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Muscle Activity during Maximal Isometric Forearm Rotation Using a Power Grip

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Abstract

This study aimed to provide quantitative activation data for muscles of the forearm during pronation and supination while performing a power grip. Electromyographic data was collected from 15 forearm muscles in 11 subjects, while the subjects performed maximal isometric pronating and supinating efforts in nine positions of forearm rotation. Biceps brachii was the only muscle with substantial activation in only one effort direction. All other muscles showed considerable muscle activity when both pronating and supinating. Brachialis, brachioradialis, flexor carpi radialis, palmaris longus, pronator quadratus and pronator teres were significantly more active when pronating the forearm. Abductor pollicis longus, biceps brachii and supinator were significantly more active when supinating. This data highlights the importance of including muscles additional to the primary forearm rotators in a biomechanical analysis of forearm rotation. Doing so will further our understanding of forearm function and lead to the improved treatment of forearm fractures, trauma-induced muscle dysfunction and joint replacements.

Introduction

In 1956, Sterling Bunnell described the upper extremity as a virtuosity of motion to place the hand in space (Bunnell, 1956). It has subsequently been described as a multi-grasp, unspecialised organ, where the entire upper limb is designed to give maximum mobility to its end organ, the hand (Rabischong, 2014). While this lack of specialised function allows versatility, it also makes studying the function of separate upper limb components difficult.

The ability to grip an object and rotate forcefully is a major function of the forearm/wrist/hand complex. Yet, of the upper limb's many functions, the generation of pronosupination torque that can be transmitted to the hand is the most poorly understood (Matsuoka et al., 2006). Forearm torque occurs about an axis that passes through the ulnar head distally and the radial head proximally (Matsuki et al., 2010; Nakamura et al., 1999). Consequently, healthy forearm rotation requires a normal ulna, ulnar head, radius and radial head and depends on normal neuromuscular function (Hagert, 1992).

Injury and dysfunction of the forearm is very common, with 15% of all fractures occurring at the distal radius (Bronstein et al., 1997). One in ten distal radius fractures results in ulnar-sided wrist pain and dysfunction at the distal radioulnar joint (DRUJ) (Geissler et al., 1996). Suboptimal treatments for distal radius fractures have also been associated with significant complications, such as radioulnar impingement and DRUJ instability (Ishii et al., 1998). Improved treatment for these conditions, especially those involving the DRUJ, requires an understanding of the forces to which the distal radius and ulnar head are exposed. In the upper limb, muscles are the major contributor to those loads. Understanding muscle function is thus a key part of understanding forearm mechanics.

Brand provided a unique understanding of musculotendon mechanics at the wrist (Brand and Thompson, 1981). Similar studies have been performed for the elbow (Murray et al., 2000). Mathematical models (Amis et al., 1979; Garner and Pandy, 2001; van der Heijden and Hillen, 1996; Werner and An, 1994) and mechanical joint simulators (Gofton et al., 2005; Gordon et al., 2006; Haugstvedt et al., 2001; Werner et al., 1996) have been used to investigate forces in the distal forearm. However, the way in which muscles contribute to forearm rotation has not been clearly established. Consequently, most of these methods have incorporated only a few forearm muscles, so that the accuracy of the models is questionable. It is widely accepted that the biceps brachii, supinator, pronator quadratus and pronator teres muscles are predominantly responsible for forearm pronation and supination (Basmajian and De Luca, 1985; Haugstvedt et al., 2001; O'Sullivan and Gallwey, 2005; Winters and Kleweno, 1993). Yet, many other muscles cross the forearm’s axis of rotation. Therefore, while their primary functions may be at the elbow, wrist or hand, these muscles could have secondary roles in forearm rotation.

Electromyography (EMG) is a useful tool for investigating muscle function. To date, relatively few studies have examined the activation of upper limb muscles during forearm rotation. The data that does exist is limited primarily to biceps brachii, brachialis and brachioradialis (Basmajian and Latif, 1957; Boland et al., 2008; de Sousa et al., 1961; Naito et al., 1998; Naito et al., 1995). Knowledge of muscle activity is essential to understanding muscle function and joint loading during pronation and supination. The purpose of this study was to provide quantitative EMG data for muscles of the forearm during a simple gripping, forearm rotation task

Methods

Study Design

Institutional Review Board approval was gained for a laboratory study of EMG muscle activity in normal adults during gripping and forearm rotation. Subjects were examined by a physician to ensure that no forearm or wrist pathology existed and excluded if they had prior forearm/wrist/elbow surgery or injury, arthritis involving the elbow or wrist, neurologic disorders, or aversion to needles. Fifteen forearm muscles were studied using fine-wire electrodes. To prevent electrode interference, the study was divided into four sub-studies (table 1). The right forearms of 11 subjects were used in each, with some subjects volunteering for more than one sub-study. Ideally, all the EMG data would be obtained from the same 11 subjects, however this was not feasible.

