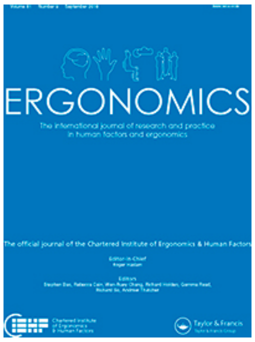

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Wrist strength is dependent on simultaneous power grip intensity

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The effect of grip activities on wrist flexion/extension strength was examined. Twelve healthy subjects performed maximum wrist flexion/extension exertions with one of five levels of simultaneous grip effort: minimum effort; preferred effort; 30%, 60% and 100% maximum voluntary contraction. As grip force increased from the minimum to the maximum effort, average wrist flexion strength increased 34% and average wrist extension strength decreased 10%. It appears that the finger flexor tendons on the volar aspect of the wrist act agonistically in wrist flexion and act antagonistically to wrist extension. When an object gripped by the hand is fragile or uncomfortable, the reduced finger flexor activity will limit wrist flexion strength. Gripping a slippery object that requires high grip effort will result in reduced wrist extension strength. Grip force should be controlled during measurement of wrist flexion or extension strength. When analysing a task that involves both grip and wrist exertions, use of grip/wrist strength values that were measured during grip exertions only, or wrist exertions only, may incorrectly estimate the true grip/wrist strength, as grip and wrist activities significantly interact with each other as demonstrated in this paper.

Keywords: wrist flexion–extension; grip force; wrist moment; hand biomechanics; wrist biomechanics

1. Introduction

1.1. Background

Human strength data are used as an ergonomic guideline in product design or workstation design. They are used to ensure that muscular efforts required to use a product or complete a given task do not exceed the strength capability of users or workers and to further prevent overexertion, localised fatigue (Rohmert 1973, Bystrom and Fransson-Hall 1994), injury and cumulative trauma disorders (Armstrong *et al*. 1993, Bernard 1997, NRC 1999, Kumar 2001, NRC/IOM 2001). Because gripping an object and applying torque with the hand is a ubiquitous task in people's daily lives, many investigators have reported grip strength data and wrist strength data (Lehman and Calhoun 1990, Hallbeck 1994, Zellers and Hallbeck 1995, Delp *et al*. 1996, Gonzalez *et al*. 1997, Fong and Ng 2000, Marley and Thomson 2000, Jung and Hallbeck 2002, Morse *et al*. 2006). Grip strength has also been used to assess the efficacy of hand surgery or rehabilitation programmes (Anderson *et al*. 1990, Boissy *et al*. 1999, Mercier and Bourbonnais 2004).

In many studies that measured wrist strengths, however, simultaneous grip force measurements were not reported, even though the anatomy of the wrist suggests that wrist

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strength should be influenced by finger flexor muscle activities. Finger flexor tendons are located on the volar aspect of the wrist flexion–extension rotation axis – the same side as wrist flexor tendons in reference to the wrist joint (Brand and Hollister 1993, Holzbaur *et al.* 2005). Thus, contraction of the finger flexor muscles will automatically generate a wrist flexion moment. Therefore, the aim of this study was to demonstrate and quantify the effect of a simultaneous grip force on wrist flexion/extension strength by systematically varying a grip force level.

1.2. Wrist model

A modified wrist moment model is proposed, which can explain the effect of a simultaneous grip force on wrist flexion/extension strength. Previously, a wrist flexion/extension moment has been modelled by Buchanan *et al.* (1993), Gonzalez *et al.* (1997) and Holzbaur *et al.* (2005). Gonzalez *et al.* (1997) and Holzbaur *et al.* (2005) calculated wrist flexion moment by summing products of all flexor muscle forces and their moment arms, as shown in Equation 1. Wrist extension moment was calculated by summing products of all extensor muscle forces and their moment arms. This model assumed that, during maximum wrist flexion exertions, all flexor muscles (including finger flexor muscles) are maximally activated, whereas all extensor muscles are 0% activated. For maximum wrist extension exertions, the model assumed that all extensor muscles are maximally activated and all flexor muscles are idle, including finger flexor muscles.

