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The effects of posture on forearm muscle loading during gripping

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The purpose of this study was to quantify the response of the forearm musculature to combinations of wrist and forearm posture and grip force. Ten healthy individuals performed five relative handgrip efforts (5%, 50%, 70% and 100% of maximum, and 50 N) for combinations of three wrist postures (flexed, neutral and extended) and three forearm postures (pronated, neutral and supinated). 'Baseline' extensor muscle activity (associated with holding the dynamometer without exerting grip force) was greatest with the forearm pronated and the wrist extended, while flexor activity was largest in supination when the wrist was flexed. Extensor activity was generally larger than that of flexors during low to mid-range target force levels, and was always greater when the forearm was pronated. Flexor activation only exceeded the extensor activation at the 70% and 100% target force levels in some postures. A flexed wrist reduced maximum grip force by 40–50%, but EMG amplitude remained elevated. Women produced 60–65% of the grip strength of men, and required 5–10% more of both relative force and extensor activation to produce a 50 N grip. However, this appeared to be due to strength rather than gender. Forearm rotation affected grip force generation only when the wrist was flexed, with force decreasing from supination to pronation ($p < 0.005$). The levels of extensor activation observed, especially during baseline and low level grip exertions, suggest a possible contributing mechanism to the development of lateral forearm muscle pain in the workplace.

1. Introduction

Upper extremity work-related musculoskeletal pain and injury have been a catalyst for research to determine the key risk factors in a variety of work tasks. The combination of high forces, awkward postures and continuous or prolonged gripping has been associated with the symptoms of upper extremity disorders (Silverstein *et al.* 1986, Armstrong *et al.* 1993, Fransson-Hall *et al.* 1995, de Zwart *et al.* 2001). Over time, ergonomic advances have led to a reduction in the external forces required of workers through improvements in work and equipment design. Nonetheless, distal upper extremity injuries continue to mount, suggesting that external forces alone cannot explain injury prevalence. This is well demonstrated by forearm muscle pain in gripping. The finger flexors are the prime movers in gripping, yet more complaints have been reported for the extensor muscles of the forearm (Ranney *et al.* 1995).

   Upper extremity posture has been shown to alter grip force production and is an important risk factor for work-related musculoskeletal disorders (WRMSD). Grip

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force is greatly decreased with wrist flexion (Imrhan 1991, Duque *et al.* 1995, Dempsey and Ayoub 1996, Halpern and Fernandez 1996, Kattel *et al.* 1996, Claudon 1998). Pronation of the forearm has also been shown to reduce grip force, but the effects of supination are less clear (Halpern and Fernandez 1996, Richards *et al.* 1996, Claudon 1998, De Smet *et al.* 1998, Mogk and Keir 2003). It also appears that some of the differences in force attributed to the type of pinch grip may be partially due to forearm rotation (e.g. Imrhan 1991).

Of these grip strength studies, few have simultaneously investigated muscular response using electromyography (EMG) (Duque *et al.* 1995, Claudon 1998). And, although extensor EMG has been examined in a number of laboratory grip studies and workplace simulations, it has typically been used as a method of monitoring muscular fatigue rather than to quantify muscle activity itself (Byström and Kilbom 1990, Byström *et al.* 1991, Dahalan and Fernandez 1993, Byström and Fransson-Hall 1994, Hägg and Milerad 1997; Hägg *et al.* 1997, Klein and Fernandez 1997). While most studies have evaluated grip force relative to an individual's maximum grip force, forces in the workplace are absolute, thus independent of the worker's strength and represent a different percentage of maximum effort for each worker. A thorough examination of the interaction between grip force and posture is needed to evaluate forearm muscle loading during grip tasks, and potential contributions to forearm pain.

The intricate nature of the forearm anatomy precludes the existence of a simple relationship between EMG amplitude and grip force. Muscle length and muscle force both play important roles in further defining this relationship. Muscle lengths will change with wrist flexion and extension (Lieber *et al.* 1994) with similar, but smaller, changes resulting from forearm rotation (Ljung *et al.* 1999a). Such changes in posture may affect EMG amplitude (Inbar *et al.* 1987, Okada 1987, Doud and Walsh 1995) as well as muscle synergies (Buchanan *et al.* 1989, Sergio and Ostry 1995). Changes in moment arms occur concurrently with muscle length changes, altering each muscle's moment potential at a given joint, thus further complicating the EMG-force relationship for each muscle (Loren *et al.* 1996).

Although not unique to the forearm, the need to stabilize a joint with multiple degrees of freedom or one which biarticular muscles cross is exemplified at the wrist. Co-contraction of the wrist extensors is necessary to stabilize the wrist during gripping tasks (Snijders *et al.* 1987), and is likely the reason that gripping tasks have been reported to fatigue the extensors more quickly than the flexor muscles (Byström *et al.* 1991, Hägg and Milerad 1997). Furthermore, extensor muscle fatigue has been attributed to sustained activation, as indicated by fewer pauses in extensor activity than in the forearm flexors (Hägg *et al.* 1997). Thus, the activation required to stabilize the wrist joint and oppose gravity appears to be important, yet has often been ignored due to its perceived negligibility (cf. Duque *et al.* 1995). Historically, muscular loading of $2-5\%$ maximum voluntary electrical activation (MVE) has been proposed as the upper limit for continuous work over the course of a day (Jonsson 1978), but some believe a limit of 1% MVE may be more appropriate for what has been termed 'static' loading (Aarås and Westgaard 1987). The simple act of holding a tool may lead to continuous low level loading, which may limit the amount of muscular rest received between work cycles and contribute to physiological damage to the forearm extensors. The level of muscular effort is dependent on individual strength, which may predispose certain individuals to an increased risk of injury.

The difficulty of measuring grip force in occupational settings has made EMG-based grip force models attractive and enduring (e.g. Armstrong *et al.* 1979). However, further development of the relationship between force, posture and muscle activity is required. Previous relationships have provided insight into the force and muscle activity levels required in the workplace, but have excluded forearm rotation (Duque *et al.* 1995), used non-normalized grip forces (Cook *et al.* 1998), or have used a supported dynamometer and examined only finger muscles (Claudon 1998). In addition, two of the aforementioned studies (Duque *et al.* 1995, Claudon 1998) were based on either males or females, thereby excluding a comparison to establish gender differences. Further examination of grip force, with the inclusion of the wrist musculature and requiring subjects to support the dynamometer, would contribute to a better understanding of the physiological basis for the loading, fatigue and injury of the extensor muscles in the workplace.

The aim of this study was to determine the effects of wrist and forearm posture on the loading of the flexor and extensor muscles of the wrist and fingers during grasping at several effort levels. This examination included absolute and relative grip forces from zero to maximal exertion. A secondary focus was on the repeatability of grip force and EMG response between test sessions, as well as gaining insight into muscle activity differences between men and women.

