The effects of isometric hand grip force on wrist kinematics and forearm muscle activity during radial and ulnar wrist joint perturbations

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The purpose of this work was to investigate forearm muscle activity and wrist angular displacement during radial and ulnar wrist perturbations across various isometric hand grip demands. Surface electromyography (EMG) was recorded from eight muscles of the upper extremity. A robotic device delivered perturbations to the hand in the radial and ulnar directions across 4 pre perturbation grip magnitudes. Angular displacement and time to peak displacement following perturbations were evaluated. Muscle activity was evaluated pre and post perturbation. Results showed an inverse relationship between grip force and angular displacement ($p \leq 0.001$). Time to peak displacement decreased as grip force increased ($p \leq 0.001$). There was an increase in muscle activity with higher grip forces across all muscles both pre- and post-perturbation ($p \leq 0.001$) and a greater average muscle activity in ulnar as compared to radial deviation ($p = 0.02$). This work contributes to the wrist joint stiffness literature by relating wrist angular displacement to grip demands during novel radial/ulnar perturbations and provides insight into neuromuscular control strategies.

1 **THE EFFECTS OF ISOMETRIC HAND GRIP FORCE ON WRIST KINEMATICS AND**

2 **FOREARM MUSCLE ACTIVITY DURING RADIAL AND ULNAR WRIST JOINT**

3 **PERTURBATIONS**

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28   **Abstract**

29   The purpose of this work was to investigate forearm muscle activity and wrist angular

30   displacement during radial and ulnar wrist perturbations across various isometric hand grip

31   demands. Surface electromyography (EMG) was recorded from eight muscles of the upper

32   extremity. A robotic device delivered perturbations to the hand in the radial and ulnar directions

33   across 4 pre perturbation grip magnitudes. Angular displacement and time to peak displacement

34   following perturbations were evaluated. Muscle activity was evaluated pre and post perturbation.

35   Results showed an inverse relationship between grip force and angular displacement ($p \leq 0.001$).

36   Time to peak displacement decreased as grip force increased ($p \leq 0.001$). There was an increase

37   in muscle activity with higher grip forces across all muscles both pre- and post-perturbation ($p \leq$

38   0.001) and a greater average muscle activity in ulnar as compared to radial deviation ($p = 0.02$).

39   This work contributes to the wrist joint stiffness literature by relating wrist angular displacement

40   to grip demands during novel radial/ulnar perturbations and provides insight into neuromuscular

41   control strategies.

42   **Keywords:** biomechanics; grip force; wrist perturbations; EMG; ergonomics

43 **1. Introduction**

44   Optimal function and control of the distal upper extremity is critical for interacting with

45 objects and performing nearly all tasks of daily life. As the end effector of the upper extremity,

46 the wrist and hand can perform both forceful exertions, as well as precise movements to

47 effectively execute fine motor tasks. An abundance of literature exists investigating

48 neuromuscular control of the wrist joint (Forman et al., 2020a; Forman et al., 2020b; Charles and

49 Hogan, 2010; 2011) and wrist joint stiffness during flexion and extension movements (Charles

50 and Hogan, 2012; Milner & Cloutier, 1993; De Serres and Milner, 1991b). Charles and Hogan

51 (2011) demonstrated that wrist rotation dynamics are vastly different from arm reaching

52 movements, since wrist rotations are influenced more by stiffness than inertia. The authors

53 concluded that a primary aspect of wrist joint control involves compensating for stiffness. Thus,

54 knowledge of wrist joint stiffness and the viscoelastic characteristics that govern stiffness is

55 essential to understanding how humans perform coordinated wrist actions (Formica et al., 2012;

56 Drake & Charles, 2014). However, most wrist and hand actions include concurrent wrist

57 exertions and gripping tasks (Forman et al. 2019; 2021) and the viscoelastic characteristics of the

58 mechanical impedance of the wrist joint can change with gripping tasks (Falzarano et al., 2021).

59 Our early work investigated muscular contributions to wrist joint rotational stiffness in flexion

60 and extension (Holmes et al., 2015). We implemented a paradigm by which increases in forearm

61 muscle co-contraction (via gripping) manipulated wrist stiffness, such that muscular responses to

62 sudden loading could be investigated with tasks representing muscular demands of tool/object

63 manipulation. To date, little is known about muscular responses to sudden loading in radial and

64 ulnar deviation. Forman et al (2020c) investigated muscular responses to radial/ulnar

65 perturbations during a dynamic wrist flexion/extension task and passive wrist stiffness has only

66   been evaluated across radial/ulnar directions in a small sample with a clinical focus (Rijnveld

67   and Krebs, 2007). Thus, the aim of this work was to quantify how grip force demands influence

68   wrist kinematics and forearm muscular contributions to sudden radial/ulnar perturbations.

69   Perturbations, due to sudden (often unexpected) external forces, are commonplace in

70   many occupations, particularly when working in an environment where external interactions may

71   occur between worker and surroundings. Understanding the effect of perturbations on task

72   performance is critical to our basic understanding of neuromuscular control and may provide

73   future insight into workplace safety. Anticipatory muscle activity and joint stiffening is one

74   method commonly used in the presence of instability or perturbing forces, particularly when a

75   perturbation is expected, to help minimize joint displacement caused by a perturbing force

76   (Forman et al., 2020a; Holmes et al., 2015). Increasing grip force has been shown to increase

77   forearm muscle activity (Mogk and Keir, 2003) and co-contraction (Holmes et al. 2015), which

78   is considered one determinant of wrist stiffness. However, pre-emptive muscle activation is

79   metabolically wasteful (Hogan, 1984) and may lead to an earlier onset of muscle fatigue. The

80   development of muscle fatigue will subsequently decrease maximal force production

81   capabilities, reduce one's ability to effectively perform accurate fine motor tasks (Forman et al.,

82   2020b; Huysmans et al., 2008), and can ultimately increase the risk of developing MSDs (Dugan

83   and Frontera, 2000). Sufficient joint stiffness is needed to protect the joint while also allowing

84   for accurate, unhindered movement of the wrist to complete a desired task. Compensatory

85   actions post-perturbation via voluntary and involutory muscle responses will also influence task

86   performance and injury risk and should be considered to completely understand neuromuscular

87   control during perturbations. Perturbation magnitude, direction, timing, and background muscle

88   activity can all influence compensatory actions at the wrist (Weinman et al., 2021).

89   Perturbation research at the wrist has consistently demonstrated increases in muscular co-

90   contraction and joint stiffness in anticipation of a perturbing force (De Serres and Milner, 1991;

91   Goodin and Aminoff, 1992; Holmes et al., 2015; Sinkjær and Hayashi, 1989). However, the vast

92   majority of this research has been performed using perturbations causing wrist flexion or

93   extension (Holmes et al. 2015; Miscio et al., 2001; Weinman et al. 2021), with little

94   consideration for radial or ulnar deviation. Investigation into the effects of radial and ulnar

95   perturbations is needed as wrist joint dynamics are complex (Charles and Hogan, 2010) and

96   primary muscles driving deviation actions can be different than flexion/extension (Horii et al.,

97   1993). Maximal force production of the wrist toward both radial and ulnar deviation is

98   considerably less compared to wrist flexion (La Delfa et al., 2015) which may lead to greater

99   relative force needed to counteract perturbing forces. Muscle activity and co-contraction in

100   response to radial and ulnar perturbations has been investigated during movement, with a self-

101   selected grip force (Forman et al., 2020b). It was found that perturbations generating radial

102   deviation, resulted in greater angular displacement compared to ulnar deviation. This may be due

103   to greater strength capabilities of the wrist in resisting ulnar perturbations (Delp et al., 1996;

104   Vanswearingen, 1983). However, the wrist exhibits a greater moment toward ulnar deviation

105   rather than radial deviation (La Delfa and Potvin, 2017). The extensor carpi radialis, extensor

106   digitorum communis, and brachioradialis produce significantly greater muscle activity during

107   ulnar perturbations, while flexor digitorum superficialis, flexor carpi ulnaris, and extensor carpi

108   ulnaris produce greater activity during radial perturbations (Forman et al., 2020c). However, the

109   relationship between grip force and angular displacement cannot be commented on as grip force

110   was neither controlled for, nor measured (Forman et al., 2020c). Additionally, the perturbations

111   in this work were delivered as participants performed a dynamic tracking task. Radial and ulnar

112   perturbations have yet to be investigated during static loading conditions. Investigation into

113   radial and ulnar perturbations during static loading is necessary to gain insight into how the wrist

114   is affected by perturbation direction under various grip force demands.

