



The influence of simultaneous handgrip and wrist force on forearm muscle activity



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ABSTRACT

The purpose of this study was to examine forearm muscle activity during simultaneous execution of dual motor tasks; hand-gripping and wrist forces. Surface electromyography was recorded from eight muscles of the upper-limb: flexor carpi radialis, flexor carpi ulnaris, flexor digitorum superficialis, extensor carpi radialis, extensor carpi ulnaris, extensor digitorum, biceps brachii and triceps brachii. Participants were seated with their forearm supported in a neutral position with an adjustable force transducer placed on either the palmar or dorsal side of the hand (for palmar/dorsal forces). Participants performed trials of simultaneous handgrip and wrist forces of various magnitudes, ranging in intensity from 0 to 40% of their maximal voluntary contraction. Trials lasted 5 s and force and electromyography data were assessed. The wrist flexors provided greatest contributions to tasks dominated by palmar forces but exhibited very low muscle activity in dorsal dominant tasks. Wrist extensors were active at moderate-to-high levels across nearly all conditions and demonstrated greater activity than the wrist flexors during handgrip-dominant tasks. These findings suggest that the wrist extensors provide the greatest contribution to wrist stiffness in complex motor tasks, and highlight the importance of investigating forearm muscle recruitment strategies under dual task parameters.

1. Introduction

The combination of direct wrist movement (flexion/extension and ulnar/radial deviation) and rotation of the radioulnar joints (supination/pronation of the forearm) allows for an extensive range of motion at the distal upper-limb. Within this intricate system is a redundant arrangement of muscles, where several muscles are capable of the same motor task (Bawa et al., 2000; Fleckenstein et al., 1994; Loren et al., 1996). This redundancy adds a layer of difficulty when exploring motor control theories and complicates computational modeling of the distal upper limb. Further, it challenges our capacity to understand and treat neuromuscular ailments of the hand, wrist, and forearm. Part of this complexity is necessitated by the dynamic capabilities of the hand. Historically, hand strength, task demands, and workplace injury risk were established based on an individual's maximum handgrip force, determined using a force dynamometer (An et al., 1985). This approach remains valid for tasks executed purely by grasping the hand, but is inappropriate for most situations. Wells and Greig (2001) presented a modern framework to better characterize hand prehensile strength. Defined as a force and moment wrench, the hand can be characterized by its internal grip force, external force, and moment wrench capabilities (Wells and Greig, 2001). This approach more effectively captures the hand's tendency to stabilize an object with grip force while simultaneously transmitting torques generated by the flexors/extensors

of the wrist and the supinators/pronators of the forearm (Kroemer, 1986). Wells and Greig also highlighted the need for research to assess prehensile capabilities in multi-component, dual-task exertions that translate better to workplace settings and tasks of daily-living (Greig and Wells, 2004; Wells and Greig, 2001). However, since this work in 2004, minimal investigations into dual-task paradigms have been conducted. Given the importance of muscle activity as an overuse mechanism for workplace musculoskeletal disorders, understanding forearm muscle recruitment in complex hand/wrist actions is a logical continuation in injury prevention. Currently, it is unclear if an isolated strength demand of the hand or wrist generates comparable muscle demands to an effort combining multiple muscle actions.

Of the literature that has examined forearm muscle activity in single axis/uni-component exertions, the following conclusions have been produced: (1) Wrist flexor muscles are highly task-dependent, with a predominant role in producing handgrip and wrist flexion forces (Duque et al., 1995; Imrhan, 1991; Kattel et al., 1996; Mogk and Keir, 2003), and (2) Wrist extensor muscles are resistant to task-dependent changes, and serve a primary role of wrist stabilization in countering the forces produced by wrist flexors (Hägg et al., 1997; Mogk and Keir, 2003). These statements are based in part by anatomical constraints, as the wrist flexors collectively possess a larger cross sectional area (CSA) and moment arm than the wrist extensor muscles (Gonzalez et al., 1997; Jacobson et al., 1992; Lieber et al., 1992). Mechanically

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disadvantaged, the wrist extensors must function at a higher percentage of their maximum to balance a wrist flexor moment, leaving them more susceptible to overuse injuries. Again, these findings have been generated mostly by studies investigating uni-component motor tasks (hand-gripping or wrist flexion/extensions in isolation). The roles of the forearm muscles in hand and wrist tasks with increasing complexity are not yet well understood.

It is currently unclear if the main themes of forearm muscle function derived from previous protocols are transferrable to the force and moment wrench framework proposed by Wells and Greig (Greig and Wells, 2004; Wells and Greig, 2001). In following with the recommendations of this work, the purpose of the present study was to examine forearm muscle activity while performing a range of handgrip contractions simultaneously with a range of wrist forces.