2. Methods

2.1. *Participants*

Ten healthy volunteers participated in this study. Five males had a mean age of 23.0 (SD 1.6) years and five females had a mean age of 25.2 (1.1) years. All participants were pain free at the time of testing, and reported no history of hand, wrist or forearm dysfunction. Male participants were 172.0 (9.0) cm tall, with a mass of 85.7 (26.0) kg, and a forearm circumference of 28.7 (3.4) cm. Female participants were 168.2 (5.3) cm tall, had a mass of 61.7 (6.3) kg, and a forearm circumference of 23.8 (1.4) cm.

2.2. *Apparatus*

Each participant sat upright in a chair with a back support inclined 15° from the vertical. The right forearm rested on a horizontal platform while the hand and wrist were unsupported (figure 1). The platform height was adjusted to standardize elbow, shoulder and trunk postures. The upper arm was aligned with the trunk and in 0° abduction, resulting in an elbow angle of 105°. Each trial was monitored on a television screen to ensure that proper posture was maintained. The height of the platform was recorded so that individual settings could be repeated for the retest.

Grip force was measured using a grip dynamometer (MIE Medical Research Ltd., Leeds, UK) with a grip span of 5.0 cm for all participants. The dynamometer had a mass of 0.454 kg. Video data was synchronized with EMG and force data for later analysis. Neutral wrist posture was defined as the anatomical position of the wrist, such that the dorsal surfaces of the hand and forearm formed a straight line and the third metacarpal was parallel to the lateral border of the radius. A mirror apparatus, angled at 45°, allowed radio-ulnar deviation and wrist flexion-extension angles to be recorded simultaneously with a single video camera (figure 1a). To ensure repeatability of the angles, lines were drawn on the forearm to represent neutral deviation for each view and forearm posture at the beginning of each session. A line
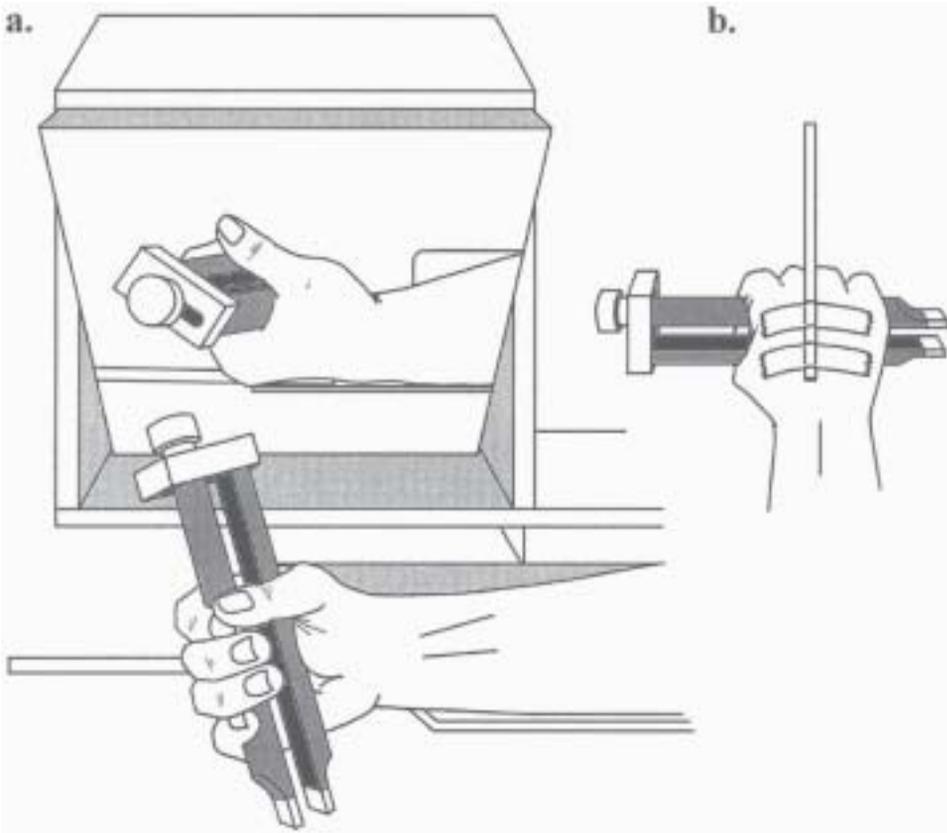
Figure 1. Schematic of the mirror apparatus designed to monitor and measure wrist angles, as seen from the video camera. (a) Illustrated is the neutral wrist and forearm posture, with wrist flexion-extension angle apparent in the mirror image. Radio-ulnar deviation was measured as the angle of the pointer relative to the line drawn on the forearm. Inset, (b) pointer affixed to the back of the hand, with the line used for radio-ulnar deviation measurements in pronation. Reprinted from *Journal of Electromyography & Kinesiology*, 13(1), p. 65, 2003, Mogk & Keir, with permission from Elsevier.

representing a neutral wrist posture for supination was drawn parallel to the radius on the ventral surface of the forearm, and another for the neutral forearm position (figure 1a). A similar line was drawn on the dorsal surface of the forearm for pronation (figure 1b). Maintenance of wrist posture was assisted by a pointer taped between the 3rd and 4th metacarpal bones, which was aligned with the corresponding line drawn on the forearm parallel to the radius (figure 1b).

2.3. *Protocol*
EMG was normalized to maximum voluntary electrical activation (MVE) after removal of signal bias (determined from a 'quiet' trial). Peak EMG values were determined through a series of trials including maximum grip force with voluntary isometric wrist extension, forceful voluntary wrist circumduction and resisted finger extension. Two efforts of each trial were used to determine MVE for each muscle, since it was desired to normalize EMG to the absolute maximum level recorded from

the muscle rather than just the maximum value observed during the given task. Peak EMGs were carefully selected to exclude extraneous values due to non-physiological spikes.

Maximum grip force (denoted 'Grip$_{max}$') was determined for each participant with the forearm in mid-prone (neutral) and the wrist in a neutral posture, taking the larger of two efforts to calculate target force levels as a percentage of Grip$_{max}$. Four relative target levels (5%, 50%, 70% and 100% Grip$_{max}$) and one absolute target force of 50 N were performed. The 50N target force was included to reflect the nature of exerted forces in the workplace, in particular the fact that an absolute amount of force is required to operate hand tools and that the relative effort exerted will be a function of the individual's strength. Each target force was performed at each of three wrist angles (45° flexion, neutral, 45° extension) in each of three forearm rotation angles (full pronation, neutral, full supination) for a total of 45 efforts (nine postures × five effort levels).

To maintain target grip force, participants viewed an oscilloscope placed directly in front of them showing the grip dynamometer output. The oscilloscope display was arranged so that the dynamometer force was maximized for each target level and a major division (line) on the oscilloscope screen represented the target force. Participants were told to maintain the force level at the target line as steadily as possible. For each trial, participants were instructed to hold the grip dynamometer in the appropriate posture without exerting any force (referred to as 'baseline' and equal to 0% Grip$_{max}$), then ramp up to the target force and hold for 3 s before returning to baseline. Each trial was completed in 10 s. It was emphasized to participants to concentrate on maintaining the desired posture throughout each trial while increasing to and sustaining target force levels.