115   The purpose of this work was to investigate forearm muscle activity and wrist angular

116   displacement during radial and ulnar wrist perturbations across various isometric hand grip

117   demands. We hypothesized that an inverse relationship would be observed between grip force

118   and angular wrist displacement following a perturbing force (Holmes et al., 2015; Mogk and

119   Keir, 2003) and radial perturbations would result in greater angular displacement than ulnar

120   perturbations (Forman et al., 2020c).

121   **2. Methods**

122   *2.1 Participants*

123   This study used a robotic device to deliver wrist perturbations to human participants.

124   University-aged individuals received a total of twenty perturbations in each direction (i.e., the

125   perturbation force caused radial/ulnar deviation) on one collection day. Post-collection data

126   processing quantified differences in wrist angular displacement, time to peak displacement and

127   muscle activity during radial and ulnar perturbations across 4 handgrip magnitudes. Twenty

128   right-handed healthy subjects, ten males and ten females (height, 173.0±10.6 cm, weight,

129   71.98±10.2 kg, age, 22.9±3.0 years) participated in this study. All participants confirmed having

130   no history of injury to the upper limb within the last 12 months and no restriction to their upper

131   limb range of motion. Each participant provided informed written consent prior to participation.

132   This study was approved by the Brock University Bioscience Research Ethics Board (File # 16-

133   263).

134   *2.2 Experimental set-up*

135   Participants were seated with their arm in a robot facing visual feedback. The robotic

136   device was placed to the right-hand side of the body and participants rested their forearm in the

137   device (WristBot, Genoa, Italy) and gripped a custom force sensing handle with their hand

138   (Figure 1A.). The handle of the robot could slide to aid in unconstrained wrist rotation and this

139   feature helped ensure a consistent starting posture for the forearm and hand across participants.

140   Each participant grasped the handle using a power grip (with fingers and thumb wrapped around

141   the handle) and the wrist was aligned with the centre of rotation of the robot. Shoulder and elbow

142   joint positions were measured prior to the experiment with a goniometer (elbow flexion: 132.5 ±

143   5.6°, shoulder abduction: 34.4 ± 5.9°, shoulder flexion: 8.6 ± 3.1°, lateral rotation: 47.7 ± 10.8°).

144   The WristBot is a custom-built manipulandum with a range of motion (ROM) that replicates

145   typical human wrist motion in three degrees of freedom: flexion/extension: ± 62°, radial/ulnar: +

146   45°/-40°, pronation/supination: ± 60° (Iandolo et al., 2019; Masia et al., 2009). The robot uses

147   four brushless motors to deliver torques that manipulate the wrist joint, compensate for hand

148   mass and provide low inertia. Motors allow isolation of a targeted plane of motion, by locking

149   the undesired degrees of freedom. Forearm pronation and supination, and wrist flexion and

150   extension were locked during this study to control for any movement in these directions. Velcro

151   straps were used to secure the participant's forearm to the WristBot, only allowing movement at

152   the wrist joint.

153

154   Muscle activity was recorded with surface electromyography (EMG) over eight upper

155   extremity muscles: flexor carpi radialis (FCR), flexor digitorum superficialis (FDS), flexor carpi

156   ulnaris (FCU), extensor carpi radialis (ECR), extensor digitorum communis (EDC), extensor

157   carpi ulnaris (ECU), brachioradialis (BR) and biceps brachii (BB). Disposable paired monopolar

158   Ag-AgCl electrodes (MediTrace 130, Kendall, Mansfield, MA, USA) were placed over the

159   muscle belly of each muscle, in-line with muscle fiber orientation, and with an inter-electrode

160   distance of 2.5 cm. Electrode placement was determined with palpation following established

161   guidelines (Perotto and Delagi, 2005) and the recording sites were shaved and scrubbed with

162   alcohol prior to placement. EMG signals were band-pass filtered (10–1000 Hz), differentially

163   amplified (CMRR > 115 dB at 60 Hz; input impedance, ~10 GΩ; AMT-8, Bortec Biomedical

164   Ltd, Calgary, AB Canada), sampled at 2000 Hz (USB-6229 BNC, National Instruments, Austin,

165   TX, USA) and synched with robot kinematics. To normalize EMG signals, 2 maximum

166   voluntary contractions (MVC) were performed for each muscle using muscle specific

167   contractions for the eight muscles. Participants were manually resisted by the researcher

168   following the maximum contraction protocol outline by (Forman et al., 2020a). Each MVC was

169   held for 5 seconds, and a minimum of 30 seconds rest was given in between contractions.

170   *2.4 Experimental Protocol*

171   Maximum grip force was measured using a custom grip force handle equipped with a

172   force transducer. Participants performed 2 maximum voluntary grip trials using the force sensing

173   handle. If these 2 grip force trials differed by more than 5%, a third trial was performed (Antony

174   and Keir, 2010; Au and Keir, 2007). The greatest peak force from the maximum grip trials was

175   used to normalize the target grip forces for experimental conditions. During experimental

176   conditions, participants were instructed to grip the handle of the robotic device to a specified

177   target grip magnitude. Real time grip force was displayed on a monitor directly in front of the

178   participant and the target grip magnitude was indicated by a horizontal line (LabView 2016,

179   National Instruments, Austin, TX, USA). Additional horizontal lines represented error bars

180   positioned ± 1.5 % MVC around the target grip (see Figure 1B).

181   Participants became familiarized with gripping to the visual target as well as the force

182   and timing of the perturbation. Once familiar with the robotic device and experimental set-up,

183   participants performed gripping tasks with targets normalized to 5/20/50/80% of their maximum

184   grip strength (% MVG). Every 7 seconds, the participant received a perturbation in the radial or

185   ulnar direction, that caused rotation of the hand at the wrist joint. Participants were made aware

186   of the perturbation timing and were prompted by the researchers to grip to the target force on the

187   monitor prior to receiving a perturbation. Perturbation timing was made known to the participant

188   to minimize muscular fatigue. Participants gripped to the target force prior and during the

189   perturbation and relaxed until the onset of the next perturbation. There were five perturbation

190   trials for each direction (radial deviation (RD) and ulnar deviation (UD)) at each of the 4 grip

191   force conditions. Perturbation direction was known to participants and grip force conditions were

192   randomized.

193   In a neutral wrist posture, the robot delivered perturbations at a force of 22.3 N, resulting

194   in an end effector wrist torque of 1.78 Nm over 100 ms. This force was chosen based on previous

195   literature that delivered wrist perturbations (Forman et al., 2020c; Holmes et al., 2015).

196   Participants were instructed to focus on maintaining the required grip force rather than hand

197   position and they were not instructed to resist the device. A perturbation warning was given 2

198   seconds before the perturbation which allowed adequate time for the participant to reach the

199   required grip force target before the perturbation (without a long grip hold that may cause

200   fatigue). The perturbations occurred every 7 seconds and was made aware to the participant. Rest

201   was given between trials and conditions based on the target grip magnitude (5% MVG: 30 s,

202 20% MVG: 60 s, 50% MVG: 90 s, 80% MVG: 120 s), to minimize fatigue. Maximal grip force

203 was also measured post-experiment to assess fatigue.

