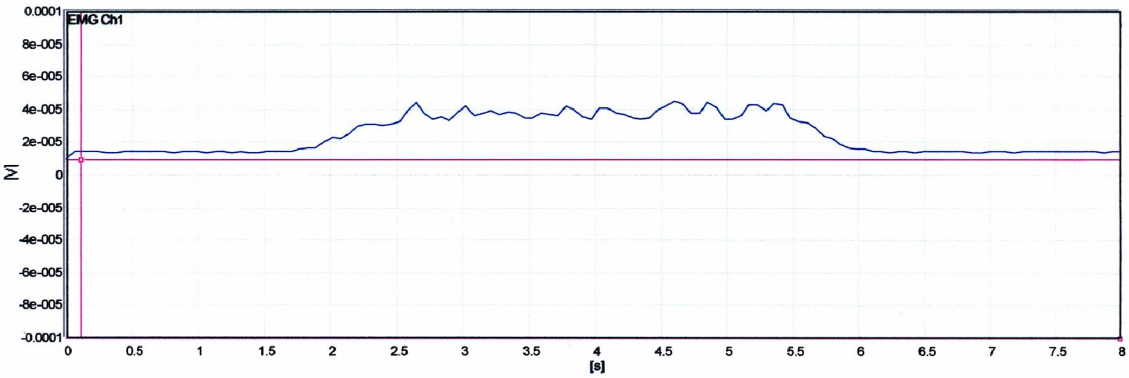


Figure (1): a) Raw EMG signals recorded from wrist extensors in position number (3). b) RMS values of the processed EMG signals of wrist extensors in position number (3).

Data analysis

Multiple regression analysis and the Pearson Product Moment Correlation Coefficient (r) were performed using StatGraphics Plus software with alpha level of significance at 0.05.

Table (1): Descriptive statistics of wrist flexors and extensors' EMG and hand grip strength (kg) and correlation between both variables

	Position (1)	Position (2)	Position (3)	Position (4)
Wrist flexors RMS EMG	2.13± 0.57	2.13±0.42	2.65±0.85	2.20±0.74
Wrist extensors RMS EMG	1.84±0.44	2.47±0.50	3.12±0.76	2.68±0.73
Hand grip strength (Kg)	37.43± 4.95	40.9±5.14	45.13±6	40.83±5.36
Correlation between RMS EMG and force of wrist flexors				
r value	0.31	0.38	0.45	0.48
p value	0.086	0.034*	0.011*	0.007*
Correlation between RMS EMG and force of wrist extensors				
r value	0.27	0.48	0.62	0.30
p value	0.14	0.007*	0.0002*	0.097