2. Methods

2.1. Participants

Experimental procedures were approved by the research ethics board (REB) of the University of Ontario Institute of Technology (REB# 14-046). Written consent was obtained for all participants prior to the experiment. Twelve, right-handed males (Height: 177.8 ± 7.2 cm; Weight: 84.5 ± 12.1 kg; Age: 23.6 ± 2.2 years) were recruited for this study. Participants completed a Physical Activity Readiness Questionnaire for Everyone (PAR-Q+; Canadian Society for Exercise Physiology) to screen for any contraindications to exercise or physical exertions. Subjects were excluded if they possessed any upper-body, neuromuscular injuries.

2.2. Experimental setup

Participants were seated at a custom-built, table-mounted apparatus that supported the dominant forearm (Fig. 1) atop two, foam pads: one at the distal, radio-ulnar joint and the second at the olecranon. The forearm was kept in a neutral orientation and the wrist in a neutral position (neither flexed nor extended; 0° of wrist flexion/extension) throughout the entire protocol. The forearm was held straight out from the participant (0° of shoulder abduction and 0° of lateral rotation) and while elbow extension and shoulder flexion angles weren't controlled during the study, they were manually assessed using a goniometer prior to the experiment (Elbow extension: $148 \pm 5.4^\circ$; Shoulder flexion: $61.8 \pm 9.4^\circ$). Elbow and shoulder angle variability was a result of the experimental set up, as we did not control for trunk posture during the protocol. Marks, corresponding to the proper location of the foam supports, were made on each participant's forearm to ensure consistent placement. Wrist exertions were measured using a force transducer (Model: BG 500, Mark-10 Corporation, New York, USA) that was manually positioned against either the front of the hand to assess palmar force or against the back of the hand to assess dorsal force. Specifically, the transducer contacted the posterior surface of the distal phalanges (closed hand) and the posterior surface of the distal metacarpal bones for palmar and dorsal trials, respectively. The force transducer was kept as close to the hand as possible to ensure that, during isometric wrist exertions, the wrist remained neutral. Participants also grasped a handgrip dynamometer (MIE Medical Research Ltd, Leeds, UK) for all experimental tasks. Hand position on the dynamometer was kept consistent. In this setup, with the hand dynamometer grasped and the force transducer against the hand, participants performed simultaneous wrist exertions and handgrip contractions. The terminology used throughout this paper has been adapted from the work of Wells and Greig (Wells and Greig, 2001). Palmar and dorsal forces are in reference to the direction of force applied to a force transducer via the production of isometric wrist flexion and extension torques, respectively.

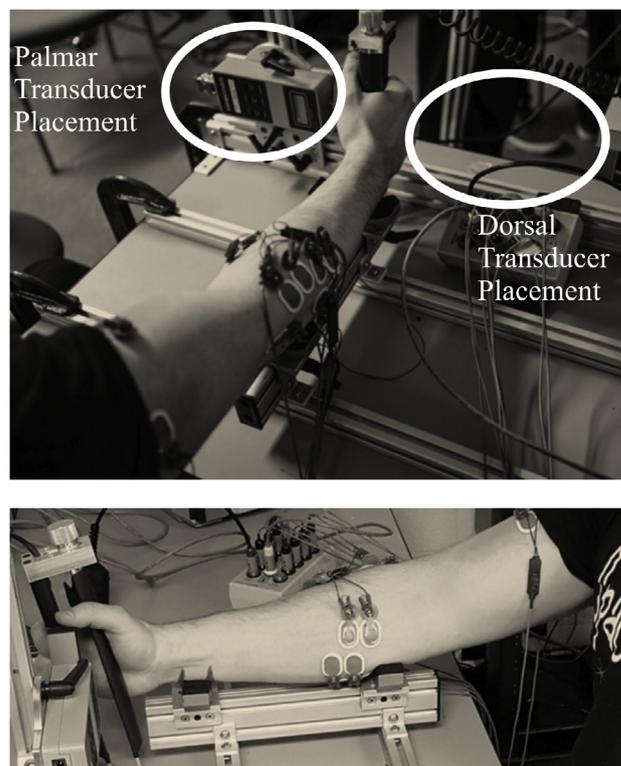


Fig. 1. Experimental setup. Participants' forearm supported by foam pads at both the distal and proximal forearm. The force transducer is shown for palmar force exertions. As indicated, the force transducer could be moved to accommodate dorsal exertion trials.