Postures and target forces were randomized with a minimum of 1 min of rest between each trial. Trials were performed in three blocks, each consisting of 15 trials (three postures × five effort levels). Prior to the first block of trials, and following each successive block of trials, a trial to test for fatigue was performed at 30% Grip$_{max}$ with the wrist and forearm in a neutral posture. A total of four fatigue tests were performed.

To examine test-retest reliability, each individual was tested on two separate days, with a minimum of 1 week between sessions.

2.4. *Data collection and analysis*

After shaving and scrubbing the recording sites with alcohol, disposable Ag-AgCl electrodes were positioned over the following forearm muscles: flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), extensor carpi radialis (ECR) extensor carpi ulnaris (ECU), and extensor digitorum communis (EDC). Using an interelectrode spacing of 3 cm, electrodes were placed as follows: FCR – one third of the distance from the proximal end of a line from the medial epicondyle to the distal head of the radius; FCU – two fingerbreadths from the ulnar border on the proximal third of the forearm; FDS – in the middle third of the forearm along a line drawn from the middle of the wrist to the biceps tendon; ECR – two fingerbreadths distal to the lateral epicondyle; ECU – just lateral to the ulnar border on the mid-forearm; and EDC – in the middle of the forearm, approximately half the distance between the radial and ulnar borders (Perotto 1994). Based on previous research, EMG crosstalk should be negligible based on the distance between muscle recording

sites (Mogk and Keir 2003). Palpation during muscle-specific movements of the wrist and fingers confirmed muscle belly locations prior to electrode application.

EMG signals were amplified differentially to maximize the raw signals (common mode rejection ratio of 90 dB at 60 Hz) and bandpass filtered (10 – 500 Hz) prior to A/D conversion (12-bit). Raw EMG and force were sampled at 1000 Hz with software created in LabVIEW (National Instruments Corp., Austin, TX). For the fatigue test trials, a sampling rate of 1024 Hz was used. If fatigue was noted (increased amplitude and decreased mean power frequency), an extra 5-min rest period was given. EMG and force data were stored on a computer for later analysis. Average EMG (AEMG) was calculated after linear envelope (3 Hz, single pass) for each muscle site over the 3 s plateau period during each target grip force exertion. Baseline AEMG was calculated over a 1.5 – 2 s plateau period before initiation of each grip force exertion.

2.5. *Statistics*

Repeated measures ANOVAs and planned comparisons (Least Significant Difference or LSD) were performed using STATISTICA (Version 6.0, StatSoft, Inc., Tulsa, OK) for absolute and relative target grip forces, AEMG and wrist angles. Unless an *F*-statistic is presented, all *p*-values reflect those determined by planned comparisons.

3. Results

No significant differences were observed between test and retest values for grip force, muscle activity or wrist angle. Therefore, all data presented in this paper have been pooled across the two sessions. By incorporating trials to test for fatigue, it was found that EMG amplitude and mean power frequency were constant, indicating that fatigue was not an issue in the study.

For brevity, specific postures are referred to by using a 2-letter code with forearm posture (pronation = 'P', neutral = 'N', and supination = 'S') preceding wrist posture (extension = 'E', neutral = 'N', and flexion = 'F'). For example, P – F denotes pronated forearm with flexed wrist.

3.1. *Grip force*

3.1.1. *Maximal grip force ($Grip_{max}$):* Mean maximum voluntary grip forces attained during the calibration trials (in posture N – N) are presented in table 1 for test and retest values, and pooled across sessions. Female participants produced significantly less force than males (60 – 65% of male grip force) and as the results in table 2 show this was found regardless of wrist or forearm posture ($F_{1,16} = 13.525$, $p = 0.002$). It should be noted that males and females did not represent two exclusive

Table 1. Maximum grip forces (N) in a neutral wrist and forearm posture, from calibration trials for test and retest and averaged across the two sessions, for males, females and with genders combined. Standard deviation is in parentheses.

	Test	Retest	Averaged across sessions
Males	398.8 (112.4)	386.4 (92.4)	392.6 (97.2)
Females	242.2 (23.0)	256.2 (37.7)	249.2 (30.3)
Genders combined	320.5 (112.5)	321.3 (95.6)	320.9 (101.6)

Table 2. Comparison of maximal grip force data (N) in different forearm rotation postures and wrist from the current study and from studies in the published literature. Data have been converted where necessary for the purpose of the table. Standard deviation is in parentheses where available.

Study	Gender (M/F)	Pronation			Neutral			Supination		
		Extension	Neutral	Flexion	Extension	Neutral	Flexion	Extension	Neutral	Flexion
Current study	M	370 (112)	351 (110)	183 (64)	386 (111)	393 (97)	213 (69)	384 (111)	359 (97)	247 (97)
	F	240 (34)	213 (34)	134 (14)	246 (41)	249 (30)	146 (19)	247 (32)	239 (38)	147 (35)
Mogk and Keir (2003)	M		320 (32)			391 (41)			326 (27)	
Fong and Ng (2001)	M				340 (88)[1]	332 (85)				
Claudon (1998)	F	279 (51)	254 (54)	188 (49)	314 (55)	301 (49)	221 (69)	309 (74)	305 (54)	214 (62)
		283 (45)[2]			343 (66)[2]			333 (65)[2]		
De Smet et al. (1998)	M		467 (69)			500 (69)			496 (69)	
	F		319 (45)			355 (52)			364 (58)	
Kattel et al. (1996)	M		433			382 (98)	280 (67)[3]			
Richards et al. (1996)[4]	M		245			473			486	
	F					268			274	
Duque et al. (1995)	M					407 (81)	212[5]			
O'Driscoll et al. (1992)	M & F				402 (29)[6a]					
					373 (29)[6b]					
					324 (29)[6c]					

[1] Force exerted with the wrist immobilized in 30° of extension.
[2] Values exerted in 'self-selected' posture, equivalent to approximately 30° of wrist extension.
[3] Reported as '2/3 wrist flexion' without mention of the corresponding absolute wrist angle.
[4] Values approximated from graphical data.
[5] Estimate based on reported percentage reduction in 'full flexion' (Duque et al. 1995)
[6] Grip force values (male and female data combined) in: (a) initial 'self-selected' (35°),
(b) final 'self-selected' (33°),
(c) with 10–15° of additional wrist extension from 'self-selected' (47°).

groups; the grip strength of one male was within the grip strength range of the females. Wrist posture significantly affected maximum grip force production ($F_{2,32}$ = 169.33, $p < 0.00001$), with 40–50% less force in flexion than in either neutral or extension. While a main effect of forearm posture was found ($F_{2,32}$ = 8.027, $p = 0.0015$), this was true only with the wrist flexed, where less force was produced in pronation than in both neutral and supination (both $p < 0.005$; table 2).