Muscles were included based on the following criteria: 1) muscles known to primarily function in forearm rotation; 2) muscles that cross the longitudinal axis of the forearm and therefore have a potential role in DRUJ loading and 3) muscles acting across the elbow that could potentially contribute to forearm pronosupination torque (Buchanan et al., 1989; van Zuylen et al., 1988). The following 15 muscles were analysed: abductor pollicis longus (APL), biceps brachii (BB), brachialis (BRA), brachioradialis (BRAR), extensor carpi radialis brevis (ECRB), extensor carpi radialis longus (ECRL), extensor carpi ulnaris (ECU), extensor indicis proprius (EIP), extensor pollicis longus (EPL), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), palmaris longus (PL), pronator quadratus (PQ), pronator teres (PT) and the supinator (SUP).

Experimental Protocol

The muscles of interest were isolated anatomically using published guidelines (Perotto, 1994). Two sterile, bipolar, Teflon-insulated, 50 μm fine-wire electrodes (California Fine Wire Co., Grover Beach, CA) with 3 – 5 mm exposed tips were inserted 1 cm apart in the muscle of interest using a two-needle, sterile insertion technique (Kelly et al., 1997). A grounding surface electrode was placed on the acromion. For each muscle, a five second baseline data set was collected with the subject's arm relaxed, followed by a maximal voluntary isometric contraction (MVIC) designed to elicit maximal activation in the relevant muscle (Kendall et al., 2005). Each MVIC was performed three times and held for five seconds with a two minute rest interval between trials.

The experimental setup is shown in Figure 1. Trials were performed with subjects standing and gripping the handle of a dynamometer (BTE Technologies, Hanover, MD). The procedure was standardised by: adjusting the height of the dynamometer so that the subject's forearm was horizontal and their elbow was flexed at 90° (Bechtel and Caldwell, 1994; Buchanan et al., 1989); placing an abduction pillow under the upper arm; marking the foot position and maintaining it between trials.

The handle of the dynamometer was randomly placed in one of nine positions: neutral, 25°, 50°, 75° and maximum pronation and supination (N, P25, P50, P75, Pmax, S25, S50, S75 and Smax). The maximum pronation and supination positions were measured using a protractor (Craftsman Tools, Sears Brands LLC., Hoffman Estates, IL). Three times in each position, the subject gripped the handle of the dynamometer and pronated the forearm with as much force as was comfortably possible for five seconds. The subject repeated the three trials while exerting a maximal supinating effort. These tasks resulted in a total of 54 pronation-supination trials per subject. A two minute rest interval was used between trials to reduce fatigue effects (Bigland-Ritchie et al., 1983; Taylor and Gandevia, 2008). The effects of muscle fatigue and order bias were also reduced by employing a Latin Squares sequence design to assign the angles used for each subject.

Data Analysis

The EMG data was collected at 2000 Hz using a portable Myopac amplifier (Run Technologies, Mission Viejo, CA) and stored on a personal computer. A digital band-pass filter of 10 – 1000 Hz was applied to the raw EMG signal prior to full wave rectification. A linear envelope was obtained from the rectified data using a 2nd order Butterworth low-pass filter with a cutoff frequency of 5 Hz. Finally, the data was smoothed using a root-mean-square (RMS) algorithm with a time constant of 20 ms. The average baseline resting recording was subtracted from all EMG data.

The peak RMS values were averaged across the three trials for each forearm position and effort direction. These were then normalised to the largest RMS value observed for the given muscle. If a larger RMS value was recorded in a trial rather than during the MVICs, this was used to normalise the EMG data. The normalised EMG data for each muscle, forearm position and effort direction was then averaged across the 11 subjects. The data was processed using Datapac 5 software (Run Technologies, Mission Viejo, CA) and Matlab 7.0.1 (The Mathworks, Natick, MA).

A repeated measures ANOVA was used to compare the normalised EMG data obtained from each muscle as a function of forearm position and effort direction. Individual differences were determined by post-hoc analyses using the Newman-Keuls test. The threshold for significance was set at 0.05 for this study.

Results

Figures 2 and 3 show the normalised muscle activity recorded for each muscle during maximal pronating and supinating efforts in each of the forearm positions. The BB was the only muscle that, in every forearm position, was significantly more active when supinating than pronating.