$$\mathrm{M} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \text{muscle force}_{\mathrm{i}}\ \mathrm{r}_{\mathrm{i}} \tag{1}$$

where M is the applied external moment, m is the number of muscles involved in generating a moment and r is the muscle moment arm vector. Muscle force was calculated by a product of the physiological cross-sectional area and the scale factor (Gonzalez *et al.* 1997, Holzbaur *et al.* 2005).

Buchanan *et al.* (1993) used electromyography (EMG) for two flexors and three extensors to estimate wrist moments using the following equation, where ρ is the force-EMG coefficient. They did not include finger flexors or extensors in the model.

$$\mathrm{M} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{EMG}_{\mathrm{i}}\ \rho_{\mathrm{i}}\ \mathrm{r}_{\mathrm{i}} \tag{2}$$

The proposed wrist model herein predicts a wrist moment (M) as a sum of products of muscle forces and moment arms (r), discounted by relative EMG levels (0–1.0), for muscles involved in generating a moment (m).

$$\mathrm{M} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \text{muscle force}_{\mathrm{i}}\ \mathrm{r}_{\mathrm{i}}\ \mathrm{EMG}_{\mathrm{i}} \tag{3}$$

This expression means that the wrist moment depends on each muscle's activity. In particular, the wrist flexion moment may increase with increasing finger flexor muscle activities, i.e. flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP). The wrist extension moment may increase with decreasing FDS and FDP muscle activities. Given that wrist exertions are rarely performed without grip exertions, it is important to quantify how much wrist flexion/extension strength is affected by a simultaneous grip force.

1.3. Hypothesis

Based on the wrist model (Equation 3), it was hypothesised that wrist flexion strength should increase with an increasing grip force and wrist extension strength should decrease with an increasing grip force.

2. Methods

2.1. Procedures

An experiment was conducted where maximum wrist flexion and extension strengths were measured while exerting grip forces at five different levels. Four pairs of bipolar surface EMG electrodes were placed over two finger flexor muscles, one wrist flexor muscle and one wrist extensor muscle. Specifically, one pair of electrodes was placed parallel to the proximal muscle belly fibres of FDP on the medial side of the right forearm (Garland and Miles 1997). The second pair was placed over distal muscle belly fibres of FDS. The other two pairs were placed over flexor carpi radialis (FCR) and extensor carpi radialis (ECR) on the middle of the volar and dorsal right forearm, respectively (Basmajian 1989).

Subjects were seated with their right elbow flexed at about 90°, the forearm semi-prone resting horizontally on a table and the wrist neutral. Subjects grasped a grip dynamometer with their right hand in a power grip, with the major axis of the force gauge perpendicular to the subjects' forearm (see Figure 1). First, subjects performed maximum isometric grip exertions to determine their grip strength. Then, subjects were instructed to perform the maximum isometric wrist flexion or extension exertions while maintaining their grip forces as follows: 1) 'as little as possible'; 2) 'as high as possible'; 3) at 30% or 4) 60% of their maximum grip force; 5) 'at a preferred level'. For wrist exertions with 30% or 60% of maximum grip force, a target grip force and an actual grip force were displayed on a computer screen so that the subjects could match their grip force to the target level. For the preferred level grip, subjects were left to decide for themselves whatever grip force they preferred to use during maximum wrist exertions. Thus, subjects could focus on wrist exertions. The authors were concerned that maintaining a specified percent effort while exerting maximum wrist flexion or extension torque was an unnatural exertion and that the recruitment of agonistic and antagonistic muscles might be altered. The preferred grip made it possible to see how the natural exertion compared with the contrived exertion used in this experiment. It also made it possible to see how natural grip force was affected by the wrist flexion or extension exertion.