3.1.2. *Relative force (% Grip$_{max}$)*: It should be noted that specific trials are referred to by the nominal target force level (i.e. % Grip$_{max}$) rather than the actual grip force level achieved. Participants were unable to produce 100% Grip$_{max}$ in all postures, especially with wrist flexion (figure 2). Despite being the same posture as the calibration trial for maximum grip force, only 92.8% Grip$_{max}$ (94.3% for males and 91.3% for females) was achieved during the 100% Grip$_{max}$ trial in the posture N–N (table 3). Normalization of grip force eliminated a gender effect. However, females did produce significantly greater relative grip force than males in 100% Grip$_{max}$ P–F trials (54.8% *vs.* 44.8% Grip$_{max}$, $p < 0.05$; table 3). Participants did not produce the desired target force in all trials, but significantly greater force was generated at each increasing target level ($p = 0.001$) regardless of posture. With the exception of the marked grip force reduction observed in the 70 and 100% Grip$_{max}$ trials with a flexed wrist, participants were generally within 2–3% Grip$_{max}$ of target force levels. Overall, a 3-way interaction was found between forearm posture, wrist posture and force level ($F_{16,256}$ = 1.912, $p = 0.0198$; figure 2). A flexed wrist resulted in only 60–80% of the target force being generated during 70% Grip$_{max}$ trials (i.e. 40–55% of Grip$_{max}$ as seen on figure 2) and 45–60% of the target force during 100% Grip$_{max}$ trials (figure 2 and table 3).

3.1.3. *Absolute (50 N) grip force*: A gender effect was present within the absolute grip force trials ($F_{1,16}$ = 26.321, $p = 0.0001$), with women exerting a greater percentage Grip$_{max}$ (19.1%) than men (12.6%) to produce a 50 N grip force (figure 2). Expressed as a percentage of maximum, the 50 N absolute grip force represented a mean relative target force of 16.9% Grip$_{max}$ when pooled across gender, while individual values ranged from 8.8% to 24.2% Grip$_{max}$.

3.2. *Average EMG (AEMG)*
3.2.1. *Relative grip force trials (% Grip$_{max}$)*: Baseline (0% Grip$_{max}$) data was collected from each trial prior to aiming for each target force level, thus for each posture the baseline AEMG value for each muscle was calculated as the mean of the baseline data over the five trials (5, 50, 70 and 100% Grip$_{max}$ and 50 N). Baseline activity was dependent on both wrist and forearm posture ($F_{20,380}$ = 12.944, $p < 0.00001$; figure 3). Extensor activation was greater than the flexor activation when pronated, while flexor activity exceeded the extensor activity with a supinated forearm posture (comparing figure 3a and b for males and c and d for females). Baseline flexor activity increased from a neutral to a flexed wrist posture, particularly in neutral and supinated forearm postures (figure 3a and c), while extensor activation increased as the wrist moved from flexion to extension, when pronated (figure 3b and d). Unlike the wrist extensor muscles, the extensor digitorum communis was particularly sensitive to wrist flexion, reaching mean levels of 10.7% MVE in the N–F posture (9.7% for men and 11.6% for women) and 13.8% MVE in the S–F
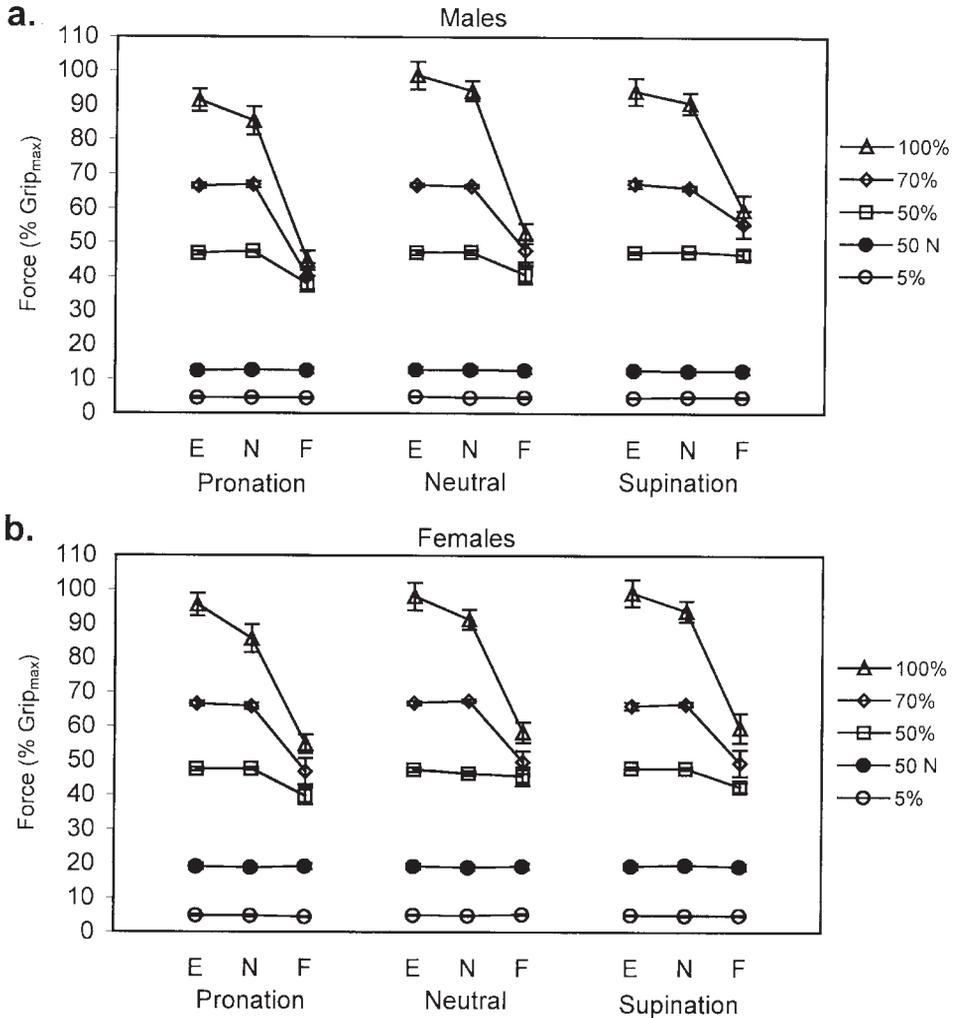
Figure 2.   Mean relative grip forces (% Grip$_{max}$) for males (top) and females (bottom), with standard error, produced during the test at each target level in each combination of wrist posture and forearm rotation. There is a difference in relative force for absolute grip (50 N) trials between males and females. Most participants could not attain target forces above 50% Grip$_{max}$ with a flexed wrist. Data pooled across sessions.

posture (12.6% for men and 15.1% for women; figure 3b and d, respectively). Females showed slightly higher baseline extensor activity than males (2–3% MVE greater) and generally comparable levels of flexor activity, but an overall gender effect did not reach statistical significance.