All other muscles showed substantial activation during both pronating and supinating efforts. When considered over all nine forearm positions, the APL and SUP were significantly more active when supinating than pronating (table 2). However, the difference was not significant at any individual forearm position. The EPL tended to be more active when supinating with the forearm in a supinated position, but this difference was also non-significant.

The PQ and PT were significantly more active when pronating than supinating in every forearm position. The BRAR, FCR and PL were also significantly more active when pronating with the arm in a supinated position. Over all nine forearm positions, the BRA and ECRL were significantly more active during pronating than supinating (table 2). However, this difference was not significant at any individual position and, particularly for ECRL, the actual difference in activation was negligible.

The remaining muscles, the ECRB, ECU, EIP and FCU, had no significant difference in activation between pronating and supinating. However, the ECU and FCU tended to be more active when supinating with the arm in a pronated position and pronating with the arm in a supinated position. Conversely, the EIP tended to be more active when pronating with the arm in a pronated position and supinating with the arm in a supinated position.

Tables 3 and 4 compare the relative activations between muscles, showing the muscles that were most and least active when pronating and supinating in each forearm position. When compared between muscles, the ECU, PL, PQ and PT were the most active muscles during pronating efforts (table 3). The PQ was the most active muscle when the forearm was in a pronated position, while the PL was the most active when the forearm was in a supinated positon. The PT was the second most active muscle in most forearm positions. The BB was the least active muscle when pronating, throughout the range of forearm rotation. The FCU was one of the least active muscles, particularly with the arm in a pronated position, while the EPL was one the least active muscles with the arm in a supinated position. The BRA and BRAR were also two of the least active muscles when pronating, particularly with the forearm in a pronated position.

When supinating, the APL, BB, ECU and SUP were the most active muscles (table 4). ECU was the most active muscle with the forearm in a pronated position, while APL and BB were the most active with the forearm in a supinated position. The SUP was the most active muscle when the forearm was in a neutral position and was one of the three most active muscles throughout the range of forearm rotation. The BRA and PT were amongst the least active muscles throughout the range of forearm rotation. The PQ was also amongst the least active in most forearm positions and BRAR was amongst the least active muscles with the arm in a supinated position.

Discussion

Muscle activity is essential for understanding muscle function and predicting joint loads during forearm pronation and supination. To date, relatively few studies have examined activation of upper limb muscles during forearm rotation. Previously published EMG data is limited primarily to the BB, BRA and BRAR (Basmajian and Latif, 1957; Boland et al., 2008; de Sousa et al., 1961; Naito et al., 1998; Naito et al., 1995), with a few studies also including the ECRB, PQ, PT or SUP (Basmajian and Travill, 1961; Gordon et al., 2004; O'Sullivan and Gallwey, 2002). This study presents activation data for 15 upper limb muscles during maximal pronation and supination efforts throughout the range of forearm rotation. This data provides insight into the secondary roles of muscles that cross the forearm’s axis of rotation and can be applied to future mathematical models of the forearm and DRUJ.

It is widely accepted that the PQ and PT are primarily responsible for pronating the forearm, while the BB and SUP are the primary forearm supinators (Basmajian and De Luca, 1985; Haugstvedt et al., 2001; O'Sullivan and Gallwey, 2005; Winters and Kleweno, 1993). The EMG data recorded in the present study supports those observations. These muscles were activated at 45-68% of their maximum throughout the range of motion during forearm pronation (the PQ and PT) and supination (the BB and SUP). They were amongst the most active muscles in each position of forearm rotation. The BB, PQ and PT were also the only muscles with significantly greater muscle activation during pronation or supination in all forearm positions. This data confirms the prominence of the BB, PQ, PT and SUP during forearm rotation.

However, arguably the most striking feature of the data, evident in figures 2 and 3, is the considerable co-contraction observed. The BB was the only muscle to show meaningful activation for only one direction of forearm rotation. All other muscles, including those that are considered primary supinators and pronators, showed considerable activation regardless of the movement direction. In particular, the SUP, so named due to its role as a primary supinator of the forearm, showed almost the same level of activation during maximal pronation (31-49%) as it did during maximal supination (46-54%). The ECU was similarly active when pronating and supinating (34-61%) and was one of the most active muscles in both effort directions. The PQ and PT were significantly more active when pronating but still showed activation of up to 29% while supinating. This co-contraction during resisted forearm rotation has been shown for the BB, BRA and BRAR (Basmajian and Latif, 1957; Boland et al., 2008; Naito et al., 1998; Naito et al., 1995), and when maximally pronating and supinating for the ECRB, PQ and SUP (Gordon et al., 2004; O'Sullivan and Gallwey, 2002). The level of co-contraction observed in this study would likely be reduced if pure forearm rotation were achieved. However, forearm rotation is difficult to isolate from gripping (or wrist bracing) and, functionally, forearm rotation will usually accompany the gripping of an object.