Subjects were instructed to keep their forearm and elbow on the table during the exertions to minimise involvement of the upper arm or torso. A cushioned wrist support was provided to steady the forearm while producing wrist moments. Subjects were instructed to keep the fingers on the grip dynamometer in a power grip posture, as opposed to flattening the hand, even during wrist exertions with minimum grip effort. Subjects were allowed to practise before testing. Each exertion lasted for 5 s. Conditions (grip force level) were presented to subjects in a random order. Each condition was tested twice. A 2-min break was provided between successive trials. The wrist flexion or extension moment, grip force and EMG was recorded simultaneously and averaged over 2 s during the maximum wrist flexion or extension exertions. Wrist moment and grip force were measured at 5 Hz.

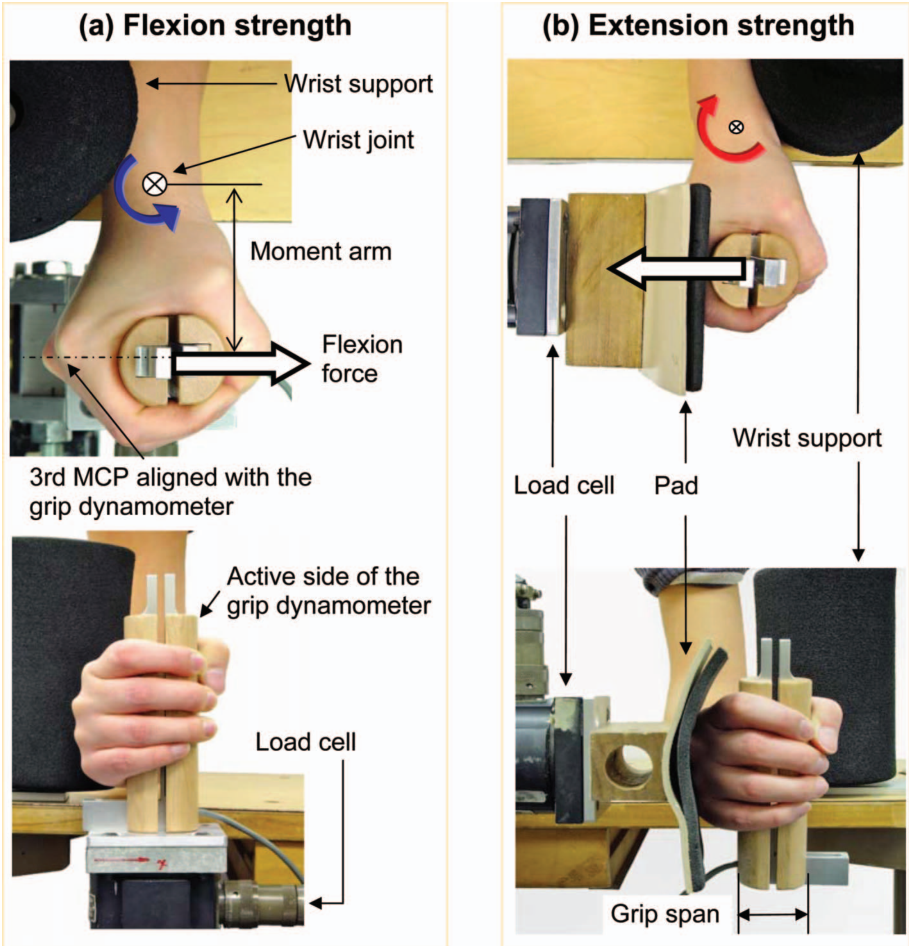


Figure 1. The top view (top) and the front view (bottom) of apparatus for measuring flexion strength (a) and extension strength (b). The major axis of the force gauge in the grip dynamometer was perpendicular to the forearm. For flexion strength measurements, the active side of the grip dynamometer was placed where the fingertips were and the grip dynamometer was attached to the load cell. Wrist flexion and extension forces were measured by the load cell. A cushioned wrist support was provided to subjects for leverage. MCP = metacarpophalangeal.