Separate repeated measures ANOVAs were used to examine each target force level (5%, 50%, 70% and 100% Grip$_{max}$). EMG amplitude was not affected by gender, but a 3-way interaction existed at each target level between each muscle and forearm and wrist postures ($F_{20,320} > 5.5$, $p < 0.01$ for each target force level; the muscle activity levels for the posture combinations are shown in figures 4 and 5, for flexors and extensors, respectively). Each ANOVA revealed lower overall muscle activity with the

Table 3. Variation in mean relative grip force (% $Grip_{max}$) achieved during 100% $Grip_{max}$ trials in each posture for females, males and combined. Standard error is in parentheses. The associated absolute forces (in N) are found in table 2 ('current study'). Data is pooled over the two test sessions.

Forearm rotation/ Wrist angle	Female			Male			Combined		
	Extension	Neutral	Flexion	Extension	Neutral	Flexion	Extension	Neutral	Flexion
Pronation	95.6 (3.7)	85.7 (5.1)	54.8 (2.7)	91.4 (2.8)	85.5 (2.7)	44.8 (2.9)	93.5 (2.3)	85.6 (2.8)	49.8 (2.2)
Neutral	98.1 (3.8)	91.3 (2.9)	58.3 (2.3)	98.7 (4.2)	94.3 (2.9)	52.8 (3.6)	98.4 (2.8)	92.8 (2.0)	55.5 (2.2)
Supination	99.1 (3.8)	93.8 (2.6)	59.6 (4.1)	94.1 (4.0)	90.7 (3.4)	59.7 (4.5)	96.6 (2.8)	92.3 (2.1)	59.6 (3.0)
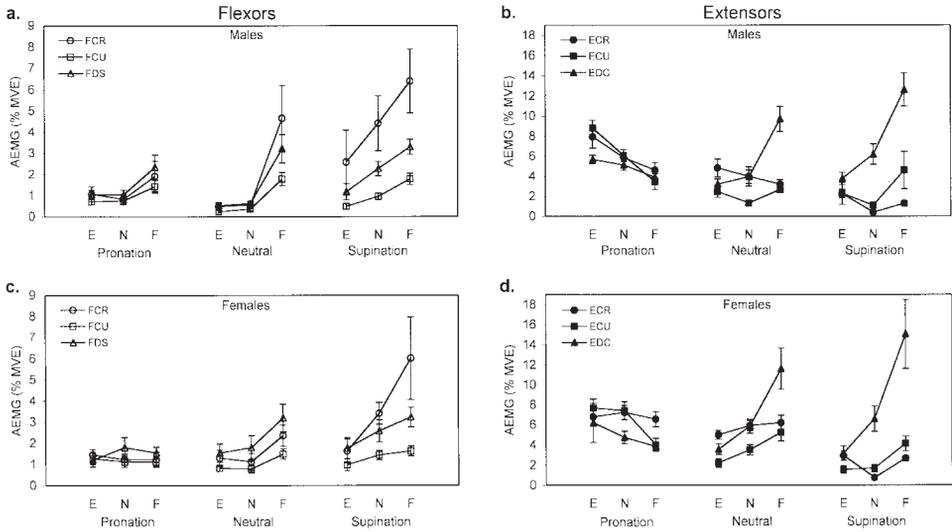
Figure 3. Mean AEMG baseline muscle activity (in % MVE), with standard error, to maintain each posture (for each combination of wrist posture and forearm rotation posture) while holding the grip dynamometer (0% grip force) for both males (top) and females (bottom). AEMG data are pooled across sessions (a) Male, flexor activity, (b) Male, extensor activity, c) Female, flexor activity, (d) Female, extensor activity. Note: y-axis scales differ between the flexor graphs (a, c) and the extensor graphs (b, d) to better display the AEMG data.

wrist extended (pooled across forearm posture) and with the forearm supinated (pooled across wrist postures; $p < 0.001$ for both). Although differences due to posture were evident, flexor (figure 4) and extensor (figure 5) activation levels did not increase in the same manner as grip force increased. Extensor activity was generally 5–10% MVE higher than the flexor activity at 0% and 5% $Grip_{max}$, became similar at 50% $Grip_{max}$, and was exceeded by flexor activity in some postures at 70% and 100% $Grip_{max}$ (comparing figures 4 and 5). This was most noticeable in the S-E and S-N postures with up to 15% MVE more flexor activity than the extensor activity in these postures. Extensor activity always exceeded the flexor activity in pronation, but neither increased markedly in the P-F posture trials beyond 50% $Grip_{max}$. Flexor activation was always greater with wrist flexion than with extension during exertions below 70% $Grip_{max}$ (figure 4). Despite lower grip force with wrist flexion, both ECR and EDC had higher activity in flexion than in extension from 50 to 100% $Grip_{max}$. This relationship was also true when comparing activity in flexion to that in a neutral wrist posture at 50 and 70% $Grip_{max}$ (figure 5). ECR activation was generally larger than ECU in neutral and supinated forearm postures, but ECU activity was typically greater than ECR in pronation, except when the wrist was flexed (figure 5). ECU activity also increased progressively from supination to pronation.