2.3. Electromyography

Muscle activity was recorded using pairs of surface electrodes (Blue Sensor, Ambu A/S, Denmark) from eight muscles of the dominant arm; flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), extensor digitorum (ED), biceps brachii (BB), and the triceps brachii (TB). Electrodes were placed over the muscle belly, in-line with fiber orientation, and procedures followed previous placement guidelines (Forman et al., 2016; Holmes et al., 2015; Mogk and Keir, 2003; Perotto and Delagi, 2011). A ground electrode was placed on the lateral epicondyle of the dominant arm. Prior to electrode placement, all recording sites were shaved of hair using a disposable razor and were sanitized with an isopropyl alcohol swab. EMG was band-pass filtered (10–1000 Hz) and differentially amplified (CMRR > 100 dB at 60 Hz; input impedance ~ 10 G Ω ; AMT-8, Bortec Biomedical Ltd, Calgary, AB, Canada). EMG, grip force, and load cell data were sampled at 2048 Hz (USB-6229 BNC, National Instruments).

2.4. Experimental protocol

Participants performed muscle-specific, isometric maximal voluntary contractions (MVCs) to determine maximal voluntary excitation (MVE) for the 8 tested muscles. MVCs were performed against the manual resistance of one of the researchers and included specific grip and wrist actions to target individual muscles (Table 1) (Holmes et al., 2015). Participants were then seated in front of the custom-built apparatus and their dominant forearm was placed onto the foam supports (Fig. 1). In this posture, participants performed a maximum handgrip using the hand dynamometer, and maximum wrist flexion/extension against the force transducer (order randomized). These were used to normalize both the handgrip and wrist exertion forces for the subsequent experimental conditions. Table 2 shows the breakdown of all

Table 1
Maximal voluntary contraction (MVC) protocol for each of the 8 muscles assessed.

Muscle	MVC Protocol
Flexor carpi radialis (FCR)	Forearm supinated, hand into fist, wrist flexion against manual resistance
Flexor digitorum superficialis (FDS)	Forearm supinated, partially opened hand grasping the hand of the researcher, combined wrist flexion and maximal grip
Flexor carpi ulnaris (FCU)	Forearm supinated, hand into fist, combined wrist flexion and ulnar deviation
Extensor carpi radialis (ECR)	Forearm neutral, hand into fist, wrist extended against manual resistance
Extensor digitorum (ED)	Forearm neutral, hand partially opened and enclosed within the hand of the researcher, combined wrist extension and maximally opening the hand against resistance
Extensor carpi ulnaris (ECU)	Forearm neutral, hand into fist, combined wrist extension and ulnar deviation
Biceps brachii (BB)	Forearm supinated, elbow and shoulder placed at 90° flexion, elbow maximally flexed against resistance
Triceps brachii (TB)	Forearm neutral, elbow and shoulder placed at 90° flexion, elbow maximally extended against resistance

Table 2
Compilation of all 10 experimental trials.

40% Combined Effort	
Grip force (% of maximum)	Wrist force (% of maximum)
0	40
10	30
20	20
30	10
40	0

Note: Values are displayed as a percentage of maximum grip and wrist force (palmar or dorsal). Wrist forces were repeated for both palmar and dorsal force.

10 experimental conditions. 40% “combined effort” was used, whereby “combined effort” was defined as the sum of the relative grip and wrist force (either palmar or dorsal). To elaborate, 40% combined effort consisted of participants performing a handgrip (relative to the participant’s own maximum grip) in combination with either a palmar or dorsal exertion (relative to the participant’s own maximum palmar/dorsal force) whose relative forces summed to 40%. While always summing to 40%, the relative contributions of the handgrip and wrist exertions were modified for each experimental condition (Table 2). The order of these conditions was randomized. Participants were given visual feedback on a computer monitor displayed in front of them. Two graphs displaying real-time force data were positioned side-by-side; one denoting handgrip force and the second denoting wrist force (LabVIEW 2017, National Instruments, Austin, TX, USA). Targets (with an allotted accuracy of ± 1.5%) were displayed as horizontal lines (one line representing the target and two, other lines representing ± 1.5% of the target) on each graph and represented the relative handgrip or wrist force required for that given experimental condition. For each condition, participants were instructed to simultaneously match each of the two targets on the screen and maintain the two forces for 3 s. A total of 3 trials were performed for each condition. To minimize the potential influence of fatigue, ample rest was given between each trial and between workloads.

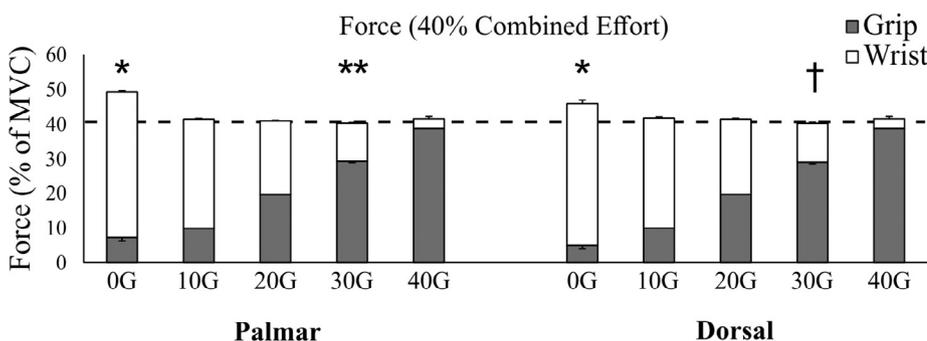


Fig. 2. Group averages (n = 12) of simultaneous handgrip and wrist forces summing to 40% combined effort. Grey/white bars represent handgrip/wrist force, respectively. Interaction effect investigated with post-hoc pairwise comparisons. * denotes a significant difference from all other conditions. ** denotes a significant difference from 10G Palmar and 20G Dorsal. † denotes a significant difference from 10G Palmar and 10G Dorsal.