2.2. Apparatus

Grip force was measured using a grip dynamometer, which consisted of a force gauge connecting two parallel bars. The grip dynamometer had a width of 3.84 cm. Grip span was adjusted so that subjects could place their third metacarpophalangeal joint aligned with the centre of the grip dynamometer and the direction of flexion/extension force, as shown in Figure 1(a). The mean grip span was 4.25 cm, with a mean handle circumference of 13.5 cm.

For wrist flexion strength measurements, the bottom of the grip dynamometer was attached to a load cell, which measured wrist flexion force from the metacarpophalangeal joints. The active side of the grip dynamometer was placed below the fingers so that finger gripping force could be measured by the grip dynamometer (see Figure 1(a)). The wrist flexion moment was determined by multiplying the wrist flexion force by a moment arm. The moment arm was the shortest distance between the wrist joint and the flexion force vector (which is the distance between the wrist joint and the centre of the grip dynamometer).

For wrist extension strength measurements, the grip dynamometer was not attached to a fixture, but grasped by the hand. Subjects placed their metacarpophalangeal joints against the middle of a cushioned pad that was attached to the load cell (Figure 1(b)) and performed maximum wrist extension exertions. The load cell measured wrist extension force. The wrist extension moment was determined by multiplying the wrist extension force by a moment arm. The moment arm is, again, the shortest distance between the wrist joint and the extension force vector.

Muscle EMG was collected using surface EMG electrodes (AMBU Neuroline 720 Wet Gel Ag/AgCl; Ambu Inc., Glen Burnie, MD). The EMG instrumentation had a pre-amplifier gain of 100 and common-mode rejection ratio of 115 dB. The raw signal was converted to real time root mean square values with a 55 ms time constant. Among all maximum exertions, the highest EMG value was used to normalise other EMG values as a percentage of maximum voluntary contraction.

ANOVA was performed to examine the relationship between the wrist strengths and the various grip forces, as well as the relationship between wrist strength and muscle activities. MINITAB® (Release 14; Minitab Inc., State College, PA) was used to perform statistical analyses.

2.3. Subjects

A total of 12 healthy subjects (six males and six females, aged between 18 and 35 years, mean age 27.1 $\pm$ 5.4) participated in the experiment. They were students or office workers. All participants were right-handed and were free of any upper extremity disorders. Each gave written informed consent prior to testing.

The subjects' hand length, measured using the method by Garrett (1971), ranged from 6th percentile to 86th percentile for males and 1st percentile to 78th percentile for females, based on air force population data from Garrett (1971). The subjects' right-hand grip strength determined with a Jamar dynamometer (Sammons Preston, Bolingbrook, IL) with a grip span of 49 mm ranged from the 24th to 96th percentile for males and 14th to 88th percentile for females, based on population data from Mathiowetz *et al.* (1985).

2.4. Model prediction

Wrist flexion and extension strengths were calculated using the model in Equation 3. Measured FDP, FDS, FCR and ECR EMG was input into the model. Other wrist flexor muscles (flexor carpi ulnaris, palmaris longus) were assumed to have the same EMG level as FCR, based on Mogk and Keir (2003). Similarly, other wrist extensor muscle, extensor carpi ulnaris, was assumed to have the same EMG level as ECR, based on Mogk and Keir (2003). Thumb muscles that generate flexion moments (abductor pollicis longus, extensor pollicis longus and flexor pollicis longus) were assumed to be maximally active during wrist flexion exertions and not active during wrist extension exertions, as in Gonzalez *et al.* (1997) and Holzbaur *et al.* (2005). Likewise, thumb and finger muscles that generate extension moments (extensor digitorum communis, extensor digiti minimi, extensor indicis proprius and extensor pollicis brevis) were assumed to be not active during wrist flexion exertions and maximally active during wrist extension exertions, as in Gonzalez *et al.* (1997) and Holzbaur *et al.* (2005). Thus, the main difference in the present model compared to the previous one in Gonzalez *et al.* (1997) and Holzbaur *et al.* (2005) was that activities for wrist flexor muscles, wrist extensor muscles and finger flexor muscles varied for each condition.