3.2.2. *Absolute (50 N) grip force*:   In the absolute load trials, although marginal, a main effect of gender was present ($F_{1,16} = 7.498$, $p = 0.0146$), with higher overall muscle activation in women than in men in most trials (figure 6). FDS activity was generally 4–5% MVE greater in flexed postures for females than for males. Extensor activation was often 5–10% MVE greater in females, regardless of posture.
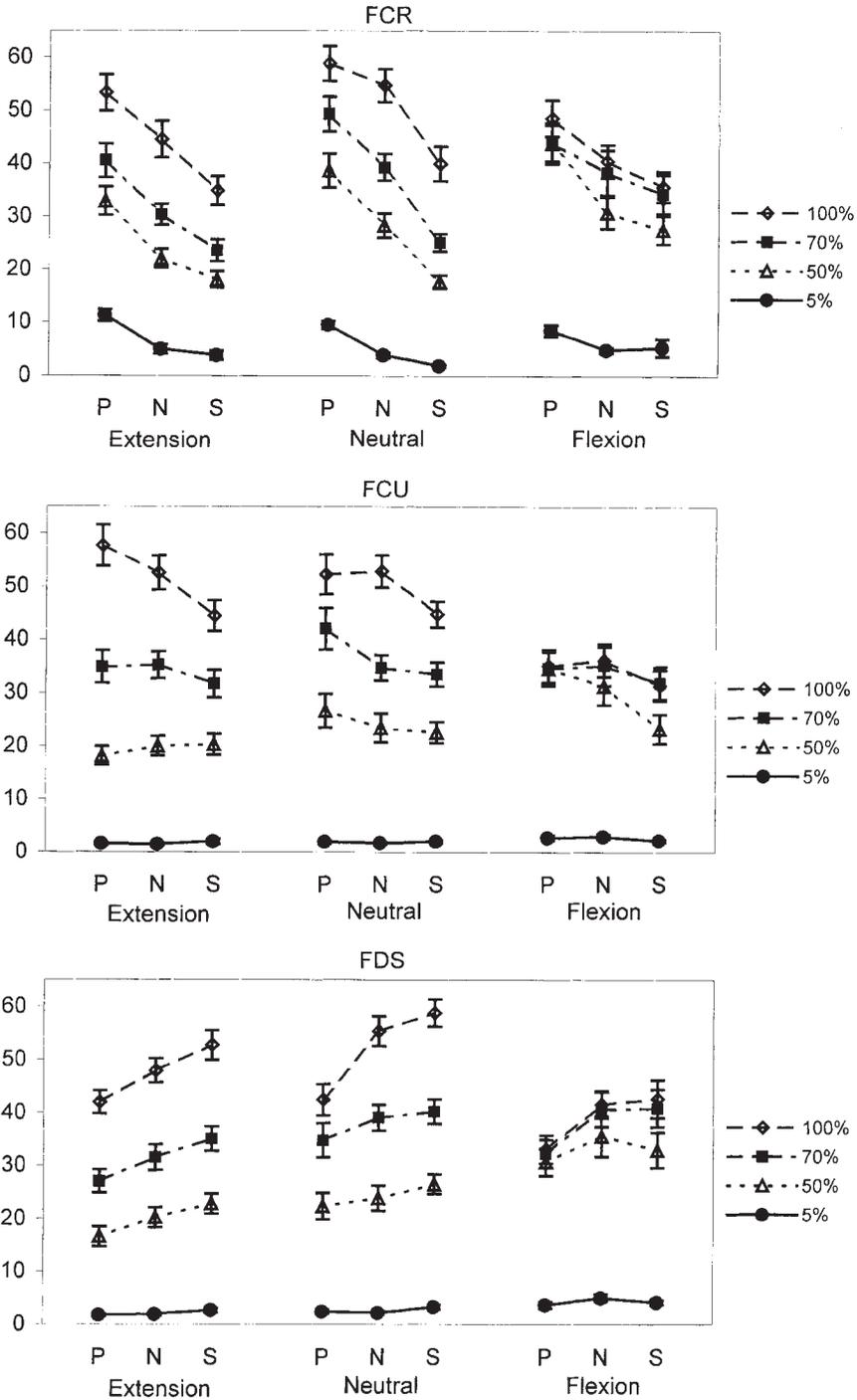
Figure 4. Mean flexor muscle activity levels (% MVE – FCR, top; FCU, middle; and FDS, bottom panel, respectively), with standard error, during the test at each of the four relative target force levels in each of the forearm rotation and wrist posture combinations, with data pooled across gender and sessions. Note: the x-axis labels have been arranged differently from figures 2, 3, and 6.
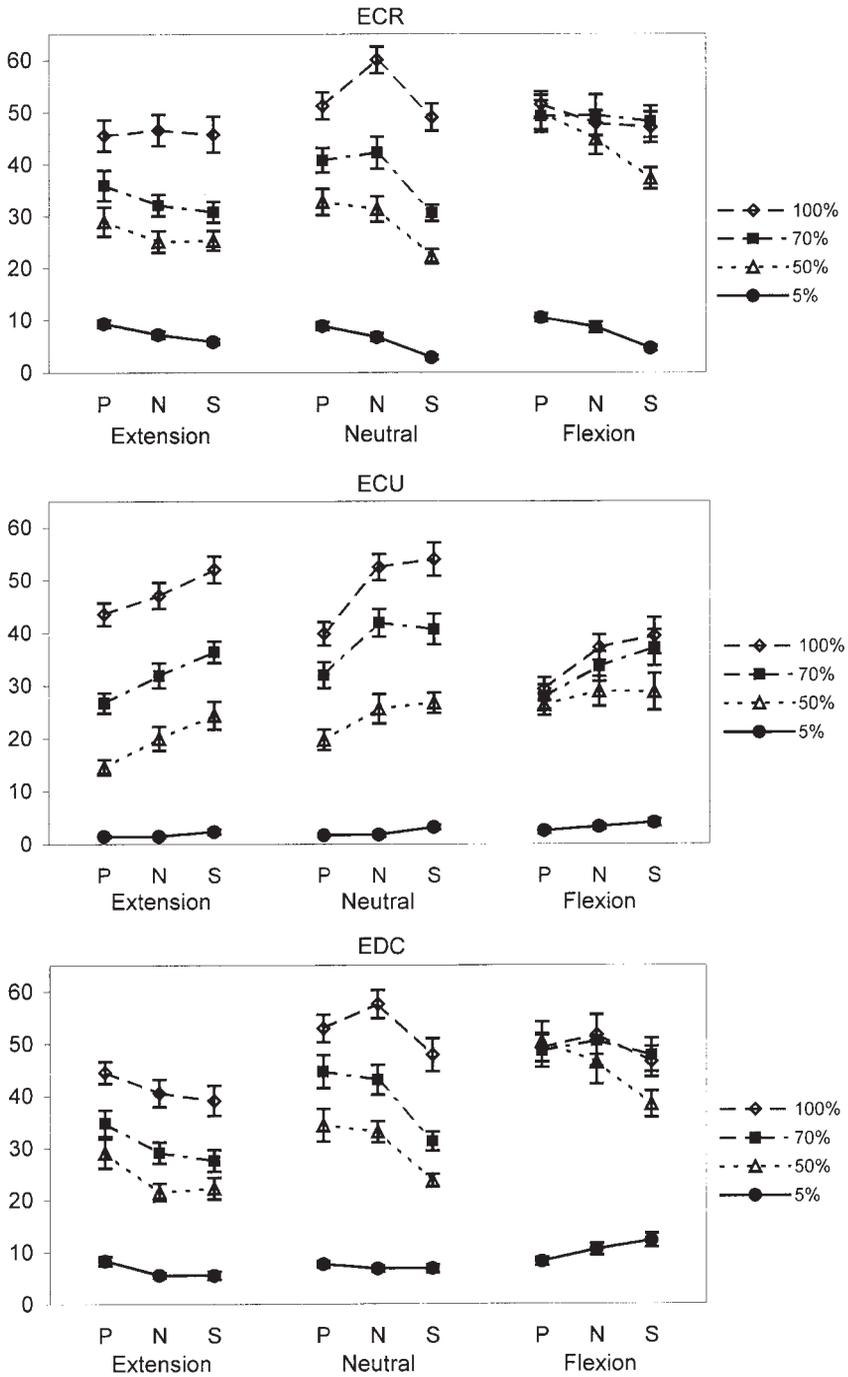
Figure 5.	Mean extensor muscle activity levels (% MVE), with standard error, during each of the four relative target force levels in each of the forearm rotation and wrist posture combinations. Top panel, ECR; Middle panel, ECU; Bottom panel, EDC. Data is pooled across gender and session. Note: the x-axis labels have been arranged differently than figures 2, 3, and 6.
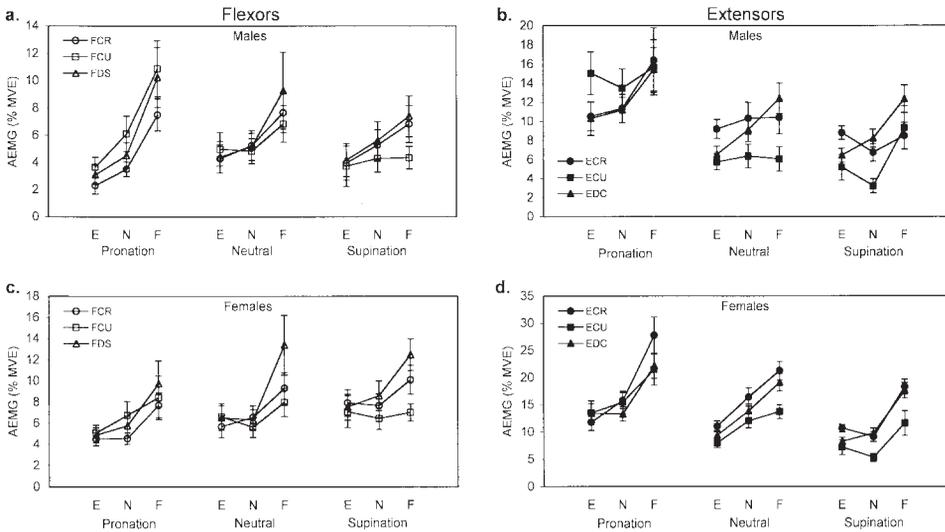
Figure 6. Mean muscle activity (% MVE), with standard error, during absolute grip force (50 N) trials for both males (top) and females (bottom) with AEMG data pooled across sessions. (a) Males, flexor activity, (b) Males, extensor activity, (c) Females, flexor activity, (d) Females, extensor activity. Note that the y-axis scales differ in each panel to better display the data. Extensor activity was higher than flexor activity, particularly in pronated and neutral forearm postures, for both males and females.