In addition to the BB, PQ, PT and SUP, several other muscles were notably more active during pronating (the BRA, BRAR, FCR and PL) or supinating (the APL) efforts. The APL is a muscle primarily responsible for abduction and extension of the thumb (Cooney et al., 1985; Drake et al., 2005; Thompson and Netter, 2002). In this study, it was also the most active muscle in the forearm during supination when the arm was at S25 and was amongst the most active at all other positions. Overall, the APL was significantly more active when supinating than it was when pronating. The primary roles of BRA and BRAR are to flex the elbow (Drake et al., 2005; Thompson and Netter, 2002). The BRA was significantly more active during pronation than supination, an observation consistent with previous research (Naito et al., 1998; Naito et al., 1995). Due to its attachment site on the ulna, the BRA cannot participate in forearm rotation by directly moving the radius. If its contribution extends beyond bracing the elbow, that contribution will be through varus-valgus and flexion movement of the ulna. Previous research has reported the BRAR to be more active during pronation than supination (Boland et al., 2008; Jamison and Caldwell, 1993; Naito et al., 1998; Naito et al., 1995), although there is some indication its activity depends on the forearm's position (Basmajian and De Luca, 1985). In this study, activation of the BRAR was only significantly greater when pronating with the forearm in a supinated position. Its activation was not significantly different when the forearm was in a pronated position. The primary role of the FCR is to flex and radially deviate the wrist (Brand and Hollister, 1993; Drake et al., 2005; Thompson and Netter, 2002). Like the BRAR, the FCR was significantly more active when pronating than supinating, but only when the arm was in a supinated position. Palmaris longus acts primarily as a wrist flexor (Brand and Hollister, 1993;

Drake et al., 2005; Thompson and Netter, 2002). In this study, it was significantly more active when pronating than supinating in all forearm positions except those from mid to full pronation. With the forearm in a supinated position, it was more active than any other muscle. Clearly, muscles beyond the primary forearm pronators and supinators should be included in any analysis of forearm rotation. Further research is necessary to understand whether these additional muscles are involved agonistically or antagonistically. Those muscles that cross the wrist (the APL, FCR and PL) may assist in the application of torque to the handle. Alternatively, they may act to brace the wrist and better facilitate transfer of the torque generated by the primary forearm rotators to the hand. The EMG data presented in this paper will be valuable to furthering that research.

There are several limitations that need to be considered when interpreting the data collected in this study. Crosstalk is an issue that can affect EMG data and is a particular concern in the forearm, given the close proximity of muscles. Fine-wire electrodes, as used in this study, substantially reduce crosstalk relative to surface electrodes (Solomonow et al., 1994). They were also necessary to record the activity of deep muscles. However, while muscle force is related to the number of activated motor units, muscles are not activated homogeneously (van Zuylen et al., 1988). The activity recorded by an electrode (especially fine-wire) may not accurately represent the activity of the muscle as a whole. This may partially explain the considerable inter-individual variability observed in this study. While these limitations are problematic, they are difficult to overcome in a study of this kind. In future research, it may be valuable to use high density EMG arrays to evaluate forearm muscle activity during pronation and supination (Rojas-Martínez et al., 2012). With 23 upper limb muscles attaching in the forearm and only one degree of freedom (pronation-supination), the forearm is a heavily over-defined system. It may be that different individuals employ different activation strategies to achieve forearm rotation.

Accounting for those activation strategies could reduce the variability observed in this study for individual muscle activations. Finally, upper limb posture can affect forearm rotation (Funk et al., 1987; Gielen and van Zuylen, 1986; O'Sullivan and Gallwey, 2002; Winters and Kleweno, 1993) and the mechanical advantage of muscles can change with the external axis of rotation (Carson et al., 2000). Therefore, the data presented in this paper is specifically applicable to gripping forearm rotation with the elbow flexed at 90° and a neutral wrist. Further research is necessary to determine muscle activity during pronation and supination with the upper limb in alternative postures.