204 *2.5 Data Analysis*

205   All EMG and kinematic data were analyzed offline using MATLAB 2015b (MathWorks

206 Inc., Natick, MA, USA). A quiet EMG trial was collected prior to the experimental conditions,

207 and the bias was removed from each EMG channel. The EMG data (both maximal contraction

208 and experimental trials) were linear enveloped (rectified and low pass Butterworth filtered using

209 a dual pass, 2nd order and 3 Hz cut-off). Considering stiffness is dependent on muscle force, our

210 signal processing may reflect an EMG-muscle force relationship (Winter, 2009). This processing

211 would allow for future joint rotational stiffness evaluations (Potvin and Brown, 2005; Holmes et

212 al. 2015b). EMG from experimental trials were normalized to the greatest muscle specific

213 maximal voluntary contraction (% MVC). Average muscle activity was measured at 3 time

214 points (Pruszynski & Scott, 2012); (1) Baseline (PRE) 0-15 ms prior to perturbation, (2) POST1,

215 20-50 ms after perturbation and (3) POST2, 50-100 ms after perturbation. Angular displacement

216 (AD) was computed and stored by the robot and measured the displacement of the WristBot

217 handle from the participants starting wrist position to peak displacement after the perturbation.

218 Time to peak displacement (TPD) was recorded as the time to the maximum angular

219 displacement following the onset of the perturbation. Wrist angular velocity was calculated from

220 the mean AD (°) and TPD (ms) across all 5 trials for each of the four grip force conditions and

221 perturbation directions. In addition, percent changes of angular velocity were calculated for each

222 of the grip forces and directions. Kinematics were measured by the robot and sampled at 100 Hz.

223 AD, TPD and muscle activity (EMG) was measured pre- and post-perturbation to evaluate the

224 influence of grip force on wrist joint kinematics.

225

226 [INSERT FIGURE 1 APPROXIMATELY HERE]

227

228 *2.6 Statistical analysis*

229 Statistical analysis focused on comparing the response of the kinematic and EMG data to

230 AD following a perturbation. A paired t-test was conducted to compare mean grip force prior to

231 radial or ulnar perturbations for each grip intensity. A 2 (perturbation direction) x 4 (grip force)

232 factorial ANOVAs with repeated measures was used to assess AD, TPD and angular velocity. A

233 2 (perturbation direction) x 3 (time) x 4 (grip force) factorial ANOVA with repeated measures

234 was used to assess EMG activity across perturbation direction (RD/UD), time point (PRE,

235 POST1, POST2), and grip magnitude (5/20/50/80% maximum). All outcome measures were

236 averaged across the 5 repetitions for each experimental condition, for each participant.

237 Assumptions of normality, homogeneity of variance and sphericity were all met ($p > 0.05$). An

238 alpha level of $p < 0.05$ was used, and a Bonferroni post-hoc test was chosen to assess interaction

239 effects. All data are presented as mean ± standard error.

240 **3. Results**

241 *3.1 Grip Force*

242   No significant differences (p = 0.82) were found between grip and direction as mean grip

243   forces were consistently held in RD and UD perturbations equally. No changes in maximum grip

244   force were found pre (292.8 ± 76.1 N) and post experiment (301.5 ± 80 N), indicating that

245   muscle fatigue did not influence the results of the study (p = 0.69). Figure 2 demonstrates raw

246   grip force and muscle activity for a representative participant, with perturbation onset indicated.

247   [INSERT FIGURE 2 APPROXIMATELY HERE]

248

249   *3.2 Wrist kinematics*

250   There was a main effect of grip force on AD (p ≤ 0.001, $F_{(3, 19)}$ = 631.06, η^2 = 1.00), a

251   Bonferroni post-hoc analysis confirmed significantly less angular displacement as grip force

252   increased (p = 0.001) (Figure 3). A main effect of direction was also found (p ≤ 0.001, $F_{(3, 19)}$ =

253   1256.19, η^2 = 0.99). There was higher mean angular displacement in RD compared to UD (RD:

254   17.31 ± 0.59 °, UD: 10.43 ± 0.47 °). No significant interaction was found between grip force and

255   perturbation direction for peak AD (p = 0.75, $F_{(3,19)}$ = 0.41, η^2 = 0.21) (Figure 3).

256   A significant main effect of grip force on TPD was found, indicating that TPD

257   significantly decreased as grip force increased, regardless of perturbation direction (Figure 4). A

258   main effect of direction was found (p ≤ 0.001, $F_{(3,19)}$ = 2035.33, η^2 = 0.99) and there was a

259   significantly slower TPD in RD (RD: 129.06 ± 1.77 ms, UD: 100.65 ± 1.67 ms). No significant

260   interaction was found between TPD (ms) and grip force (p = 0.31, $F_{(3,19)}$ = 3.170, η^2 = 0.71)

261   (Figure 4).

262   Percent change scores for angular velocity were calculated between two consecutive

263   measurements: 5-20, 20-50, 50-80 %MVG (Figure 5). No significant interactions were found for

264   angular velocity (p = 0.84) and no significant main effects of grip and direction (p's = 0.25).

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267   [INSERT FIGURE 3 APPROXIMATEY HERE]

268   [INSERT FIGURE 4 APPROXIMATEY HERE]

269   [INSERT FIGURE 5 APPROXIMATEY HERE]

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272   *3.3 EMG and muscle activation responses*

273   There was a significant main effect of direction for ECR, EDC and BR (p = 0.02, $F_{(1, 19)}$ =

274   5.69, η^2 = 0.12). A Bonferroni post-hoc analysis revealed significantly larger mean muscle

275   activation in UD as compared to RD for all grip conditions. No significant effect of time was

276   found across any muscles (Table 1). Extensor muscles (RD: 23.27 ± 16.45 %MVC, UD: 24.00 ±

277   17.04 %MVC) produced greater muscle activation compared to flexor muscles (RD: 17.19 ±

278   15.59 %MVC, UD: 16.25 ± 15.40 %MVC) across all grip forces.

279   No significant interactions were found between AD, TPD and grip conditions (Table 1).

280   A significant main effect of grip force magnitude was observed across all muscles. There was an

281   increase in muscle activation with increasing grip forces across all muscles (p ≤ 0.001, $F_{(3, 19)}$ =

282   774.19, η^2 = 0.84) excluding BB which showed no differences in muscle activity throughout (p =

283   0.72) (Figures 6 and 7).

284

285   [INSERT TABLE 1 APPROXIMATEY HERE]

286   [INSERT FIGURE 6 APPROXIMATEY HERE]

287   [INSERT FIGURE 7 APPROXIMATEY HERE]

288

289

290   **4. Discussion**

291   The purpose of this study was to determine how radial and ulnar perturbations affect the

292   wrist joint musculature during isometric gripping and to explore the relationship between grip

293   force magnitude and angular wrist kinematics. Results support our first hypothesis where a

294   greater grip force resulted in a smaller angular wrist displacement following a perturbing force in

295   both radial and ulnar deviation. Indeed, there was a significant decrease in angular displacement

296   with increasing grip force and this corresponds with an increase in muscle activity, suggesting

297   that joint stiffness increased with an increase in muscle activity (Franklin & Milner, 2003).

298   Although wrist angular displacement significantly decreased by 2.02° from the 50 to 80% grip

299   conditions, this difference was 4.18° between 20 to 50 %MVG, considering both directions.

300   Similarly, angular velocity was 13.56% slower when gripping from 20 to 50 %MVG in radial

301   deviation and 6.85% slower when gripping from 50 to 80 %MVG. Thus, increasing grip

302   demands from 50 to 80 %MVG may not provide additional benefit for minimizing joint rotation.

303   Results of the study also support hypothesis 2; radial perturbations had a significantly greater

304   mean angular displacement (17.31 ± 0.59°) compared to ulnar perturbations (10.43 ± 0.47°)

305   across all grip conditions. This finding may be explained by the strength capabilities of the

306   forearm muscles. ECR and EDC produced greater activity in UD as compared to RD for all grip

307   conditions. This is supported by findings of greater angular displacement following a

308   perturbation that moves the wrist into radial deviation compared to ulnar deviation (Forman et

309   al., 2020c). The forearm extensors contribute substantially to wrist joint stability (Holmes et al.,

310   2015; Holzbaur et al., 2005), due to a combination of muscle activity and geometric (i.e., line of

311   action and moment arm) advantages as compared to the flexors (Gonzalez et al., 1997). Further,

312   ECR activity may be prioritized when opposing ulnar perturbations due to a more direct muscle

313   line of action (Bawa et al., 2000; Horii et al., 1993). Our noted muscle activity differences could

314   contribute to the greater angular displacement exhibited during radial perturbations compared to

315   ulnar perturbations. It should be noted that our experimental set up required participants to grasp

316   a handle using a power grip. This requirement could favour radial deviation. Future work may

317   want to consider the roles of extensor pollicis longus and extensor pollicis brevis, which can

318   contribute to wrist deviation and extension, via musculoskeletal modelling.