3.3. *Wrist angle*

Although participants were positioned in the desired posture prior to each trial, grip force exertion resulted in some deviation from the desired joint angle in most individuals. Forearm rotation significantly altered the wrist angle attained ($F_{4,64} = 6.843$, $p = 0.00012$), with lower extension angles in supination (38.6°) than in neutral or pronated forearm positions (42.4° and 43.4°, respectively). With the forearm supinated, men were observed to have wrist flexion and extension angles 5° less than women.

4. Discussion

This study is one of the most comprehensive examinations of the inter-relationships between wrist posture, forearm posture and grip force, with consideration of gender, on forearm muscle activity during isometric grip (as demonstrated in table 2). Posture was found to significantly alter grip force production and muscle activity. Wrist flexion resulted in a 40–50% reduction in maximal grip force, regardless of forearm posture, but a similar reduction in EMG was not found. Pronation of the forearm increased extensor activation while supination increased flexor activation. Determination of baseline activation was particularly useful. The extensor muscles were more active than the flexors while simply holding the dynamometer, especially with the forearm pronated where the extensors reached 3–9% of maximum activation. Grip strength was found to be repeatable between sessions, as has been shown previously (Fong and Ng 2001). Despite the redundancy and relatively small size and proximity of the forearm muscles, the EMG levels of individual muscles associated with each grip force exertion were also repeatable between days as has been shown previously (Maier and Hepp-Reymond 1995, Cook *et al.* 1998). While

women required a higher percentage of both grip strength and muscle activation during the 50 N (absolute force) trials, similar strength and relative activation levels were seen in one of the male participants.

In the past, research has tended to focus on the (potentially) high forces required to operate tools at the expense of the 'negligible' muscle activity associated with holding a tool (e.g. Duque *et al.*, 1995). However, it was found that the muscle activity necessary to support the hand and dynamometer against gravity was anything but negligible. The activity was largely posture dependent, with the greatest mean flexor activity in supination (0.5–6.4% MVE) and greatest mean extensor activation in pronation (3.5–8.8% MVE, as shown in figure 3). Baseline extensor activation of women was 2–3% MVE greater than for men, which was not surprising given that the weight of the dynamometer was constant and should represent a higher relative load for most women. Non-optimal muscle lengths further altered baseline activity levels. For example, flexor activity increased with wrist flexion and supination, while extensor activity increased with wrist extension and pronation. The latter corroborates a recent analysis of typing posture that found that increasing wrist extension led to higher extensor loading (Keir and Wells 2002). Both flexor and extensor baseline activity increased with wrist flexion, particularly for the extensor digitorum communis, which increased to 10.7 and 13.8% MVE in neutral and supinated forearm postures, respectively (figure 3b and d). These loading responses corroborate a recent clinical and anatomical study that suggested that the EDC muscle may play a greater role in the development of lateral epicondylitis than previously thought (Fairbank and Corlett 2002). If the baseline activity is used to represent a continuous load during a work day, the findings indicate that the extensors would exceed suggested 'static' load levels of 2–5% MVE even before exerting any grip force, and could often reach 10–14% MVE, suggested as a limit for intermittent or dynamic contractions (Jonsson 1978, Sjogaard *et al.* 1986, 1988). This type and level of activation would likely lead to a lack of muscular rest or EMG 'gaps', which has been associated with muscle pain (Veiersted *et al.* 1990). The dynamometer used was not particularly heavy (4.5 N), so that even greater levels of muscle activation than reported here would occur during workplace tasks implementing heavier tools, particularly unsupported power tools. The purpose of these 'no load' trials was to simulate the act of simply holding a tool (without exerting a grip force), and the findings suggest that prolonged duration in these postures may limit muscular rest between work cycles and contribute to fatigue, particularly in the extensor muscles. These findings indicate the importance of avoiding certain postures during rest periods, as well as the benefit of implementing tool supports.