In conclusion, this paper presents the muscle activation data for 15 upper limb muscles during maximal gripping pronation and supination, in nine positions of forearm rotation. Consistent with literature, the primary forearm pronators and supinators, the BB, PQ, PT and SUP, were all significantly more active in their respective effort directions. The APL, BRA, BRAR, FCR and PL were also significantly more active in one effort direction than the other. With the exception of BB, significant co-contraction was observed for all muscles, regardless of the effort direction. This information is important for understanding joint loads in the forearm and will be particularly valuable when modelling forearm biomechanics. Most muscles with attachments in the forearm are active during resisted forearm rotation and will contribute to the loads experienced at the DRUJ. Incorporating their activity into future biomechanical analyses will provide more accurate estimates of forearm joint loads and facilitate advances in the treatment of forearm fractures, trauma-induced muscle dysfunction and joint replacement implants and techniques.

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Conflict of interest statement

There are no financial or personal conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Table 1. List of muscles included in the study with their abbreviations.

Abbreviation	**Muscle**
APL	Abductor pollicis longus
BB	Biceps brachii
BRA	Brachialis
BRAR	Brachioradialis
ECRB	Extensor carpi radialis brevis
ECRL	Extensor carpi radialis longus
ECU	Extensor carpi ulnaris
EIP	Extensor indicis proprius
EPL	Extensor pollicis longus
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
PL	Palmaris longus
PQ	Pronator quadratus
PT	Pronator teres
SUP	Supinator

Table 2. Muscles and subjects in sub-studies.

Group	Muscles	Subjects	Male	Female	Mean Age (SD)	Repeats
1	APL, ECU, FCU	11	7	4	26.3 (2.5)	0
2	BB, ECRB, EPL, FCR	11	8	3	25.6 (3.2)	6
3	ECRL, EIP, PT, SUP	11	6	5	26.5 (2.6)	9
4	BRA, BRAR, PL, PQ	11	6	5	26.4 (3.1)	9

Table 3. Significant differences in muscle activity. Sup indicates significantly more muscle activity when supinating the forearm than pronating. Pro indicates significantly more muscle activity when pronating the forearm than supinating. NS indicates no significant difference in muscle activity when pronating and supinating the forearm.

Muscle	**Direction**	**p-value**
APL	Sup	<0.0001
BB	Sup	<0.0001
BRA	Pro	<0.0001
BRAR	Pro	0.0479
ECRB	-	NS
ECRL	Pro	0.0227
ECU	-	NS
EIP	-	NS
EPL	-	NS
FCR	Pro	0.0103
FCU	-	NS
PL	Pro	0.0056
PQ	Pro	<0.0001
PT	Pro	<0.0001
SUP	Sup	0.0042

Table 4. Relative activation of muscles when pronating the forearm. Muscles are listed in descending order of activity (highest to lowest) at each forearm position.

	Pmax	P75	P50	P25	N	S25	S50	S75	Smax
1	PQ	PQ	PQ	PQ	PQ	PL	PL	PL	PL
2	PT	PT	PT	PT	PL	PT	PT	PQ	FCR
3	EIP	ECU	FCR	ECU	ECU	PQ	PQ	FCR	ECU
4	ECU	EIP	ECU	PL	PT	FCR	ECU	ECU	PQ
5	SUP	SUP	ECRB	FCR	FCR	ECU	FCR	PT	PT
6	ECRL	EPL	EPL	EIP	ECRB	SUP	SUP	SUP	SUP
7	EPL	ECRL	PL	SUP	SUP	BRAR	BRAR	BRAR	BRAR
8	PL	ECRB	EIP	ECRL	ECRL	EIP	APL	ECRB	FCU
9	APL	APL	APL	ECRB	EIP	ECRL	BRA	BRA	APL
10	ECRB	PL	ECRL	EPL	EPL	APL	EIP	APL	ECRB
11	BRA	FCR	SUP	APL	APL	FCU	ECRL	FCU	ECRL
12	BRAR	BRAR	BRAR	BRAR	BRAR	ECRB	ECRB	EIP	EIP
13	FCR	BRA	BRA	BRA	BRA	BRA	FCU	ECRL	BRA
14	FCU	FCU	FCU	FCU	FCU	EPL	EPL	EPL	EPL
15	BB	BB	BB	BB	BB	BB	BB	BB	BB

Table 5. Relative activation of muscles when supinating the forearm. Muscles are listed in descending order of activity (highest to lowest) at each forearm position.