2.5. Data analysis and statistics

EMG and force data were analyzed off-line (MatLab 2015b, Mathworks Inc., Natick, MA, USA). Signal bias was removed from both EMG and force data. EMG was full-wave rectified and digitally low pass filtered (Butterworth, dual pass, 2nd order, 3 Hz cut-off). Force data were low pass filtered with a 10 Hz cutoff (Butterworth, dual pass, 2nd order). EMG was normalized to MVCs and expressed as a percentage of maximum voluntary exertion (% MVE). For each of the 3 trials for each experimental condition, a single point was manually labelled by one of the researchers where the grip force and wrist force were simultaneously matched with their respective targets. A ± 0.25 s window about that point was averaged for both force and EMG. The values for the 3 trials were averaged into a single EMG and force value for each experimental condition. Co-contraction was calculated as a ratio of antagonist/agonist for all pairs of flexors and extensors (ie. FCR-ECR, FCU-ECU, FDS-ED, and BB-TB) (Damiano et al., 2000). Two-way, repeated measures ANOVAs (force direction × condition) were conducted for both combined force outputs and for each individual muscle to assess significant differences across experimental conditions for EMG and force (SPSS, V24, International Business Machines Corporation, Armonk, NY, USA). Effect sizes were evaluated using partial Eta Squared calculated as the division of the sum of squares of the effects (SS_{Effect}) by both the SS_{Effect} and the sum of squares of the error (SS_{Error}). Significance level was set at P < .05. Data is reported as mean ± SD and illustrated in figures as SE.

3. Results

3.1. Combined handgrip & wrist forces

Fig. 2 depicts the mean data for simultaneous handgrip and wrist forces combined to 40% of MVC. Force targets were accurately maintained, with the noted exception of the ‘0G’ conditions, in which participants produced excess handgrip force during high wrist-only exertions. Other than ‘0G,’ it is unlikely that any differences between the other conditions influenced the interpretation of muscle activity data. The 0G conditions produced significantly higher combined force than the other 9 conditions for both palmar and dorsal forces (both,