It was found that all of the women in the study, and one man, required approximately 20% of their maximum grip strength to produce a relatively modest 50 N grip force. At 20%, these participants exceeded a level proposed for acceptable intermittent handgrip contractions of 17% of maximal grip force based on physiological measures in a study by Byström and Fransson-Hall (1994). However, in that study the hand of each participant was supported, and thus excluded muscle activity required to support the hand and dynamometer as a contributing factor in forearm muscle fatigue. The implication is that the proposed level of 17% of maximal (and supported) grip force may overestimate the acceptable level of intermittent handgrip exertions when hand or tool support is unavailable, as is often the case. In the present study, to create a 50 N grip force, weaker individuals often

elicited as much as 5 – 10% MVE more muscle activation than stronger participants, especially in the extensors. This additional 5 – 10% MVE could limit blood flow sufficiently to increase the likelihood of muscle fatigue over the course of a workday (Sjogaard *et al.* 1986, 1988). Co-contraction of the extensors, as found in the present study, is likely a control strategy to increase joint stiffness and minimize deviation from the desired position with grip exertion (De Serres and Milner 1991). A similar phenomenon has been demonstrated at the elbow joint for which co-activation is higher during tasks requiring position control than during isometric force production (Buchanan and Lloyd 1995). However, constrained tasks in the laboratory are likely different from what would be expected in the workplace. For example, grip force is required to support a pistol grip drill and operate the trigger, but wrist and forearm moments are also present to balance the tool against gravity and to generate the force needed to drive a screw (Wells and Greig 2001). Therefore, it is likely that even greater levels of muscle contraction would occur in the workplace than in the constrained task performed in the present study, further contributing to the possibility of fatigue. The findings regarding gender differences in relative force and muscle activation required to exert an absolute load support epidemiological data that indicate a greater prevalence of extensor muscle injury in women than in men (Fransson-Hall *et al.* 1995, de Zwart *et al.* 2001). However, based on the present data, it is plausible that this is due to strength rather than to gender per se.

Being the prime movers in gripping tasks, it might be expected that finger flexor activity would be the largest and most representative of grip force levels. However, the findings suggest that this may only be true at elevated force levels, which has been shown previously (Claudon 1998). In the present study, it was found that extensor activation generally exceeded flexor activation at low grip forces (5% $Grip_{max}$ and 50 N), but that flexors and extensors had similar activity levels at and above 50% $Grip_{max}$. Extensor activation always exceeded the flexor activation when the forearm was pronated regardless of wrist posture or effort level. With the forearm pronated, the extensors must support the weight of the hand and grip dynamometer; however, other biomechanical factors also play a role and should be considered. For example, the total moment-generating capacity of the flexor muscles crossing the wrist is greater than that of the extensors, due to a larger total physiological cross-sectional area and larger moment arms (Gonzalez *et al.* 1997). Consequently, the extensor muscles require a greater proportion of maximal activation to generate the forces required to balance the flexor moment and stabilize the wrist. Other findings may also be explained by forearm anatomy. ECU activity decreased from pronation to supination (figure 6), while its moment arm has been shown to increase over the same range (Loren *et al.* 1996); therefore, less activity (and hence force) should be expected to produce the same moment at the wrist. It was also found ECR activity was greater than ECU activity in neutral and supinated forearm postures, likely reflecting the ECU's primary role as an ulnar deviator rather than as a wrist extensor (Loren *et al.*, 1996). Loading of ECR has been suggested to be a key factor in pathophysiology of lateral forearm muscle pain (Ljung *et al.* 1999b).

Wrist flexion decreased maximum grip force by 40 – 50% in both men and women. This reduction of grip force with a flexed wrist has previously been reported for grasp (Duque *et al.* 1995, Kattel *et al.* 1996, Claudon 1998), pinch grip (Imrhan 1991,

Dempsey and Ayoub 1996, Halpern and Fernandez 1996) and finger strength (Hazelton *et al.* 1975). The overall effects of posture on maximal grip force are summarized in table 2 to allow comparison with other grip studies. Both Duque *et al.* (1995) and Claudon (1998) also observed a 40–50% decrease in grasp strength, albeit in 'maximum' flexion. Kattel *et al.* (1996) reported a reduction of only about 25% with 2/3 of maximum wrist flexion, but did not report the absolute wrist angles observed. In the present study, even with reduced grip force, the flexors often had higher activation with flexion than in the other wrist postures, except in the 70 and 100% trials (figure 4). Wrist flexion causes the flexor muscles to shorten which may reduce their force potential by more than 50% (Lieber and Fridén 1998). In addition, wrist and finger flexion act to lengthen the extensor muscles, leading to increased passive extensor muscle force which must be overcome by the flexors (Keir *et al.* 1996). The net result of these factors would be to increase flexor activity and decrease grip force. This is particularly important in workplace analysis where external forces are easily measured but, in many postures, these vastly underestimate the loads being borne by the muscles.

There are several limitations to the present study. Firstly, EMG signals were normalized to peak muscle activation levels, which in some cases were taken from test trials rather than during the calibration trials designed to elicit maximum activations. These adjustments were made prior to statistical analysis to (i) reflect the true maximum activation of the muscles, (ii) minimize over-estimation of relative muscle activity, and (iii) eliminate activity levels exceeding 100% MVE as reported in previous studies (e.g. Duque *et al.* 1995). Secondly, it was found that participants produced only 93% $Grip_{max}$ during the 100% target grip force trials with a neutral wrist and forearm posture. This may be partially explained by the decision to use the peak force from one maximal grip exertion to calculate target force levels while the test data were averaged over a 3 s period. Likely having a larger effect was that participants concentrated on maintaining their posture while aiming for 100% $Grip_{max}$ rather than producing as much force as possible. Also, since force variability was minimal, viewing of the oscilloscope and, perhaps, parallax error more likely caused undershooting of the target levels (2–3% on figure 2). Thus, discrepancies between the achieved and target forces do not indicate the inability of participants to produce a desired force level in all cases. Thirdly, the combination of wrist flexion, forearm supination and gripping the dynamometer made it difficult for two male participants to maintain 45° of wrist flexion; they completed the study using 30–40° of wrist flexion. Slight discomfort reported with some postures while holding the apparatus may have inhibited grip force generation. The participants' slight deviation from the desired wrist angles was not entirely surprising, as minor deviation has been shown even when the wrist is splinted (Keir and Wells 1999). Finally, it was decided not to use an electrogoniometer due to reported crosstalk with forearm rotation (Jonsson and Johnson 2001), and concern that compression of the electrogoniometer against the supporting platform would alter posture, or induce measurement error.

5. Conclusions

This investigation demonstrated the levels to which the forearm muscles can be loaded statically during gripping tasks, as well as muscle loading differences due to variation in grip strength. Forearm posture only affected grip force when the wrist was flexed, but altered muscle contributions in each wrist posture, particularly without grip force or at low to mid-range grip force levels. The 40–50% grip force

reduction found with a flexed wrist posture was not reflected in muscle activity levels, as wrist flexion generally resulted in higher muscle activation than in either a neutral or extended wrist posture. The extensor muscles worked at a higher level (5–15% MVE) than the flexors in most postures during low to mid-range force gripping tasks, and may reflect grip force better than the flexors, particularly in this force range. Despite the muscle redundancy of the forearm, consistent muscle responses were found. Findings of this study offer important new information on how forearm muscle loading, and overloading, can occur with relatively low external forces, and should be implemented in workplace and job design. These findings offer insight into the effects of forearm and wrist posture on the loading of the muscles of the forearm, which may help to explain, and ultimately reduce, the prevalence of work-related forearm pain.

Acknowledgements

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