* Significant at alpha level < 0.05

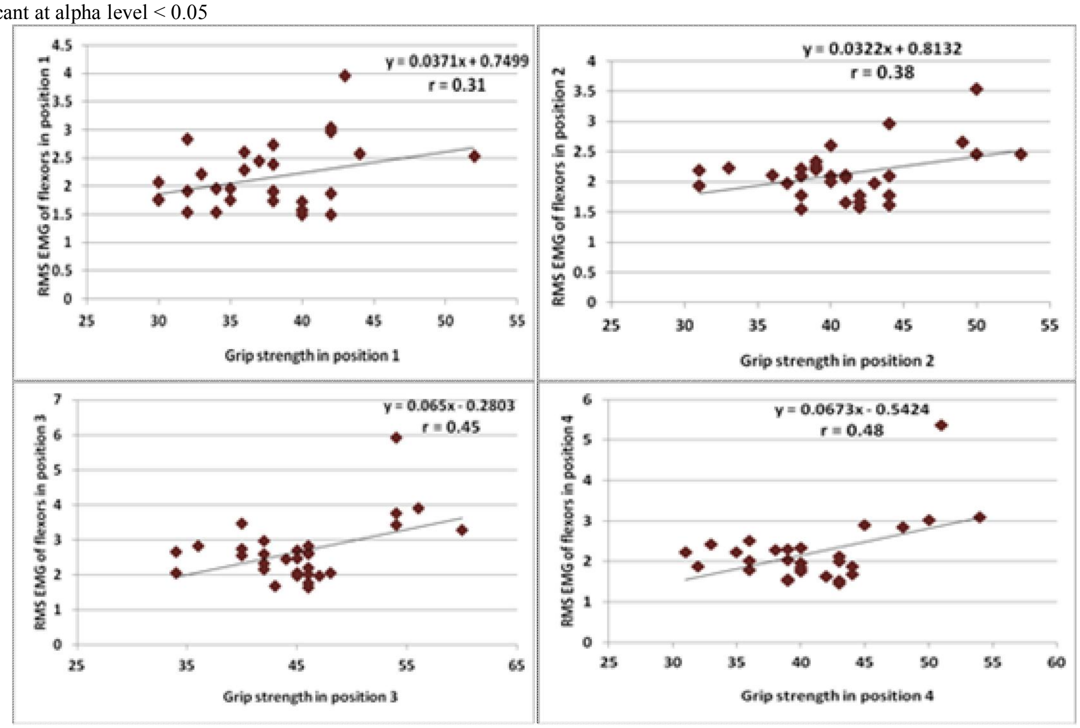


Figure (2): RMS EMG- force relationship of wrist flexors during gripping at 4 different shoulder and elbow positions.

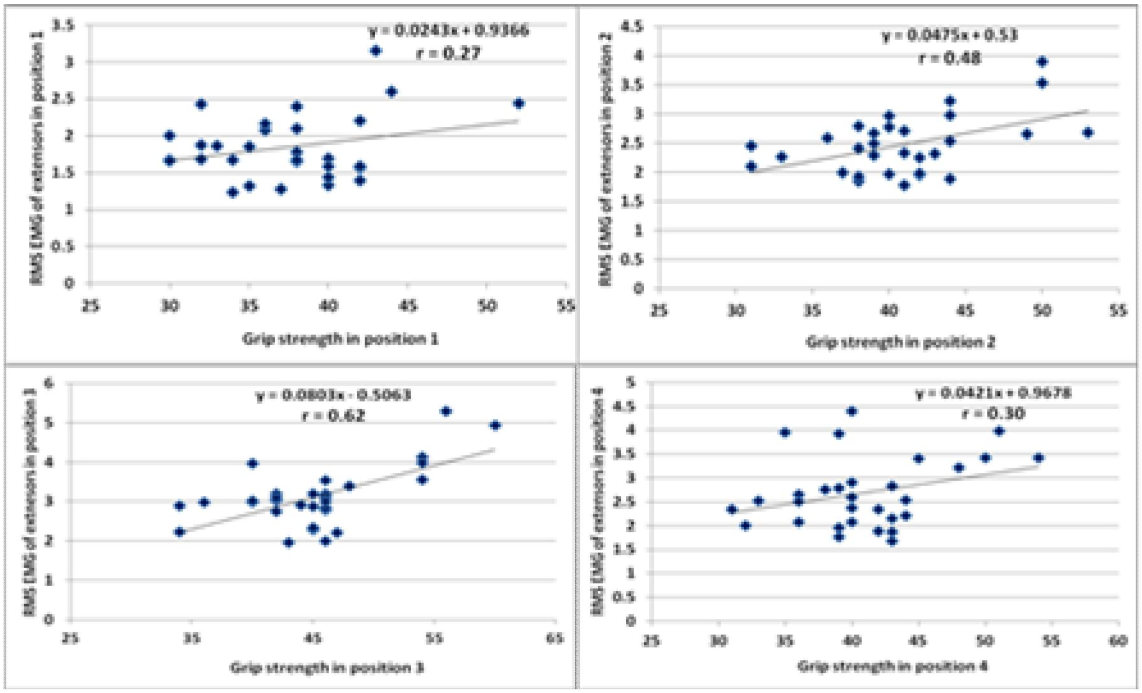


Figure (3): RMS EMG- force relationship of wrist extensors during gripping at 4 different shoulder and elbow positions.