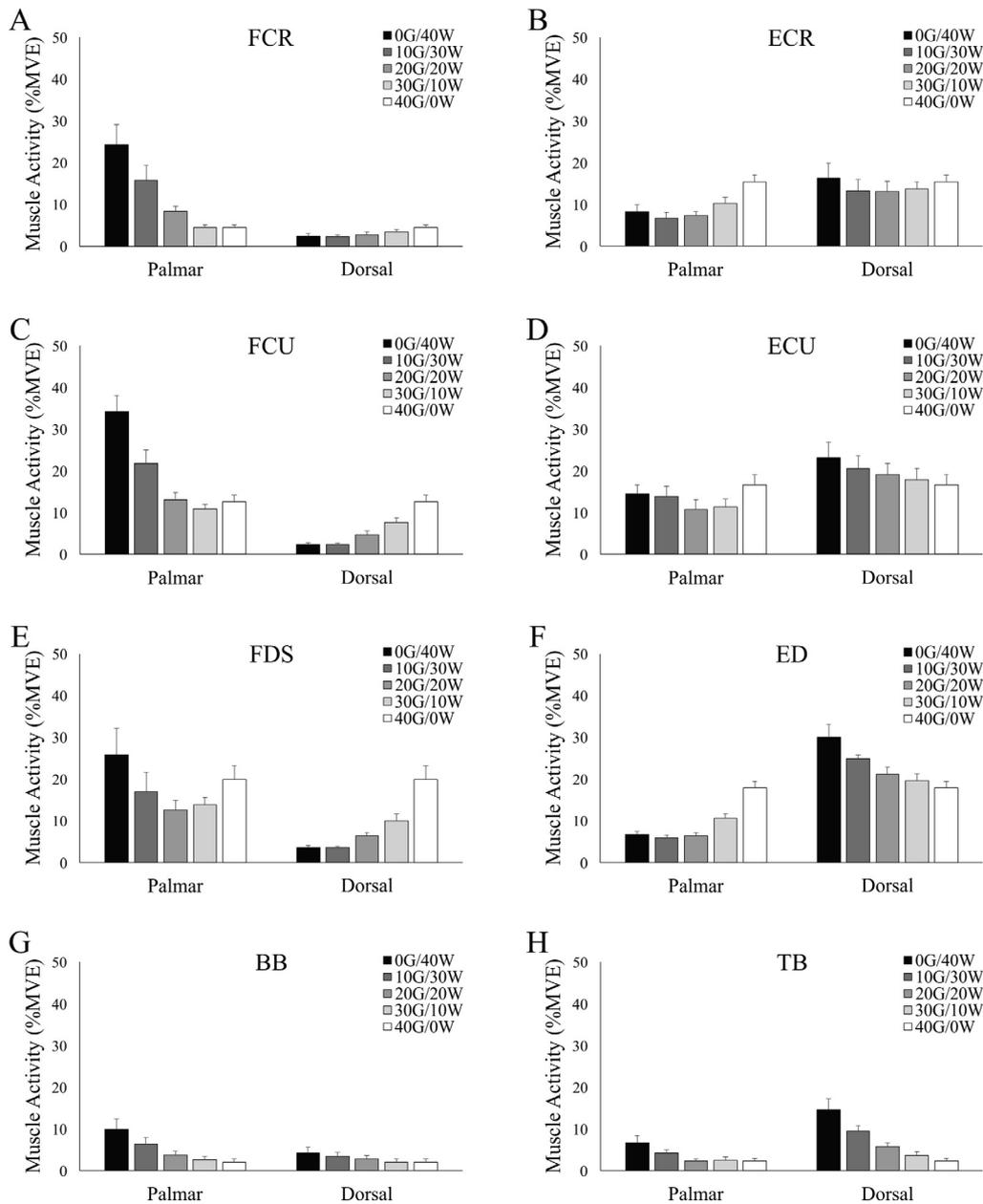


Fig. 3. Group averages (n = 11) of mean muscle activity (displayed as a % MVE) during combined handgrip and wrist exertions (palmar/dorsal). Darker bars represent conditions with greater wrist force. Lighter bars represent conditions with greater handgrip forces.

Table 3

P-Values, Partial ETA Squared (η_p^2) and F-statistics for the interaction (force direction \times condition).

	FCR	FCU	FDS	ECR	ECU	ED	BB	TB
P-Value	0.001	< 0.001	0.008	0.08	0.02	< 0.000	0.03	0.047
Effect size	0.631	0.842	0.497	0.267	0.373	0.827	0.344	0.319
F-Statistics	$F_{4,11} = 17.1$	$F_{4,11} = 53.3$	$F_{4,11} = 9.9$	$F_{4,11} = 3.6$	$F_{4,11} = 5.9$	$F_{4,10} = 43.1$	$F_{4,11} = 5.3$	$F_{4,11} = 4.7$

$P < .05$). Additionally, the 30G trial during palmar force was significantly lower than the 10G trial in palmar and the 20G trial in dorsal (Palmar 30G: $40.3 \pm 0.6\%$ of MVC, Palmar 10G: $41.5 \pm 0.5\%$ of MVC, Dorsal 20G: $41.5 \pm 1.0\%$ of MVC, $P < .05$). The 30G trial of dorsal force was also significantly lower than both 10G trials (Dorsal 30G: $40.3 \pm 0.6\%$ of MVC, Palmar 10G: $41.5 \pm 0.5\%$ of MVC, Dorsal 10G: $41.7 \pm 1.0\%$ of MVC, $P < .05$).

3.2. Muscle activity

Fig. 3 illustrates the mean muscle activity during both palmar and dorsal forces across the five conditions. All muscles demonstrated a significant interaction between wrist force direction and condition, with the exception of ECR ($P = .08$). However, ECR did demonstrate a main effect for both force direction (Palmar: $9.6 \pm 1.1\%$ MVE, Dorsal: $14.3 \pm 2.3\%$ MVE, $P < .05$) and condition, with muscle activity increasing as conditions became more handgrip-dominant. Collapsed

between the two force directions, the 40G condition produced significantly greater activity than the 30G and 20G conditions, with 30G also greater than 20G (40G: $15.4 \pm 1.7\%$ MVE, 30G: $12.0 \pm 1.6\%$ MVE, 20G: $10.2 \pm 1.5\%$ MVE, $P < .05$). Table 3 displays both the P -values of the interaction effects as well as the effect sizes for all 8 muscles. The wrist flexors exhibited large effect sizes (particularly FCR and FCU), with muscle activity significantly greater in conditions dominated by palmar forces (see Fig. 3A, C, and E). All three wrist flexors produced less than 5% of maximum EMG in the pure dorsal force conditions. While ED had a larger effect size than FDS, ECR and ECU had smaller effect sizes than their respective antagonists (FCR and FCU) (Table 3). Although the wrist extensor muscles were most active in dorsal (extension-dominant) conditions, they produced equal, if not greater muscle activity than the wrist flexors in handgrip-dominant conditions. The wrist extensors were also active in the palmar force conditions, producing 8.2 ± 5.6 , 14.5 ± 7.4 , and $6.7 \pm 2.7\%$ MVE in the ECR, ECU, and ED, respectively. The BB and TB (Fig. 3G and H) also exhibited interaction effects with large effect sizes. Both muscles were significantly more active in conditions of high wrist forces compared to high handgrip forces. However, the BB contributed more to the palmar force conditions, whereas the TB was more active in dorsal force.