319   Deviation of the wrist from a neutral position, particularly while generating high wrist or grip

320   force requirements can pose as a risk factor for musculoskeletal disorders. Experiencing

321   perturbations in the workplace (either from tool forces or unexpected sudden loading) can cause

322   rapid muscle stretch and eccentric forces, which may, over time be a contributing factor for

323   injury development. Two adaptive behaviours can occur in response to a sudden perturbation, it

324   can be either proactive – an anticipatory response, or reactive – a compensatory response to a

325   sudden disturbance (Stuphorn and Emeric, 2012). In this work, no significance was found across

326   muscles for any of the measured time points (PRE, POST1, and POST2). Background muscle

327   activity is thought to influence post perturbation and voluntary responses differently (Pruszynski

328   et al. 2009). In our work, there appeared to be a transition from a reactive to proactive muscle

329   recruitment strategy as grip force increased. An emerging trend demonstrates more of a reactive

330   response associated with lower grip forces (5 %MVG and 20 %MVG) as POST2 had greater

331   muscle activity compared to higher grip conditions. Whereas a proactive response is visible with

332   the higher grip forces (50 %MVG and 80 %MVG) as muscles are more active during the pre-

333   perturbation phase, generating wrist stiffness and resulting in a smaller post response. These

334   trends are demonstrated following both radial and ulnar perturbations. These responses could

335   have been a result of the participants knowledge of perturbation timing (Forgaard et al., 2016)

336   thus, creating a proactive response before the perturbation occurred with higher grip forces.

337   These results are similar to work done by (Holmes & Keir, 2014), who found that known

338   perturbations result in a voluntary muscle response to prematurely stiffen the joint and unknown

339   perturbations result in a greater post or involuntary response.

340   Another possibility as to why POST2 responses had a larger contribution in lower grip force

341   conditions could be due to the focus of attention, velocity, and muscle activation at the different

342   grip intensities. At lower grip forces, the participants required minimal effort and little muscle

343   activity to obtain 5 and 20% of their maximum grip force and were probably less focused on the

344   perturbations, which may have resulted in a larger reactive response. In the higher grip force

345   scenarios participants may have focused more of their attention on the higher effort gripping task

346   directly before the perturbation; by focusing more on the timing of the perturbation component

347   they may have created an increase in voluntary muscle contraction that prematurely stiffened the

348   wrist. Previous work using an applied pre-loading wrist torque producing approximately 10% of

349   maximum muscle activity to investigate short latency (SLR) and long latency reflexes (LLR)

350   could be considered similar to our low grip force condition (Miscio et al. 2001). Miscio et al.

351   (2001) found smaller LLR amplitudes for muscles that shorten during perturbation as compared

352   to muscles that lengthen (flexion/extension direction). However, Weinman et al. (2021) found

353   significant modulation of LLR in shortened muscles, and this was influenced by perturbation

354   velocity, duration, background torque and task instruction and represents a physiological

355   decoupling of various muscle responses. Our trends speculate that there are differing

356   neuromuscular patterns associated with changes in grip force (pre-loading). Finally, a more

357   general effect could be due to higher level motor control mechanisms that intervene in the

358   planning of voluntary contraction (Morasso et al., 2014).

359

360   **5. Limitations**

361   This study only used University-aged participants and thus, the results of this work may be

362   difficult to generalize across all populations or age groups. It is important to note that crosstalk is

363   always a considerable factor when using surface EMG of the forearm. However, careful

364   placement of the electrodes (Underwood, 2006) and skin preparation guidelines were followed to

365   minimize this risk. To control for the many variables that could play a role in the experiment, we

366   used an innovative, quantitative, and repeatable robot-based perturbation delivery. There was

367   inherent bias due to forearm position. Participants were positioned in the robotic device in a

368   neutral wrist posture (defined as mid-pronation) and were instructed to grasp the handle using a

369   power grip. Extensor pollicis longus and extensor pollicis brevis, which can contribute to wrist

370   deviation and extension, were not measured given potential limitations with surface EMG from

371   these muscles. Due to the wrist posture associated with grasping the handle, these muscles could

372   be active during radial deviation and wrist extension. Future work should investigate wrist

373   stiffness during perturbations from different starting postures and consider contributions from the

374   hand/finger musculature. Future work should investigate the onset of muscle fatigue (Mugnosso

375   et al., 2018), the assessment of pain (Albanese et al., 2019), changes in wrist joint stiffness

376   (Falzarano et al., 2020) and the role of proprioception (Albanese et al., 2021).

377   **6. Conclusions**

378   This work sought to understand the effects of grip force (as a determinant of changing wrist

379   joint stiffness) in response to sudden perturbing forces in radial and ulnar deviation. It is

380   important to understand the point of diminishing returns in tasks that require gripping. Results of

381   this study show a significant decrease in wrist angular displacement and angular velocity as grip

382   force increases, with a slight plateau between 50-80% maximum grip. An increase in angular

383   displacement and slower angular velocity following radial perturbations suggest that sudden

384   radial displacement of the wrist joint may need to be investigated further. Lastly, there was a

385   noticeable but non-significant trend of reactive muscular responses in the lower grip forces

386   compared to a proactive response in higher grip forces, indicating potential differences in

387   neuromuscular patterns associated with altered grip force conditions. Further work investigating

388   co-contraction and joint stiffness in response to radial/ulnar perturbations are necessary to

389   contribute to the understanding of the relationship between grip force and wrist joint stiffness.

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400 **References**

401 Albanese, G. A., Holmes, M. W. R., Marini, F., Morasso, P., & Zenzeri, J. (2021). Wrist Position

402   Sense in Two Dimensions: Between-Hand Symmetry and Anisotropic Accuracy Across

403   the Space. *Frontiers in Human Neuroscience*, *15*, 662768.

404   https://doi.org/10.3389/fnhum.2021.662768

405 Albanese, G. A., Marini, F., Taglione, E., Gasparini, C., Grandi, S., Pettinelli, F., Sardelli, C.,

406   Catitti, P., Sandini, G., Masia, L., & Zenzeri, J. (2019). Assessment of human wrist

407   rigidity and pain in post-traumatic patients [*]. *2019 IEEE 16th International Conference*

408   *on Rehabilitation Robotics (ICORR)*, 89–94.

409   https://doi.org/10.1109/ICORR.2019.8779508

410 Antony, N. T., & Keir, P. J. (2010). Effects of posture, movement and hand load on shoulder

411   muscle activity. J*ournal of Electromyography and Kinesiology*, 20(2), 191-198

412 Au, A. K., & Keir, P. J. (2007). Interfering effects of multitasking on muscle activity in the upper

413   extremity. *Journal of Electromyography and Kinesiology*, 17(5), 578-586

414 Bawa, P., Chalmers, G. R., Jones, K. E., Søgaard, K., & Walsh, M. L. (2000). Control of the

415   wrist joint in humans. *European Journal of Applied Physiology*, *83*(2–3), 116–127.

416   https://doi.org/10.1007/s004210000270

417 Charles, S. K., & Hogan, N. (2010). The curvature and variability of wrist and arm movements.

418   *Experimental Brain Research*, *203*(1), 63–73. https://doi.org/10.1007/s00221-010-2210-x

419 Charles, S. K., & Hogan, N. (2011). Dynamics of wrist rotations. *Journal of Biomechanics*,

420   *44*(4), 614–621. https://doi.org/10.1016/j.jbiomech.2010.11.016

421   Charles, S. K., & Hogan, N. (2012). Stiffness, not inertial coupling, determines path curvature of

422   wrist motions. *Journal of Neurophysiology*, *107*(4), 1230–1240.