Muscle forces were adopted from Holzbaur *et al.* (2005). Moment arms (r in Equation 3) for each muscle were adopted from Brand and Hollister (1993). The model prediction was compared to the measured wrist flexion/extension strengths using paired t-test.

3. Results

Maximum grip strength and wrist flexion and extension strengths for each grip force are summarised in Table 1 along with EMG recorded for each condition. The average grip strength measured using the grip dynamometer was 462 ± 61 N for males and 211 ± 58 N for females (337 ± 142 N for all subjects). The average wrist flexion strength in the neutral posture was 13.7 ± 3.5 Nm for males and 6.8 ± 2.7 Nm for females. The average wrist extension strength in the neutral posture was 8.4 ± 2.8 Nm for males and 4.2 ± 1.1 Nm for females. The average wrist strength was 63% greater for flexion than for extension. The average wrist flexion and extension strengths for males was twice those for females.

The average wrist flexion strength increased 34% from minimum to maximum grip force. The average wrist extension strength increased 10% from maximum to minimum grip force. The highest grip force observed during maximum wrist flexion was, on average, 85% of the subjects' grip strength. The highest grip force observed during maximum wrist flexion was significantly less than the subjects' grip strength ($p < 0.01$). The highest grip force observed during maximum wrist extension was, on average, 54% of their grip strength. The average preferred grip force observed when the subjects were not instructed

Table 1. Maximum grip strength (max grip) and maximum wrist flexion and extension strengths for different grip force levels with electromyography (EMG) of the wrist flexor (FCR), wrist extensor (ECR) and finger flexors (FDS, FDP).

	Grip level	Grip force (N)	Wrist strength (Nm)	FCR (%)	ECR (%)	FDS (%)	FDP (%)
Max Grip	Max grip	337 ± 142					
Wrist Flexion	Min	56 ± 54	9.1 ± 4.2	68 ± 18	11 ± 5	32 ± 16	64 ± 19
	30%	111 ± 57	9.1 ± 4.4	67 ± 17	11 ± 5	40 ± 16	62 ± 16
	Preferred	165 ± 115	10.6 ± 4.9	76 ± 17	12 ± 6	57 ± 25	76 ± 16
	60%	189 ± 81	10.4 ± 4.8	71 ± 20	12 ± 6	57 ± 20	68 ± 14
	Max	289 ± 125	12.2 ± 5.5	84 ± 12	13 ± 5	85 ± 16	90 ± 12
Wrist Extension	Min	38 ± 38	−6.6 ± 3.3	10 ± 7	75 ± 17	11 ± 5	12 ± 6
	30%	95 ± 42	−6.5 ± 3.6	14 ± 10	71 ± 16	14 ± 7	16 ± 8
	Preferred	102 ± 65	−6.4 ± 3.2	11 ± 8	79 ± 14	19 ± 9	17 ± 11
	60%	162 ± 77	−5.8 ± 2.5	21 ± 17	81 ± 11	28 ± 12	25 ± 11
	Max	181 ± 72	−6.0 ± 2.8	23 ± 21	85 ± 15	30 ± 16	28 ± 18