3.Results

Correlation between hand grip strength measured in kg and RMS EMG of wrist flexors revealed significant positive correlation between both variables in positions (2), (3) and (4) (r = 0.38, 0.45, 0.48 respectively). In position (1) the analysis revealed a non significant positive correlation (r =0.31, p = 0.08). Table (1) and figure (2) illustrate the previous findings. Correlation between muscle force and RMS EMG of wrist extensors revealed significant positive correlation between both variables only in positions (2) and (3) (r = 0.48, 0.62 respectively). In positions (1) and (4) correlation coefficient values were (r = 0.27, 0.30 respectively) which indicate non significant positive correlation (Table (1) and figures (3).

4. Discussion

Hands are frequently used for actions and also involved in writing, handling, manipulating, gripping and many other activities. Hand grip strength has often been used as an indicator of general body health. Understanding the impact of shoulder and elbow loading on hand activity or gripping is necessary in order to establish appropriate assessments and clinical evaluations. The results of the current study concluded that higher RMS EMG activities of both wrist flexors and extensors were significantly recorded in position (3) where the shoulder is 90° abducted and the elbow is fully extended.

This study revealed that there were significant positive correlations between hand grip strength and EMG of wrist flexors when the shoulder joint was 90° abducted (position 3, 4) than neutral (position 1) or flexed (position 2) either with flexed or extended elbow. Correlation between wrist extensors EMG and hand grip strength indicated that position (3) had the highest coefficient (r = 0.62) compared to the remaining three positions. This highlighted the role of shoulder abduction with elbow extension in elevating the wrist extensors EMG activity, increasing the hand grip strength and improving the linear relationship between isometric muscle force and the recorded RMS EMG.

The linear relationship between force generated and EMG level has been documented by several authors. Duque *et al.* (1995) investigated the relationship between handgrip forces on a dynamometer and the normalized EMG of the flexor digitorum superficialis (FDS) for several wrist positions (flexion–extension) using a static calibration method. Using multiple non-linear regression analysis, they observed a correlation coefficient between predicted and observed forces of 0.90. Gurram *et al.* (1995) found correlation coefficients ranging from 0.91 to 0.99 under static loads and from 0.78 to 0.99 under dynamic loads for the relation between grip force and the EMG of the flexor muscles when using a power curve regression analysis. Thus, EMG of the FDS may be useful to predict grip force, but this method has not yet been optimized for the actual evaluation of hand tools considering the variety of tools and conditions that are present at the workplace. This confirms that extensor muscle activity is highly associated with the power grip activity for counteracting the wrist flexion torque caused by the finger flexor tendons (Hoozemans and van Dieen, 2005).

The evolution of recent anatomical and physiological studies suggested that the motor cortex may contribute to the mechanisms required to specify the arm muscle recruitment patterns as a function of its geometry or postures. A large body of evidence suggests that motor cortex controls the different limb segments as a whole rather than individually (Scott, 2000). It is of importance that the evoked pattern of muscle activity strongly depended on the starting position of the arm. Interestingly, the cortical map of arm postures is similar to the map of the leg position found by electrical stimulation in the spinal cord of the frog (Giszter *et al.*, 1993). These findings refute the traditional view that movement is controlled at a single joint, or muscle level and suggest that movement control might be organized in terms of behaviorally useful actions aimed toward a goal posture. It implies that a number of basic postural synergies exist. Ginanneschi *et al.* (2006) suggested that excitability changes of the corticospinal pathway to forelimb muscles after changing shoulder joint position reflects a postural synergy. It could be behaviorally meaningful during prehension movements, where joint angle variations are not controlled independently, but in a synergic way (Desmurget and Prablanc, 1997). These synergies are not static, but they are modulated in time to allow subjects to reach and to grasp objects of different shapes and sizes (Mason *et al.*, 2001). Ginanneschi *et al.* (2005) showed that the corticomotor excitability of the abductor digiti minimi (a muscle contributing to opening of the hand) was significantly higher with shoulder joint placed at 30° adduction than at 30° abduction in the horizontal plane.