423   https://doi.org/10.1152/jn.00428.2011

424   De Serres, S. J., & Milner, T. E. (1991a). Wrist muscle activation patterns and stiffness

425   associated with stable and unstable mechanical loads. *Experimental Brain Research*,

426   *86*(2), 451–458.

427   De Serres, S. J., & Milner, T. E. (1991b). Wrist muscle activation patterns and stiffness

428   associated with stable and unstable mechanical loads. *Experimental Brain Research*,

429   *86*(2), 451–458. https://doi.org/10.1007/BF00228972

430   Delp, S. L., Grierson, A. E., & Buchanan, T. S. (1996). Maximum isometric moments generated

431   by the wrist muscles in flexion-extension and radial-ulnar deviation. *Journal of*

432   *Biomechanics*, *29*(10), 1371–1375. https://doi.org/10.1016/0021-9290(96)00029-2

433   Drake, W. B., & Charles, S. K. (2014). Passive Stiffness of Coupled Wrist and Forearm

434   Rotations. *Annals of Biomedical Engineering*, *42*(9), 1853–1866.

435   https://doi.org/10.1007/s10439-014-1054-0

436   Dugan, S. A., & Frontera, W. R. (2000). Muscle Fatigue and Muscle Injury. *Physical Medicine*

437   *and Rehabilitation Clinics of North America*, *11*(2), 385–403.

438   https://doi.org/10.1016/S1047-9651(18)30135-9

439   Falzarano, V., Holmes, M. W. R., Masia, L., Morasso, P., & Zenzeri, J. (2021). *Evaluating*

440   *viscoelastic properties of the wrist joint during external perturbations: Influence of*

441   *velocity, grip and handedness*. https://doi.org/10.3389/fnhum.2021.726841

442   Falzarano, V., Petrella, G., Marini, F., Holmes, M. W. R., Masia, L., Morasso, P., & Zenzeri, J.

443   (2020). Preliminary evaluation of a robotic measurement system for the assessment of

444   wrist joint spasticity*. *2020 8th IEEE RAS/EMBS International Conference for*

445   *Biomedical Robotics and Biomechatronics (BioRob)*, 539–544.

446   https://doi.org/10.1109/BioRob49111.2020.9224343

447   Forgaard, C. J., Franks, I. M., Maslovat, D., & Chua, R. (2016). Perturbation Predictability Can

448   Influence the Long-Latency Stretch Response. *PLOS ONE*, *11*(10), e0163854.

449   https://doi.org/10.1371/journal.pone.0163854

450   Forman, D. A., Forman, G. N., Avila-Mireles, E. J., Mugnosso, M., Zenzeri, J., Murphy, B., &

451   Holmes, M. W. R. (2020). Characterizing forearm muscle activity in university-aged

452   males during dynamic radial-ulnar deviation of the wrist using a wrist robot. *Journal of*

453   *Biomechanics*, *108*, 109897. https://doi.org/10.1016/j.jbiomech.2020.109897

454   Forman, D. A., Forman, G. N., Mugnosso, M., Zenzeri, J., Murphy, B., & Holmes, M. W. R.

455   (2020). Sustained Isometric Wrist Flexion and Extension Maximal Voluntary

456   Contractions Similarly Impair Hand-Tracking Accuracy in Young Adults Using a Wrist

457   Robot. *Frontiers in Sports and Active Living*, *2*, 53.

458   https://doi.org/10.3389/fspor.2020.00053

459   Forman, G. N., Forman, D. A., Avila-Mireles, E. J., Zenzeri, J., & Holmes, M. W. R. (2020).

460   Investigating the Muscular and Kinematic Responses to Sudden Wrist Perturbations

461   During a Dynamic Tracking Task. *Scientific Reports*, *10*(1), 4161.

462   https://doi.org/10.1038/s41598-020-61117-9

463   Formica, D., Charles, S. K., Zollo, L., Guglielmelli, E., Hogan, N., & Krebs, H. I. (2012). The

464   passive stiffness of the wrist and forearm. *Journal of Neurophysiology*, *108*(4), 1158–

465   1166. https://doi.org/10.1152/jn.01014.2011

466 Franklin, D. W., & Milner, T. E. (2003). Adaptive control of stiffness to stabilize hand position

467   with large loads. *Experimental Brain Research*, *152*(2), 211–220.

468   https://doi.org/10.1007/s00221-003-1540-3

469 Gonzalez, R. V., Buchanan, T. S., & Delp, S. L. (1997). How muscle architecture and moment

470   arms affect wrist flexion-extension moments. *Journal of Biomechanics*, *30*(7), 705–712.

471   https://doi.org/10.1016/S0021-9290(97)00015-8

472 Goodin, D. S., & Aminoff, M. J. (1992). The basis and functional role of the late EMG activity

473   in human forearm muscles following wrist displacement. *Brain Research*, *589*(1), 39–47.

474   https://doi.org/10.1016/0006-8993(92)91159-C

475 Hogan, N. (1984). Adaptive control of mechanical impedance by coactivation of antagonist

476   muscles. *Automatic Control, IEEE Transactions On*, *29*, 681–690.

477   https://doi.org/10.1109/TAC.1984.1103644

478 Holmes, M. W. R., & Keir, P. J. (2014). Muscle Contributions to Elbow Joint Rotational

479   Stiffness in Preparation for Sudden External Arm Perturbations. *Journal of Applied*

480   *Biomechanics*, *30*(2), 282–289. https://doi.org/10.1123/jab.2013-0135

481 Holmes, M. W. R., Tat, J., & Keir, P. J. (2015a). Neuromechanical control of the forearm

482   muscles during gripping with sudden flexion and extension wrist perturbations. *Computer*

483   *Methods in Biomechanics and Biomedical Engineering*, *18*(16), 1826–1834.

484   https://doi.org/10.1080/10255842.2014.976811

485 Holmes, M. W. R., Tat, J., & Keir, P. J. (2015b). Neuromechanical control of the forearm

486   muscles during gripping with sudden flexion and extension wrist perturbations. *Computer*

487   *Methods in Biomechanics and Biomedical Engineering*, *18*(16), 1826–1834.

488   https://doi.org/10.1080/10255842.2014.976811

489   Holzbaur, K. R. S., Murray, W. M., & Delp, S. L. (2005). A Model of the Upper Extremity for

490   Simulating Musculoskeletal Surgery and Analyzing Neuromuscular Control. *Annals of*

491   *Biomedical Engineering*, *33*(6), 829–840. https://doi.org/10.1007/s10439-005-3320-7

492   Horii, E., An, K. N., & Linscheid, R. L. (1993). Excursion of prime wrist tendons. *The Journal*

493   *of Hand Surgery*, *18*(1), 83–90. https://doi.org/10.1016/0363-5023(93)90250-7

494   Huysmans, M. A., Hoozemans, M. J. M., van der Beek, A. J., de Looze, M. P., & van Dieën, J.

495   H. (2008). Fatigue effects on tracking performance and muscle activity. *Journal of*

496   *Electromyography and Kinesiology*, *18*(3), 410–419.

497   https://doi.org/10.1016/j.jelekin.2006.11.003

498   Iandolo, R., Marini, F., Semprini, M., Laffranchi, M., Mugnosso, M., Cherif, A., De Michieli, L.,

499   Chiappalone, M., & Zenzeri, J. (2019). Perspectives and Challenges in Robotic

500   Neurorehabilitation. *Applied Sciences*, *9*(15), 3183. https://doi.org/10.3390/app9153183

501   La Delfa, N. J., Langstaff, N. M., Hodder, J. N., & Potvin, J. R. (2015). The interacting effects of

502   forearm rotation and exertion direction on male and female wrist strength. *International*

503   *Journal of Industrial Ergonomics*, *45*, 124–128.