	Pmax	P75	P50	P25	N	S25	S50	S75	Smax
1	ECU	ECU	ECU	ECU	SUP	APL	BB	BB	BB
2	SUP	SUP	BB	SUP	ECU	SUP	APL	APL	SUP
3	BB	APL	SUP	BB	BB	BB	SUP	SUP	APL
4	APL	BB	APL	APL	APL	ECU	EIP	EPL	ECU
5	ECRB	ECRB	FCR	ECRB	EPL	EPL	EPL	EIP	EPL
6	ECRL	PL	ECRB	EPL	EIP	ECRB	ECU	ECU	EIP
7	FCU	FCR	EIP	EIP	ECRL	ECRL	ECRB	FCR	FCR
8	BRAR	ECRL	PL	FCR	ECRB	EIP	PQ	ECRL	ECRL
9	EPL	BRAR	ECRL	ECRL	PQ	FCR	ECRL	FCU	FCU
10	PL	EIP	EPL	PL	FCR	FCU	PL	ECRB	PL
11	EIP	EPL	BRAR	FCU	BRAR	PL	FCU	PL	ECRB
12	FCR	FCU	FCU	BRAR	FCU	PQ	BRA	BRA	PT
13	PQ	PQ	PQ	PQ	PL	BRAR	FCR	PQ	BRA
14	BRA	BRA	BRA	BRA	BRA	PT	PT	PT	PQ
15	PT	PT	PT	PT	PT	BRA	BRAR	BRAR	BRAR