3.3. Co-contraction ratios

Fig. 4 illustrates the group data for antagonist/agonist co-contraction ratios. For the FCR – ECR pairing, an interaction effect was observed ($F_{(4,11)} = 26.4$, $P < .05$), with significantly greater co-contraction in the ECR, particularly in high handgrip conditions. Although both the FCU and ECU produced greater co-contraction in handgrip dominant conditions, the ECU was greater than the FCU, with main effects of force direction ($F_{(1,11)} = 5.9$, $P < .05$) and condition ($F_{(4,11)} = 41.5$, $P < .05$). While the FDS – ED pairing behaved similarly, only a main effect of condition as found ($F_{(4,10)} = 48.2$, $P < .05$). A main effect of condition was also found for the BB – TB pairing ($F_{(4,11)} = 7.4$, $P < .05$), with greater co-contraction in handgrip-dominant conditions.

4. Discussion

This work examined forearm muscle recruitment during simultaneous execution of handgrip and palmar/dorsal directed wrist forces to investigate motor control strategies during a dual task paradigm. Our findings indicate that the wrist flexors are highly task-dependent, in that changing task parameters significantly alters their activation. In contrast, the wrist extensors are less susceptible to variations of task demands and exhibit constant activity across all conditions. While the wrist flexors likely generate greater force, the wrist extensors exhibit equal, if not more activity during tasks which are dominant in handgripping. The results of this study suggest that, despite the added complexity of a dual-task protocol, the wrist extensors act to stiffen the wrist joint. This work highlights the potential vulnerability of the extensor muscles to overuse injuries in workplaces or activities of daily living that rely heavily on handgrip forces and/or wrist exertions.

4.1. Wrist flexors vs extensors

The novelty of the present work is that, by simultaneously modifying handgrip forces and wrist exertions across a wide array of intensities, the behavior of the wrist flexors and extensors could be examined under greater complexity than has previously been utilized. Additionally, this experimental design addresses recommendations raised by earlier investigators that ergonomic research shift towards multi-component, dual-task protocols that better translate to tasks of daily-living (Wells and Greig, 2001). However, despite the dual task methodology of the present protocol, our results are in agreement with much of the uni-component literature. Data revealed that the wrist flexors were more task-dependent than the extensors, with effect sizes larger in most comparisons (Table 3). Using isolated handgrip forces across a variety of wrist and forearm postures, Mogk and Keir (2003) showed similar findings. With no grip force, wrist extensors displayed significantly higher levels of muscle activity than the wrist flexors. Across all magnitudes of grip force, the wrist flexors demonstrated a greater postural-dependence than the wrist extensors, significantly influencing FCR activity with minimal change to ECR. In agreement with our findings, Mogk and Keir (2003) demonstrated that in a neutral wrist