504   https://doi.org/10.1016/j.ergon.2014.12.012

505   La Delfa, N. J., & Potvin, J. R. (2017). A musculoskeletal model to estimate the relative changes

506   in wrist strength due to interacting wrist and forearm postures. *Computer Methods in*

507   *Biomechanics and Biomedical Engineering*, 1–9.

508   https://doi.org/10.1080/10255842.2017.1366994

509   Masia, L., Casadio, M., Sandini, G., & Morasso, P. (2009). Eye-Hand Coordination during

510   Dynamic Visuomotor Rotations. *PLoS ONE*, *4*(9), e7004.

511   https://doi.org/10.1371/journal.pone.0007004

512 Milner, TheodoreE., & Cloutier, C. (1993). Compensation for mechanically unstable loading in

513   voluntary wrist movement. *Experimental Brain Research*, *94*(3).

514   https://doi.org/10.1007/BF00230210

515 Miscio, G., Pisano, F., Del Conte, C., Pianca, D., Colombo, R., & Schieppati, M. (2001). The

516   shortening reaction of forearm muscles: The influence of central set. *Clinical*

517   *Neurophysiology*, *112*(5), 884–894. https://doi.org/10.1016/S1388-2457(01)00468-0

518 Mogk, J., & Keir, P. (2003). The effects of posture on forearm muscle loading during gripping.

519   *Ergonomics*, *46*(9), 956–975. https://doi.org/10.1080/0014013031000107595

520 Morasso, P., Casadio, M., De Santis, D., Nomura, T., Rea, F., & Zenzeri, J. (2014). Stabilization

521   strategies for unstable dynamics. *Journal of Electromyography and Kinesiology*, *24*(6),

522   803–814. https://doi.org/10.1016/j.jelekin.2014.10.006

523 Mugnosso, M., Marini, F., Holmes, M., Morasso, P., & Zenzeri, J. (2018). Muscle fatigue

524   assessment during robot-mediated movements. *Journal of NeuroEngineering and*

525   *Rehabilitation*, *15*(1). https://doi.org/10.1186/s12984-018-0463-y

526 Perotto, A., & Delagi, E. F. (2005). *Anatomical guide for the electromyographer: The limbs and*

527   *trunk* (4th ed). Charles C Thomas

528 Potvin, J. R., & Brown, S. H. (2005). An equation to calculate individual muscle contributions to

529   joint stability. Journal of Biomechanics, 38(5), 973-980.

530 Pruszynski, J. A., & Scott, S. H. (2012). Optimal feedback control and the long-latency stretch

531   response. *Experimental Brain Research*, *218*(3), 341–359.

532   https://doi.org/10.1007/s00221-012-3041-8

533   Rijnveld, N., & Krebs, H. I. (2007). Passive Wrist Joint Impedance in Flexion—Extension and

534   Abduction—Adduction. *2007 IEEE 10th International Conference on Rehabilitation*

535   *Robotics*, 43–47. https://doi.org/10.1109/ICORR.2007.4428404

536   Sinkjær, T., & Hayashi, R. (1989). Regulation of wrist stiffness by the stretch reflex. *Journal of*

537   *Biomechanics*, *22*(11–12), 1133–1140.

538   Stuphorn, V., & Emeric, E. E. (2012). Proactive and reactive control by the medial frontal

539   cortex. *Frontiers in Neuroengineering*, *5*. https://doi.org/10.3389/fneng.2012.00009

540   Underwood, F. B. (2006). Anatomical Guide for the Electromyographer: The Limbs and Trunk,

541   ed 4. *Physical Therapy*, *86*(7), 1043–1043. https://doi.org/10.1093/ptj/86.7.1043

542   Vanswearingen, J. M. (1983). Measuring Wrist Muscle Strength. *Journal of Orthopaedic &*

543   *Sports Physical Therapy*, *4*(4), 217–228. https://doi.org/10.2519/jospt.1983.4.4.217

544   Weinman, J., Arfa-Fatollahkhani, P., Zonnino, A., Nikonowicz, R. C., & Sergi, F. (2021).

545   Effects of Perturbation Velocity, Direction, Background Muscle Activation, and Task

546   Instruction on Long-Latency Responses Measured From Forearm Muscles. *Frontiers in*

547   *Human Neuroscience*, *15*, 178. https://doi.org/10.3389/fnhum.2021.639773

548   Winter, D. A. (2009). Biomechanics and motor control of human movement. John Wiley &

549   Sons.

Significant main effects and interactions for muscle activity across all muscles.
Significant of $p < 0.05$ noted by *.

1 **Table 1.** Significant main effects and interactions for EMG activity across all muscles.
2 Statistically significant, p<0.05*.

Muscle Activity p-values

Muscle	Direction	Time	Grip	Direction x Time	Direction x Grip	Time x Grip	Direction x Time x Grip
FCR	0.203	0.855	<0.001*	0.897	0.855	0.897	0.997
FDS	0.209	0.947	<0.001*	0.541	0.987	0.942	0.996
FCU	0.214	0.950	<0.001*	0.565	0.472	0.709	0.999
ECR	<0.001*	0.445	<0.001*	1.264	5.053	0.809	0.989
EDC	<0.001*	0.763	<0.001*	0.405	0.531	0.870	1.000
ECU	0.323	0.096	<0.001*	0.596	0.826	0.411	0.994
BR	0.006*	0.576	<0.001*	0.801	0.393	0.999	1.000
BB	0.797	0.916	0.722	0.943	0.992	0.995	0.999

Figure 1

Experimental protocol and participant set up

A. Participant completing the experimental protocol. Gripping a custom grip force handle, electromyography placed over eight forearm muscles and black Velcro straps to isolate the wrist joint. **B.** Represents the grip force visual feedback (LabView) during the protocol. Participants were instructed to grip the white line to the target depicted by the green line. Error bars were located 1.5 SD from the target and are depicted by the blue dotted lines.

A

B

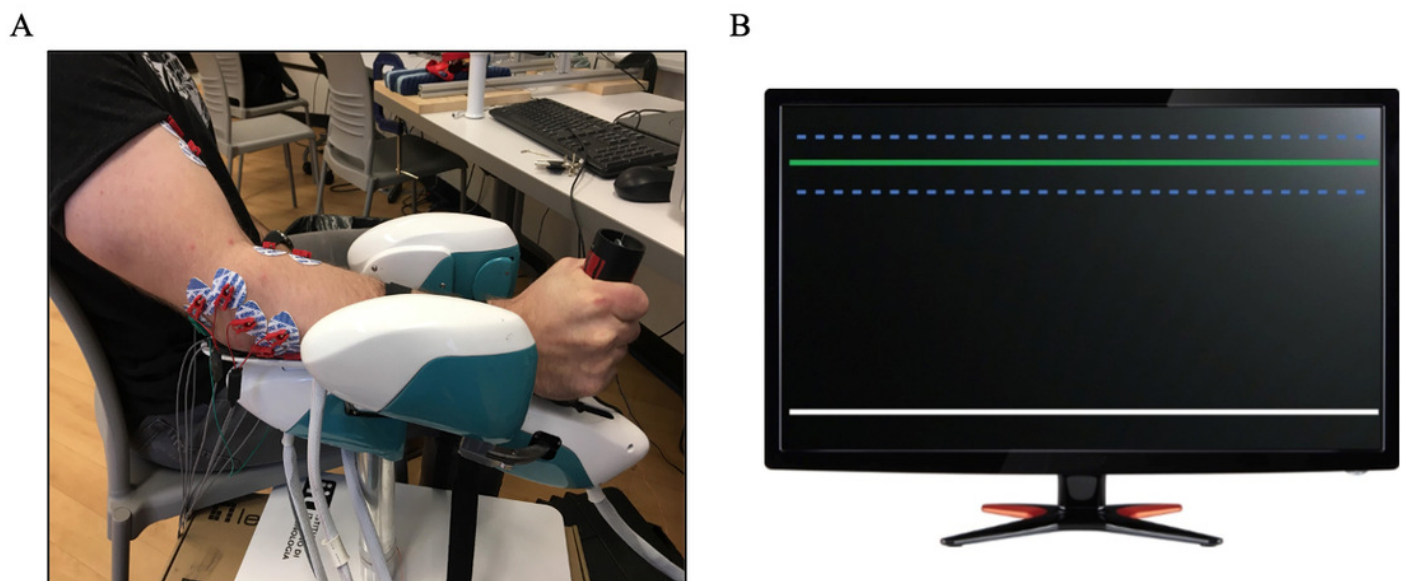



Figure 2

Representative data from participant

Representative data of one trial (4 perturbations, 1 in each direction). Grey is raw EMG of a representative muscle; Black is the grip force normalized to maximum grip; vertical red lines indicate the start of the perturbation.