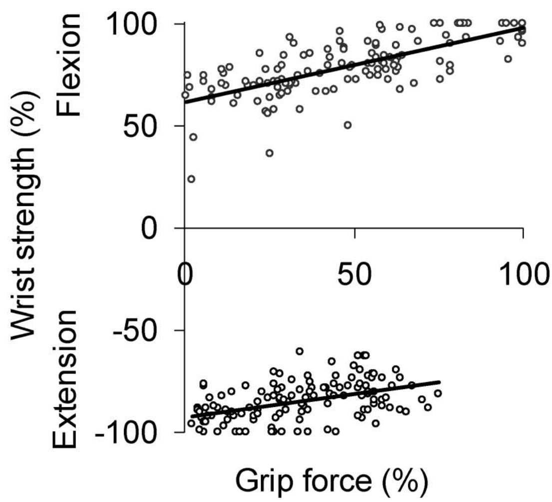
FCR = flexor carpi radialis; ECR = extensor carpi radialis; FDS = flexor digitorum superficialis; FDP = flexor digitorum profundus.

Note: Mean ± SD, data are pooled for six males and six females.

to exert a specific grip force level during maximum wrist flexion exertions was 51% of grip strength (95% CI 43%, 59%). The average preferred grip force during maximum wrist extension exertions was 29% of grip strength (95% CI 22%, 36%).

Wrist flexion and extension strengths are plotted as a function of grip force in Figure 2. Increasing grip force was associated with increasing wrist flexion strength ($p < 0.01$). For wrist extension exertions, increasing grip force was associated with decreasing wrist extension strength ($p < 0.01$). The amount of wrist strength change per 10 N increase in grip force was, on average, + 0.12 Nm for flexion and –0.07 Nm for extension.

In Figure 3, wrist flexion and extension strengths are plotted as a function of finger flexor (FDS, FDP) muscle activities. Wrist flexion strength increased significantly with increasing FDS EMG or increasing FDP EMG ($p < 0.01$). Wrist flexion strength was not significantly correlated with FCR or ECR EMG ($p > 0.05$). Wrist extension strength decreased with increasing FDS or FDP EMG ($p < 0.01$) and increased with increasing ECR EMG ($p < 0.01$). Wrist extension strength was also not significantly correlated with



Response: Flexion strength (%)

Predictor	Coefficient	*p*-value
Constant	61.80	0.00
Grip force (%)	0.36	0.00
R^2 = 50%		

Response: Extension strength (%)

Predictor	Coefficient	*p*-value
Constant	93.29	0.00
Grip force (%)	–0.25	0.00
R^2 = 26%		

Figure 2. Wrist flexion and extension strengths (%, normalised to the maximum flexion or extension strength for each subject) are plotted as a function of grip force level (%, normalised to the maximum grip force for each subject). Data are pooled for six males and six females.

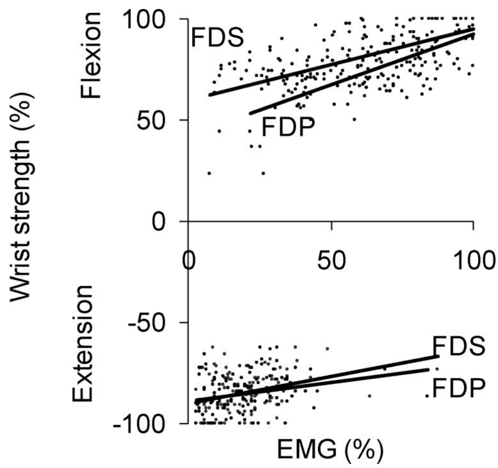


Figure 3. Wrist flexion and extension strengths (%) are plotted as a function of finger flexors (flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP)) electromyography (EMG). Wrist flexion and extension strengths were normalised to each subject's maximum wrist flexion and extension strengths, respectively. Data are pooled for 12 subjects. Wrist flexion and extension strengths (%) significantly varied with finger flexor EMG.

FCR EMG ($p > 0.05$). During wrist extension exertions, a significant negative correlation was found between the finger flexor (FDS, FDP) EMG and ECR EMG.