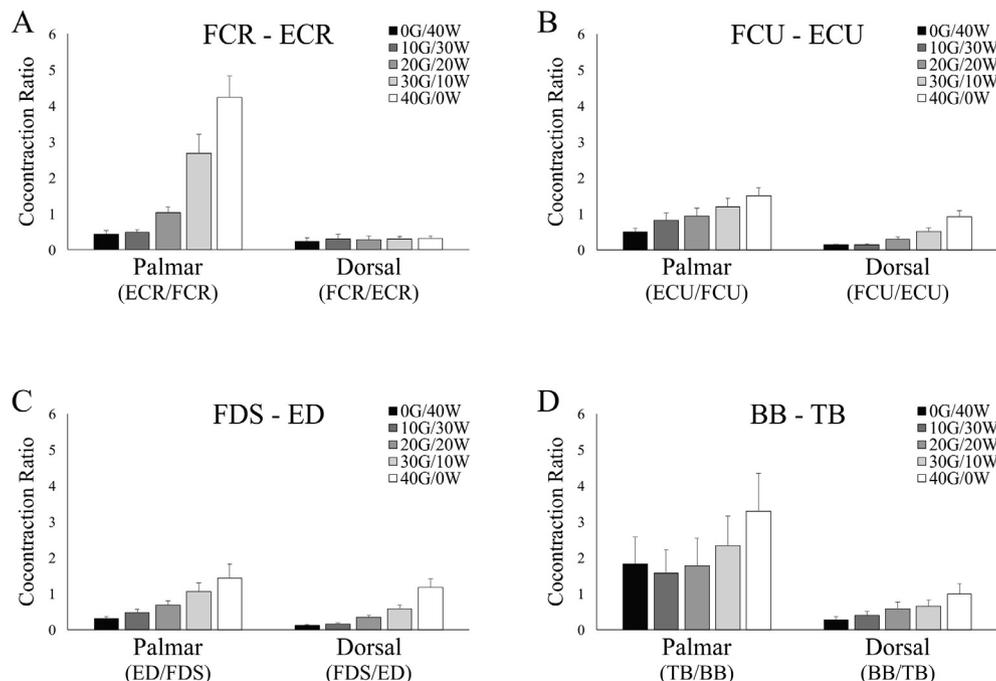


Fig. 4. Group averages ($n = 11$) of co-contraction ratios (antagonist/agonist muscle pairings). Darker bars denote conditions with greater wrist force (palmar or dorsal). Lighter bars denote conditions with greater handgrip forces.

and forearm orientation, wrist extensor activity was approximately equal to flexor activity (although no direct statistical analysis was performed), underlining the importance of extensors providing wrist stability. Indeed, it has been reported that wrist flexor activity only exceeds extensors at high handgrip forces, and is either equal or less active than wrist extensors at moderate-to-low handgrip forces (Claudon, 1998).

The relationship between the wrist flexors and extensors during wrist forces appears more complex. In the present study, conditions dominated by palmar exertions continued to demonstrate elevated extensor activity (8.2, 14.5, and 6.7% MVE across the ECR, ECU, and ED, respectively), while conditions dominated by dorsal forces demonstrated almost lower flexor activity (2.4, 2.4, and 3.6% MVE across the FCR, FCU, and FDS, respectively). Averaged across the three flexors and extensors, this collectively represents a 3.5-fold greater activity in the extensors. This indicates that while substantial extensor activity is required to stabilize the wrist during palmar forces, minimal flexor activity is needed to counter dorsal forces. Of the work that exists on this matter, our findings are in agreement. In examining facilitatory and inhibitory reflex arcs to the ECR, (Fujii et al., 2007) found that FCR activity was almost non-existent in the presence of high ECR activity. Protocols examining wrist forces in combination with various grips (power grip/pinch grip) have shown higher extensor activity in stabilizing roles (Greig and Wells, 2008). This body of literature is supported by recent findings that the wrist extensors dominate the wrist stabilizing role, and whose mechanisms are driven by muscle activity, geometry, length and moment arms (Holmes et al., 2015). For both handgripping and wrist force production, biomechanical and anatomical factors are noteworthy. The cross-sectional area (CSA) and moment arms of the wrist flexors are larger than extensors (Gonzalez et al., 1997). The sum total CSA of the anterior compartment of the forearm is $\sim 24.8 \text{ cm}^2$ in comparison to 11.8 cm^2 for the posterior (Gonzalez et al., 1997; Jacobson et al., 1992; Lieber et al., 1992). This manifests as a decreased force generating capacity and evidence has shown that wrist extension MVCs produce significantly less force than flexion (Delp et al., 1996; Hallbeck, 1994; La Delfa et al., 2015). Thus, wrist extensor muscles require a greater % activation to balance flexors forces, and is the leading mechanism responsible for both the earlier onset of fatigue and development of chronic overuse injuries (Bystrom et al., 1991; Snijders et al., 1987).

4.2. Flexor-extensor muscle differences

In the present study, FCU and ECU (FCU: 12.2% MVE, ECU: 16.5% MVE, averaged across all experimental trials) demonstrated higher activity than FCR and ECR (FCR: 7.2% MVE, ECR: 11.9% MVE, averaged across all experimental trials), respectively, in nearly every experimental condition. Initial interpretations suggest that muscles located near the ulna contribute more to hand and wrist exertions than those near the radius. Anatomically, the FCU has a 41.3% greater muscle mass and a 72% larger CSA than the FCR (Lieber et al., 1990), although the FCR possesses a larger moment arm (Ettema et al., 1998). Thus, in the present study, it is possible that motor control strategies prioritize the greater strength of the FCU over the greater mechanical advantage of the FCR in generating wrist flexion. However, this explanation is inconsistent when viewed from the perspective of the extensors. Lieber et al., (1990) demonstrated that ECR brevis and ECR longus combined were 88.2% more massive with a 61.2% larger CSA than ECU. ECR also possesses a larger moment arm than the ECU (Ettema et al., 1998). Being both smaller and at a mechanical disadvantage compared to the ECR, it is therefore possible that the ECU produces greater activation in order to adequately stabilize the wrist. While these two proposed rationales may seem at odds between the flexors and extensors, this may tie in to the separate roles of each muscle group. The wrist flexors, task-dependent muscles that are typically the prime movers in nearly all hand and wrist movements (Duque et al., 1995; Imrhan, 1991; Kattel

et al., 1996; Mogk and Keir, 2003) may prioritize a muscle's size and strength when executing a motor task. In contrast, the wrist extensors, whose primary functions are to stabilize the wrist by balancing the considerable forces produced by the flexors (Hägg et al., 1997; Holmes et al., 2015; Mogk and Keir, 2003; Snijders et al., 1987) may be required to maintain a given level of wrist extension force. In doing so, the weaker, smaller extensor muscles will exhibit higher muscle activity.