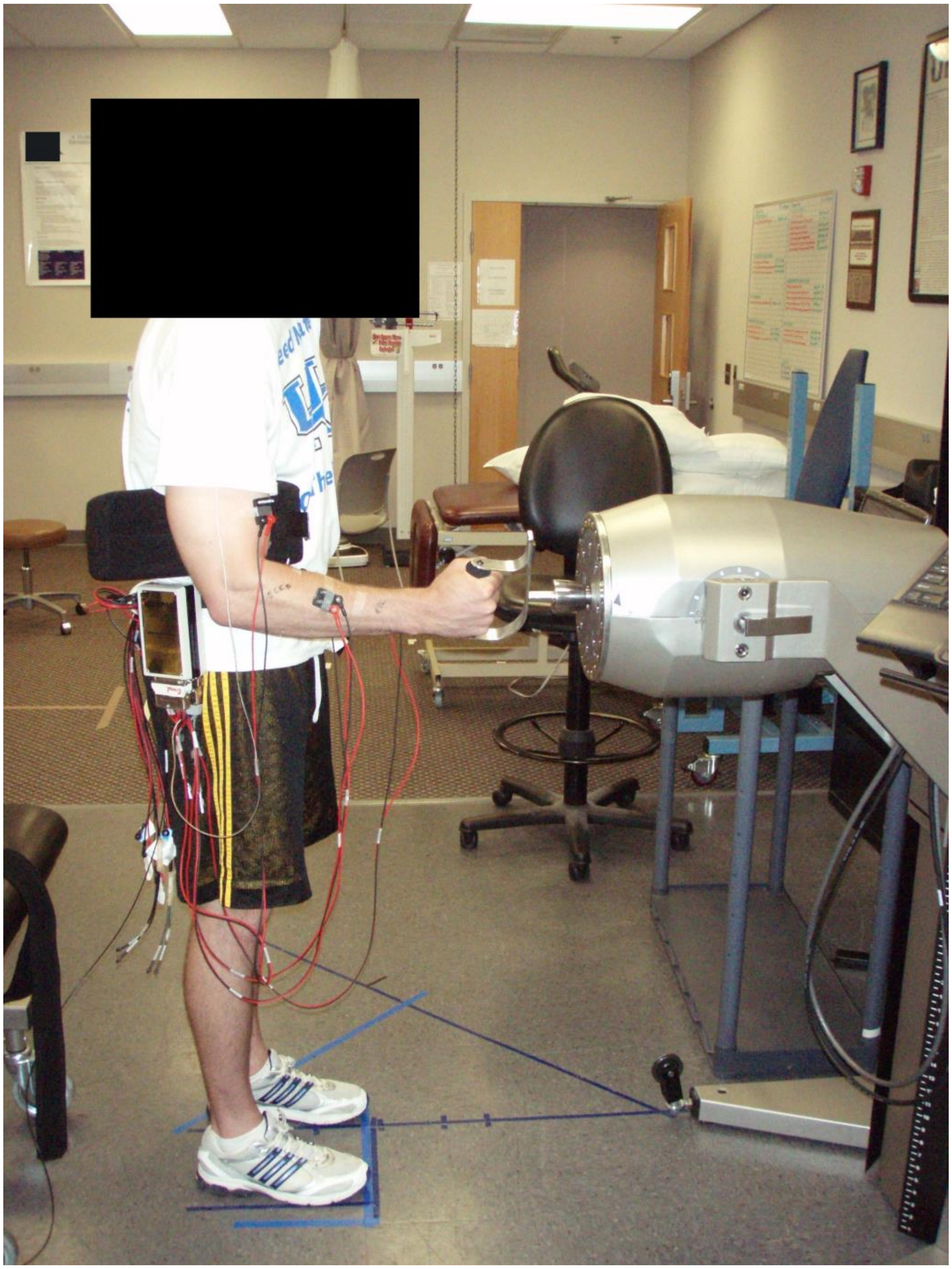

Figure 1. Experimental setup. Subject stood and gripped handle of dynamometer with elbow flexed at 90°. Position of feet was marked and abduction pillow placed under upper arm to standardise posture between trials.

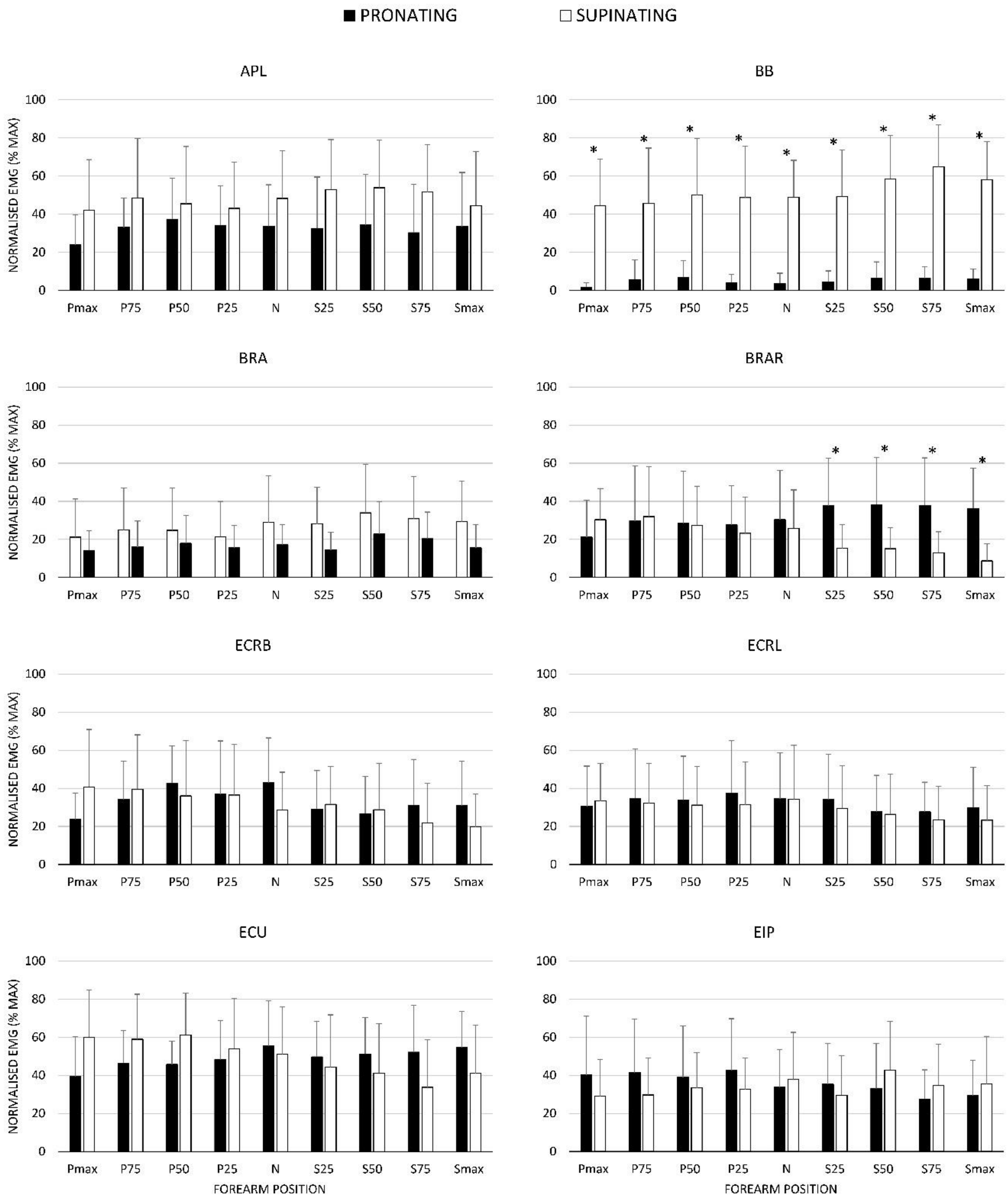

Figure 2. Average, normalised muscle activity during maximum voluntary isometric pronation (black) and supination (white). Error bars represent one standard deviation. * indicates a significant difference ($p < 0.05$) in muscle activity between pronating and supinating.