Predicted wrist flexion and extension strengths compared favourably, as shown in Figure 4, when plotted as a function of grip force using a normalised strength scale. The model predicts that wrist flexion strength increases with increasing grip force and wrist extension strength decreases with increasing grip, as observed experimentally. The predicted wrist flexion and extension strengths were not significantly different from the measured wrist flexion and extension strengths in normalised values (normalised to each subject's maximum strength) ($p < 0.05$). In absolute values, predicted wrist strengths were, on average, 19% less than the measured ($p < 0.05$).

4. Discussion

The data support the proposed hypothesis: wrist flexion strength increased by 34% with a simultaneous grip activity, whereas wrist extension strength decreased by 10% with a simultaneous grip activity (Table 1; Figure 2, Figure 3). Thus, the data support the proposed model in Equation 3. The average predicted wrist strength was 19% less than the measured, probably because subjects who participated in this study were stronger than the average. The average grip strength measured using a Jamar dynamometer for these subjects was 16% higher than the norm provided in Mathiowetz *et al*. (1985). When wrist strength values were normalised to the maximum strength for each subject, the model could predict the measured wrist strength well, as shown in Figure 4. It indicates that the relationship between grip force and wrist strength predicted by the model (Equation 3) was empirically demonstrated.

The present study has the following distinctions from previous studies. Unlike Gonzalez *et al*. (1997) and Holzbaur *et al*. (2005), the present model accounts for antagonistic and agonistic muscle activities (EMG) when predicting wrist strength. Given that pure wrist flexion/extension exertions are seldom performed in people's daily

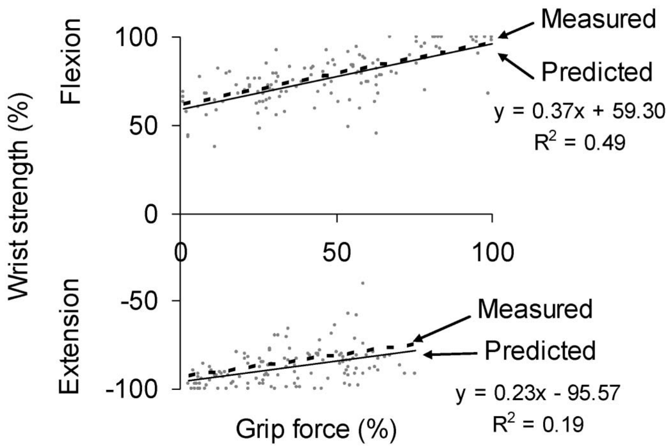


Figure 4. Comparison between measured (the bold segmented regression line, no data point shown) and predicted (the thin solid regression line and data points) wrist moment normalised to each subject's maximum strength.

lives, the data provided in this study can have greater impacts on ergonomic design and analysis.

When subjects were allowed to decide for themselves how much grip force to use, their preferred grip force was 51% of grip strength for wrist flexion exertions and 29% of grip strength for wrist extension exertions. These reflect grip force levels that subjects can generate without concentrating on grip force. The average preferred grip force during wrist flexion exertions was greater than that during wrist extension exertions, probably because grip helps flex the wrist.

The present findings also extend the study of Zellers and Hallbeck (1995), who measured wrist flexion and extension strengths with or without a simultaneous grip. They did not find a statistically significant effect of simultaneous grip on wrist strength. It is probably because grip force levels were not systematically controlled in their study. In addition, potential reasons for why wrist strength would be affected by a simultaneous grip exertion were not provided in their study. The model proposed in the present study (Equation 3) provides a biomechanical basis to explain the effect of grip force on wrist strength.

The present findings imply that, when both grip and wrist extension exertions are required, such as loosening a screw using a screwdriver, wrist extension strength may be significantly limited by the simultaneous grip effort due to muscle antagonism (0.07 Nm decrease in extension moment per 10 N increase in grip force). On the other side, when the grip effort must be limited for a fragile, delicate or an uncomfortable object, reduced finger flexor activity can limit wrist flexion strength (0.12 Nm decrease in flexion moment per 10 N decrease in grip force).