4.3. Dual tasks

The present work builds on a small body of literature that has investigated simultaneous muscle actions of the hand and wrist. This work holds a distinct advancement within the field by providing insight into forearm muscle recruitment strategies during tasks relevant to workplace settings. Of particular interest is the applicability of these findings to overuse injury risk; principally of the wrist extensors. It is well established that both the intensity of a muscle contraction and duration that the activity is maintained are key factors in the development of overuse injuries (Mathiassen et al., 2003; Visser and van Dieën, 2006). Recommendations have encouraged companies and job sites to reduce the loads workers are exposed to while also providing appropriate work-to-rest intervals. Ideally, work loads should be normalized to an individual's strength, and in the case of hand-dominant tasks, is typically normalized to maximum grip strength. Research by Wells and Greig propose that this approach is inappropriate in most scenarios, given that purely grasping the hand is rarely used to accomplish motor tasks (Wells and Greig, 2001). Rather than operating in a single vector, the hand should instead be viewed as a force and moment wrench, capable of both exerting grip forces and transferring torques produced at the wrist. Indeed, more recent work has shown that grip force, when used to transmit forces and moments to the environment, poorly relate with muscle activation (Greig and Wells, 2008). Our present work adheres closely to this framework. By manipulating task parameters (handgrip and wrist forces) muscle activity changed significantly. Demonstrating this issue most clearly is the FCR (Fig. 3A). In the pure handgrip trial, the FCR averaged 4.4% MVE, but steadily increased with added palmar forces. Any workplace settings normalizing work loads to maximum grip, but whose tasks involve significant palmar forces, would likely underestimate the true load applied to the FCR. This task-specificity manifests not only in EMG, but in force outputs as well. When coupled with greater handgrip forces, wrist flexion MVCs produce significantly more force while wrist extensions MVCs are impaired (Seo et al., 2008). Collectively, this work demonstrates the need of workplace assessments to utilize dual-task or multi-component protocols, particularly when tasks involve increasingly complex hand manipulation. If only handgrip strength is chosen, estimates are likely to be erroneous.

4.4. Elbow flexors/extensors

In the present study, the biceps and triceps brachii demonstrated elevated levels of EMG during conditions dominant in palmar and dorsal forces, respectively (see Fig. 3). Neither were highly active in the pure handgrip conditions. This suggests the biceps and triceps brachii serve a stabilizing role during wrist exertions, which is likely facilitated through multi-articular muscles spanning the humerus and forearm. This is not the first study to report a distal-proximal relationship on neuromuscular measures of the upper-limb (Forman et al., 2016; Sporrang et al., 1996). Additionally, our findings indicate that an elbow flexion moment may stabilize the forearm during palmar forces while an elbow extension moment may stabilize the forearm during dorsal forces.

4.5. Implications

The findings of this study solidify previous work that the wrist extensors play a stabilizing role in hand/wrist actions, exhibiting moderate-high levels of activity across all tasks. This has potential consequences for workplace design and injury prevention. A key factor in the development of chronic overuse injuries is insufficient rest intervals between periods of muscle loading. Simply varying workplace parameters throughout the day to provide episodic rest to different muscles is unlikely to benefit the wrist extensors. Any upper-limb task involving gripping or wrist exertions will result in significant extensor loading. Complete cessation of work may be required for adequate rest periods. However, it should be clarified that this investigation was still exploratory in nature, and not ergonomically focused. Tasks were also strictly isometric, and should be followed by dynamic work.

5. Conclusions

Despite challenges associated with executing simultaneous handgrip and wrist forces, forearm muscle recruitment matched with anatomical constraints. Findings were in agreement with previous work that has investigated forearm muscle activity under simpler motor tasks. The wrist flexors demonstrated clear task-dependency across various conditions, whereas the wrist extensors behaved as would be expected of joint stabilizers; persistently elevated muscle activity regardless of condition. The mechanisms behind these findings are rooted at least in part by the CSA, strength, and moment arms of individual muscles. These findings demonstrate the importance of assessing forearm muscle recruitment under dual task or multi-component designs. These results could have potential implications for future work geared towards the development of chronic overuse injuries of the forearm.

Conflict of interest

The authors declare that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jelekin.2019.02.004>.

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