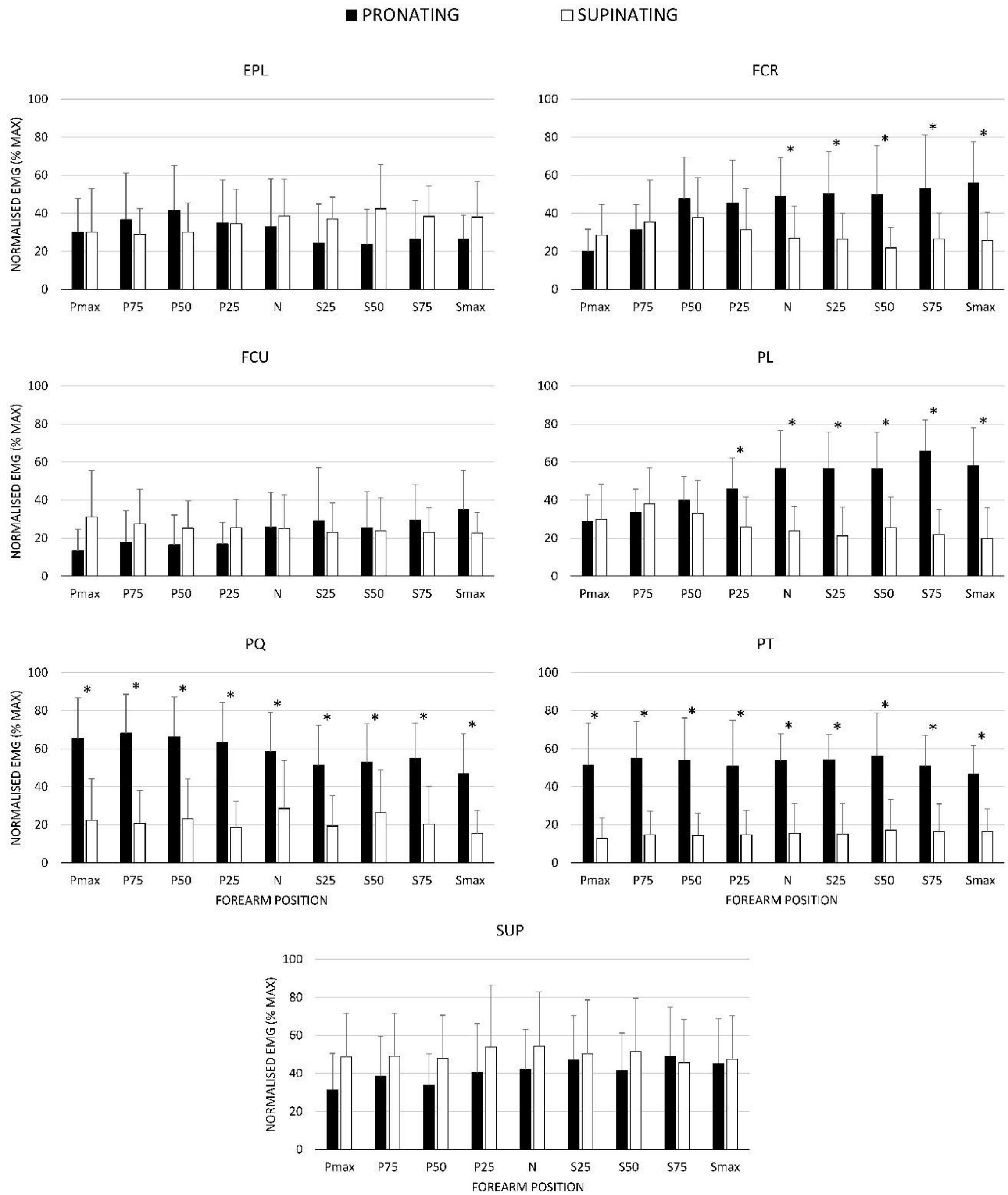

Figure 3. Average, normalised muscle activity during maximum voluntary isometric pronation (black) and supination (white). Error bars represent one standard deviation. * indicates a significant difference ($p < 0.05$) in muscle activity between pronating and supinating.