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) was examined recently by Del Santo *et al.* (2007). 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 sec duration) by analyzing RMS, median frequency (Mf) of the power spectrum and non-linear recurrence quantification analysis. They 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. Their results support the findings of the present study of increased linearity and the higher significance of correlation recorded at abducted shoulder position than adducted or flexed positions.

Similarly, Del Santo *et al.* (2007) found that the averaged Mf of the EMG power spectrum was significantly higher in POST that in ANT. 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. They concluded that discharge from sensory receptors signaling 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.

Motor commands are ultimately translated into skeletal muscle force, through two interrelated processes as stated by Del Santo *et al.* (2007), 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 (Kukulka and Clamann, 1981, De Luca *et al.*, 1982) Two broadly different characteristic forms of the surface EMG amplitude-isometric force relation have been described for small and large muscles (Milner-Brown and Stein, 1975; Moritani and deVries, 1978; Lawrence and De Luca, 1983, Woods and Bigland-Ritchie, 1983, Basmajian and De Luca, 1985; Solomonow *et al.,* 1990a,b;). 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.

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 did not modify the general shape of the EMG–force relationship, while they significantly affected the slope.

In particular, as the slope was higher in abducted shoulder position than in adducted or flexed positions indicated that EMG signal in abduction increased more than force. This is in agreement with Del Santo *et al.* (2007) who reported that 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. Therefore Del Santo *et al.* (2007) 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.

Several confounding factors can affect the accuracy of force estimation using sEMG. For static sEMG data recorded at multiple joint angles, or dynamic data recorded as the joint angle is changing, sEMG amplitude is impacted by the force–length characteristics of the muscle, changing muscle moment arm, and shifts in the location of the IZ with respect to the recording electrodes. Hashemi *et al.* (2013) introduced a calibration procedure, based on sub-maximal constant sEMG amplitude contractions. The calibration procedure was used in force–sEMG modeling of isometric contractions of the biceps and triceps brachii at several elbow joint angles. The effectiveness of the calibration procedure was studied under different conditions: using calibration coefficients obtained from all seven operational joint angles, using coefficients from a subset of operational joint angles, and using coefficients from angles which did not coincide with operational joint angles. In all cases, models evaluated with calibrated datasets exhibited statistically better performance than those using non-calibrated datasets (p = <0.005). Models calibrated using coefficients measured at all seven operational joint angles, in general, showed better performance than models for which fewer measured coefficients were used, but this was not statistically significant ($p > 0.005$).

A method was developed by Hashemi *et al.* (2013) to calibrate the amplitude of sEMG signals collected from active bipolar sensors placed on the biceps and triceps brachii during isometric contractions at a range of elbow joint angles. SEMG calibration coefficients were calculated for each joint angle from constant SEMG level isomeric recordings. The calibration coefficients compensate for variations in SEMG amplitude due to changes in muscle length, muscle moment arm and IZ displacement relative to the recording electrodes. The experimental results show significant improvement in force prediction using calibrated data compared to using non-calibrated data. It was also noted that fewer joint angle-dependent nonlinear functions are selected in the models for the calibrated SEMG datasets implying more consistency and less dependency on joint angle in modeling the SEMG–force relationship.

Conclusion

This study supports the idea of linear and direct relationship between isometric muscle force and RMS EMG signals. On the basis of this rationale, one can depend on EMG recorded from specific muscles to predict the output forces from the same muscles.

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