Smith

(content unclear)

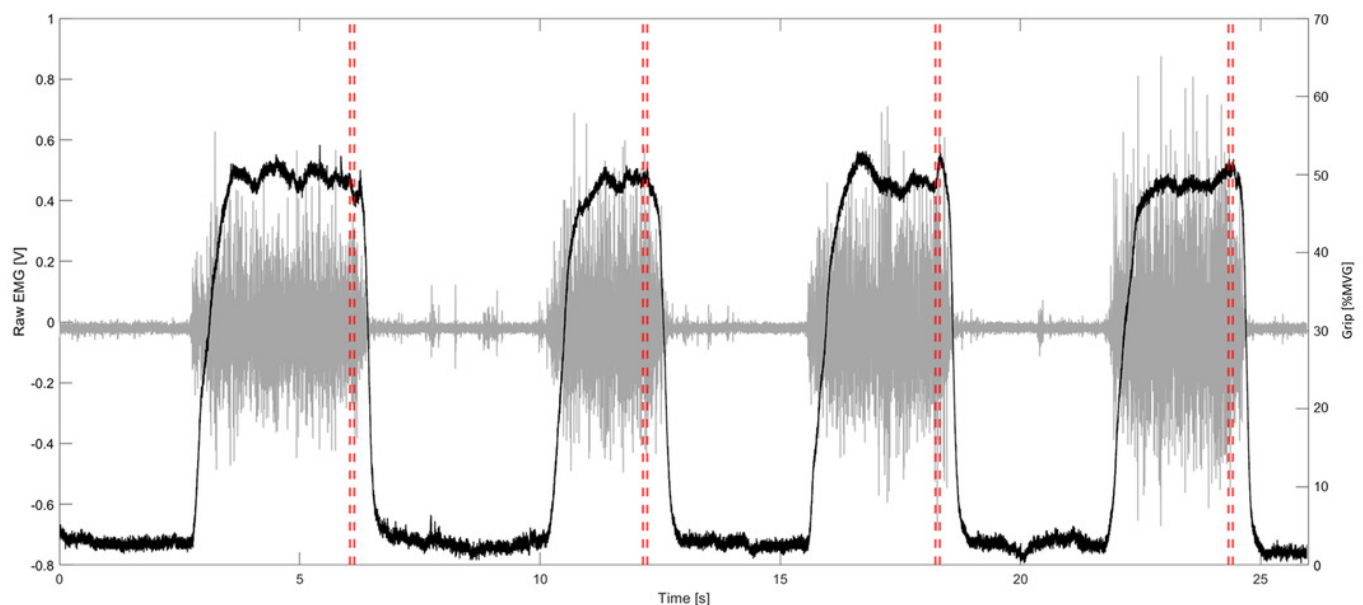



Figure 4

Time to peak displacement measured for each grip condition.

Time to peak displacement across 4 grip conditions in RD (grey) and UD (black). TPD displayed as (ms) along the y-axis. TPD significantly decreased as grip force increased ($p \leq$ 0.001). A main effect of direction ($p \leq 0.001$) as there was a significantly slower TPD in RD. No significant interaction was found between TPD (ms) and grip force ($p = 0.31$).

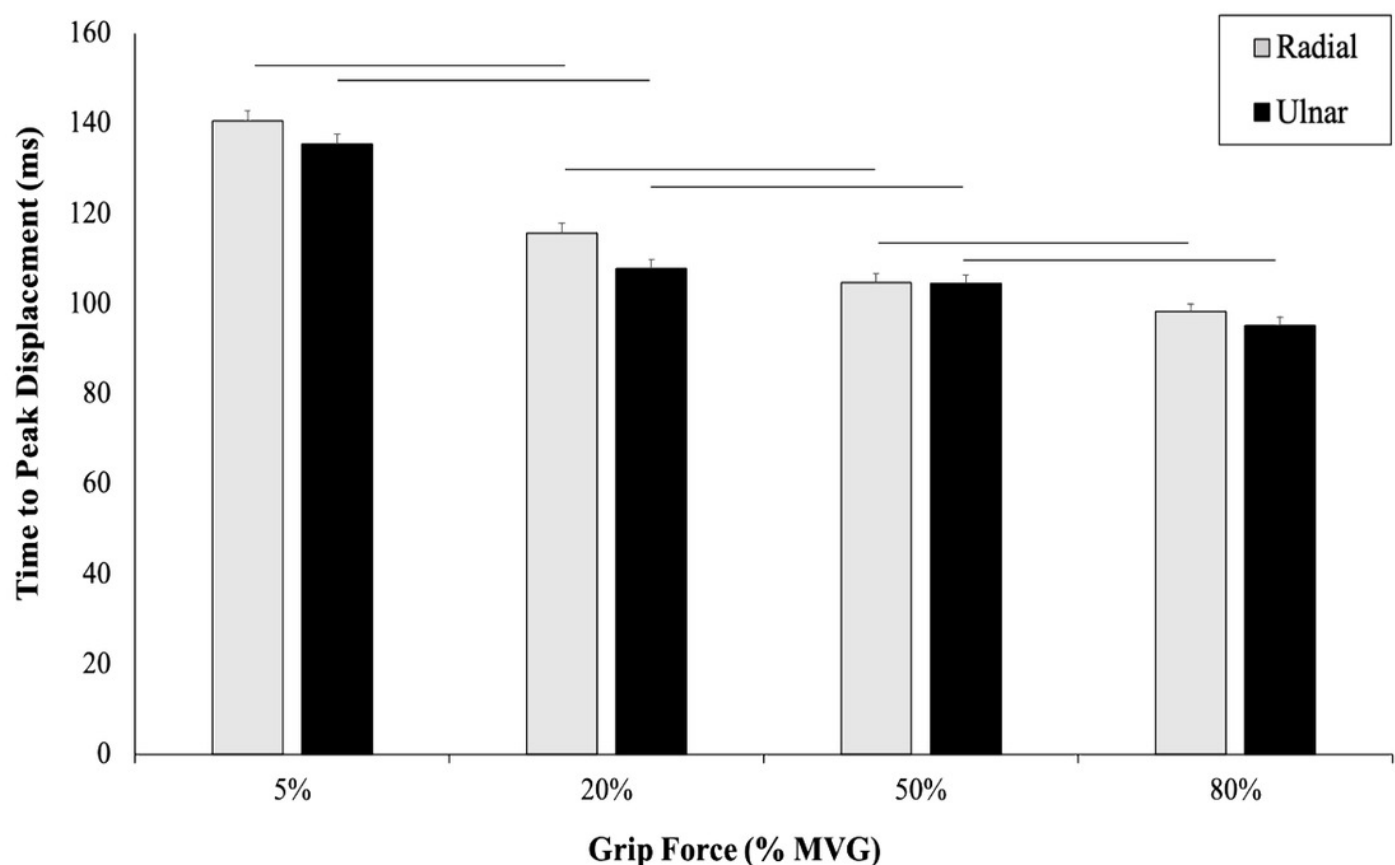
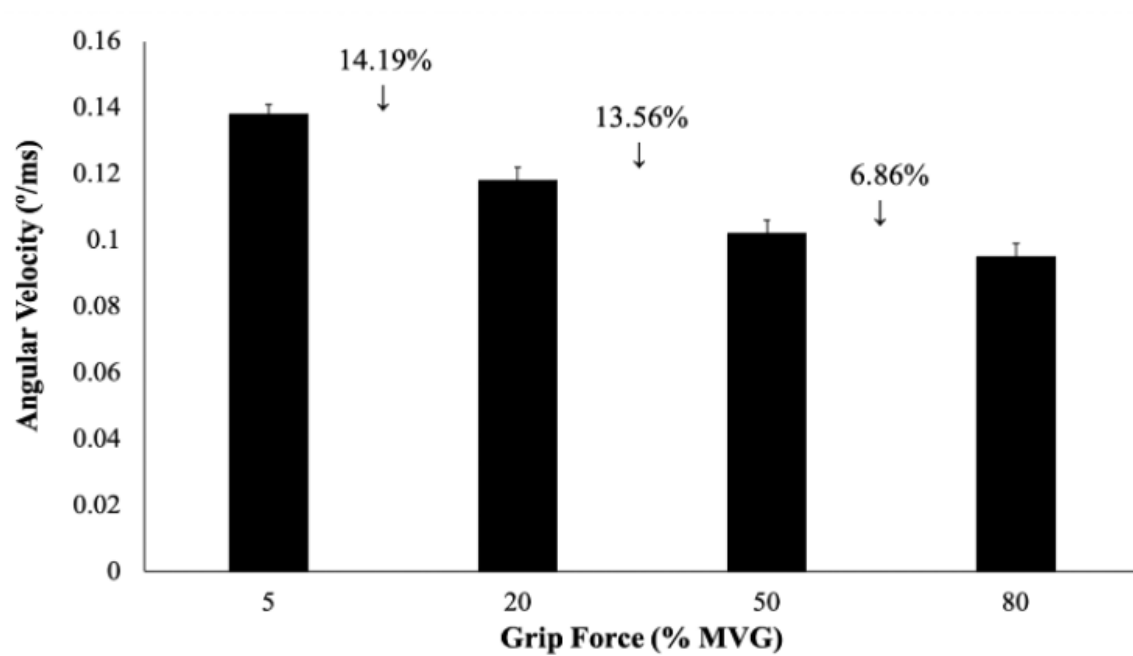