When analysing a task that involves both grip and wrist exertions, use of grip or wrist strength values that were measured during only grip exertions, or only wrist exertions, may not correctly estimate the true grip and wrist strength, as grip and wrist exertions interact with each other. In addition, the finding indicates that, when wrist strength is the outcome measure used to assess strength capacity or the efficacy of hand surgery or rehabilitation programmes, then finger flexor activity should be controlled. Recording finger flexor activities or providing instructions to subjects in regard to grip effort will help ensure consistent and relevant results.

From a theoretical perspective, wrist strength can be maximised by activating 100% of all muscles that generate a desired wrist moment and turning off all other muscles that generate the opposite wrist moment. However, activation of antagonistic muscles is often observed in maximal effort tasks. Specifically, some ECR EMG activity was observed during maximum wrist flexion. Also, some FCR EMG activity was observed during maximum wrist extension. This co-contraction of antagonistic muscles that are unnecessary for generating the prescribed moment has been observed in previous studies (Buchanan *et al.* 1993, Delp *et al.* 1996) and has been discussed as a strategy used to increase the stiffness and stability of a joint (Milner *et al.* 1995, Cholewicki and McGill 1996, Kornecki *et al.* 2001, Milner 2002, De Serres and Milner 1991).

For wrist extension, the ECR EMG increased with decreasing FDS and FDP EMG. It may be that controlling finger and wrist muscles independently was unnatural to subjects. Activating two muscle groups that create an opposite wrist moment might have been particularly difficult. The ECR and finger flexor muscles (FDS, FDP) may have inhibited each other by a central nervous system mechanism (Sherrington 1906, Aymard *et al.* 1995, Carroll *et al.* 2005). In fact, the grip force measured during maximum wrist extension with maximum grip effort was only 54% of the subjects' grip strength and FDS and FDP EMG levels were only 30% and 28%, respectively. This decreased grip force with simultaneous wrist extension agrees with Zellers and Hallbeck (1995). This finding implies that human force capabilities are sensitive to the context as well as the activities of synergist and antagonist muscles and that they cannot be estimated by superposition of individual strengths of multiple muscles.

Consistent with previous studies, wrist strength was greater for males than for females (Hallbeck 1994, Zellers and Hallbeck 1995, Morse *et al.* 2006) and for flexion than for extension (Hallbeck 1994, Delp *et al.* 1996, Gonzalez *et al.* 1997, Marley and Thomson 2000, Morse *et al.* 2006). Wrist strengths measured in this study were not significantly different from those reported by others (Ketchum *et al.* 1978, Anderson *et al.* 1990, Delp *et al.* 1996, Holzbaur *et al.* 2007).

The exertions performed in this study were isometric. Muscle lengths remained constant throughout the study. Muscle lengthening velocities were zero. For tasks that involve wrist movements, changing muscle lengths and muscle shortening and lengthening will significantly influence both grip and wrist strengths (Loren *et al.* 1996, Fong and Ng 2000, 2001).

In this study, EMG was measured for four muscles – two finger flexor muscles (FDS, FDP), one wrist flexor muscle (FCR) and one wrist extensor muscle (ECR). Although these four muscle EMGs were sufficient to demonstrate the effect of grip on wrist strength (Figure 4), measurement of EMG for more muscles, especially the finger extensor (EDC), is expected to improve the accuracy of model prediction. The contraction of the EDC muscle may contribute to generating a wrist extension moment based on its tendon location at the wrist (Brand and Hollister 1993, Holzbaur *et al.* 2005). Not being able to maximally contract EDC during grip could have been associated with reduced wrist extension strength. In addition, intrinsic hand muscles or the thumb contribute to grip. Future studies may investigate the contribution of EDC and the thumb to wrist and grip exertions.

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