Figure 5

Angular wrist velocity for radial and ulnar perturbation directions.

Group averages for angular velocity (degrees/ms) and percent change scores. **A**. Angular velocity in radial deviation, **B**. Angular velocity in ulnar deviation. No significant interactions or main effects were found for angular velocity despite the larger percent change between each grip condition.

A

B

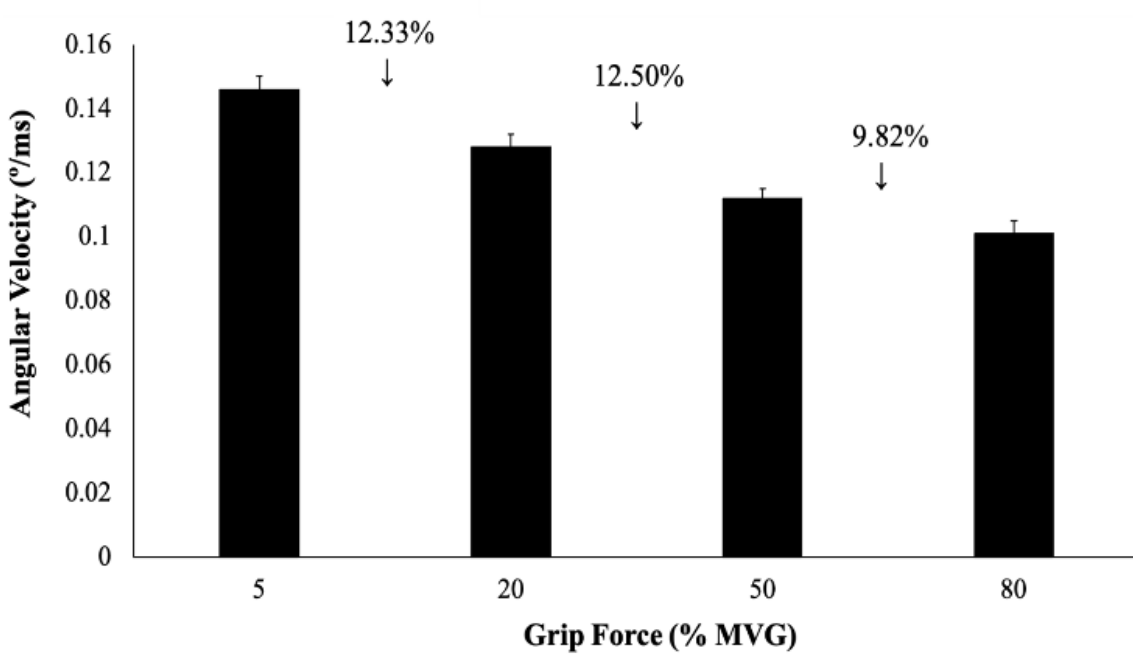



Figure 6

Muscle activity during radial perturbations for each grip condition.

Group averages for muscle activity (%MVC) for RD. **A**. 5% grip force, **B**. 20% grip force, **C**. 50% grip force and **D**. 80% grip force.

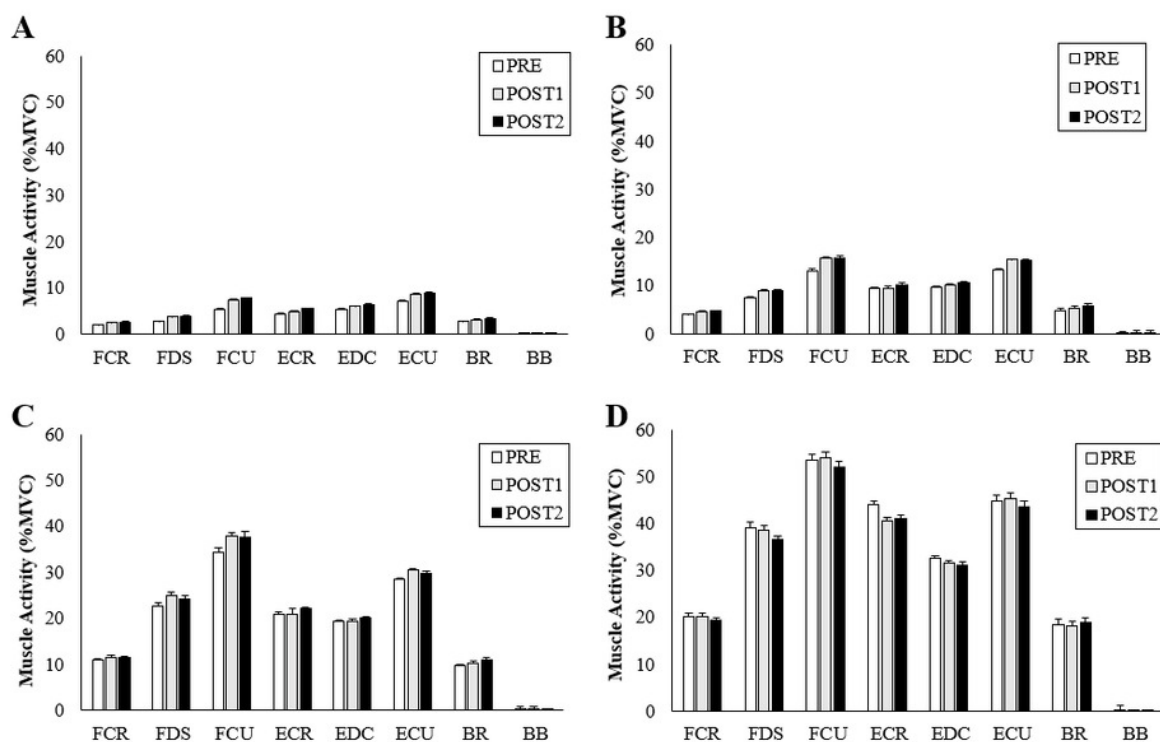



Figure 7

Muscle activity during ulnar perturbations for each grip condition.

Group averages for muscle activity (%MVC) for UD. **A**. 5% grip force, **B**. 20% grip force, **C**. 50% grip force and **D**. 80% grip force.