Human Movement Science 67 (2019) 102516

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

# Force and electromyography responses during isometric force release of different rates and step-down magnitudes

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ARTICLE INFO

*Keywords:*
Electromyography
Isometric contraction
Co-contraction
Trajectory tracking

ABSTRACT

This study investigated motor responses of force release during isometric elbow flexion by comparing effects of different ramp durations and step-down magnitudes. Twelve right-handed participants (age: 23.1 ± 1.1) performed trajectory tracking tasks. Participants were instructed to release their force from the reference magnitude (REF; 40% of maximal voluntary contraction force) to a step-down magnitude of 67% REF or 33% REF and maintain the released magnitude. Force release was guided by ramp durations of either 1 s or 5 s. Electromyography of the biceps brachii and triceps brachii was performed during the experimental task, and the co-contraction ratio was evaluated. Force output was recorded to evaluate the parameters of motor performance, such as force variability and overshoot ratio. Although a longer ramp duration of 5 s decreased the force variability and overshoot ratio than did shorter ramp duration of 1 s, higher perceived exertion and co-contraction ratio were followed. Force variability was greater when force was released to the step-down magnitude of 33% REF than that when the magnitude was 67% REF, however, the overshoot ratio showed opposite results. This study provided evidence proving that motor control strategies adopted for force release were affected by both duration and step-down magnitude. In particular, it implies that different control strategies are required according to the level of step-down magnitude with a relatively short ramp duration.

## 1. Introduction

Humans not only increase but also release force to perform activities of daily living. Recent studies have shown that motor unit control for regulating force release is independent from the one for force increase (Andrzejewska, Jaskólski, Jaskólska, Gobbo, & Orizio, 2014; Onushko, Baweja, & Christou, 2013; Orizio, Baruzzi, Gaffurini, Diemont, & Gobbo, 2010). This difference of motor unit control might emerge as altered behavioral responses, such as increased variability during force release (Park, Kwon, Solis, Lodha, & Christou, 2016).

Force release and muscle relaxation are prerequisites for skillful and precise movements (Sugawara, Tanabe, Suzuki, Saitoh, & Higashi, 2016; Suzuki, Sugawara, Takagi, & Higashi, 2015). Nonetheless, several studies regarding sports, playing instruments, and caregiving have indicated that muscle relaxation might be difficult especially when the movements are unfamiliar (Daikoku & Saito, 2008; Kato, Muraoka, Higuchi, Mizuguchi, & Kanosue, 2014; Sakurai & Ohtsuki, 2000; Wada & Yoshida, 2016). Similarly, recent studies on human-robot cooperation showed that although assistive force is provided to aid joint movements, robot users

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https://doi.org/10.1016/j.humov.2019.102516
Received 17 April 2019; Received in revised form 27 August 2019; Accepted 4 September 2019
Available online 17 September 2019
0167-9457/ 

might not easily release their muscular force (Muraki, Hayashi, Nasir, & Loh, 2018; Rosen & Perry, 2007). The common feature of those movements is that muscular force is released to a particular step-down magnitude, rather than complete relaxation to achieve precise and smooth performance. However, few studies have focused on how the force output and corresponding muscle activity are altered under varying conditions of force release to step-down magnitudes.

Several studies showed that varying ramp rates to guide isometric force release were associated with altered force variability and error during joint movements (Naik, Patten, Lodha, Coombes, & Cauraugh, 2011; Orizio et al., 2010). Additionally, gradual force release increased corticospinal excitability in the antagonist muscle (Yoshida, Yamaguchi, Saitou, Tanabe, & Sugawara, 2015). On the other hand, maintaining varying degrees of step-down magnitude, which follows force release might also affect behavioral responses. There is evidence that force variability and error increased if isometric force was greatly released to lower magnitude (Choi, Loh, & Muraki, 2018; Masumoto & Inui, 2010). Further, maintaining lower force magnitudes might raise force variability (Galganski, Fuglevand, & Enoka, 1993; Griffin, Painter, Wadhwa, & Spirduso, 2009; Kumar et al., 2017).

Regulation of force release to step-down magnitude can be a type of target-directed aiming movements. Specifically, fast and forceful movements might cause noises such as overshoot, which represents the degree of passing through the target (Elliott, Hansen, Mendoza, & Tremblay, 2004). The overshoot arisen during bottom-up target-directed force control is known to be costlier than the undershoot (Kesar, Chou, & Binder-Macleod, 2008). It is because corrective and time-consuming sub-movement is required to overcome the inertia and recover the target after the overshoot (Elliott et al., 2004; Sparrow & Newell, 1998). Conversely, if overshoot occurs during top-down force control, this might be even costlier as the sub-movement to recover the target level requires force increase with additional muscle contraction. Although previous studies have shown that relatively small and rapid changes in force cause larger overshoot during bottom-up force control (Dideriksen, Feeney, Almuklass, & Enoka, 2017; Hu, Loncharich, & Newell, 2011), it is unclear how top-down force control with varying ramp rates and step-down magnitudes affect the degree of overshoot.

The objective of this study is to examine the force output and muscle activity during the isometric force release and maintenance. Force variability and overshoot ratio are calculated from the force output to evaluate the motor performance. Simple voluntary exertion of isometric elbow flexion is investigated as a basic study, where this exercise excludes various biomechanical factors, such as angle movement and velocity that may affect the sole performance of motor control by agonist and antagonist muscles. Visuomotor tracking tasks are conducted to guide force control with different levels of ramp duration and step-down magnitude, in which the isometric force of elbow flexion and the corresponding muscle activity are simultaneously measured. We hypothesize that different ramp durations and step-down magnitudes would alter the motor performance and muscle activity during isometric elbow flexion.

## 2. Methods

### 2.1. Participants

Twelve healthy male adults (age: 23.1 ± 1.1 years, height: 173.3 ± 6.3 cm, weight: 67.0 ± 8.6 kg) were recruited. None of the participants reported any history of musculoskeletal disorders or functional upper limb impairment. Hand dominance was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). Each participant provided informed consent prior to participating in the experiment. This study was approved by the Research Ethics Committee of the Faculty of Design, Kyushu University.

### 2.2. Experimental setup

Each participant was asked to sit on a fixed chair in an upright position and face a 19-inch screen monitor (RDT196LM; Mitsubishi Electric, Tokyo, Japan). A monitor was placed, at eye level, about 0.6 m away from the participant. The participant was instructed to sit with his upper body being maintained straight and to keep the elbow of the dominant arm at 90° of flexion in the sagittal plane, with the forearm supinated. Their right wrist was then fixed by equipping a strap at the level of the styloid process of the right radius, and a tensile sensor (T.K.K. 1269f; Takei Scientific Instruments Co., Ltd, Niigata, Japan) was placed between the strap and floor with an inelastic chain. The chain facilitated the measurement of isometric force from the elbow flexion by preventing any elbow joint flexional angle change. Once participants pulled the strap upward, the corresponding isometric force was measured by the tensile sensor and transmitted to an A/D converter (PowerLab 16/30; ADInstruments, Dunedin, New Zealand). Simultaneously, the digitized force data were obtained by analysis software (LabChart 7; ADInstruments) and its feedback was presented on the monitor (Fig. 1).

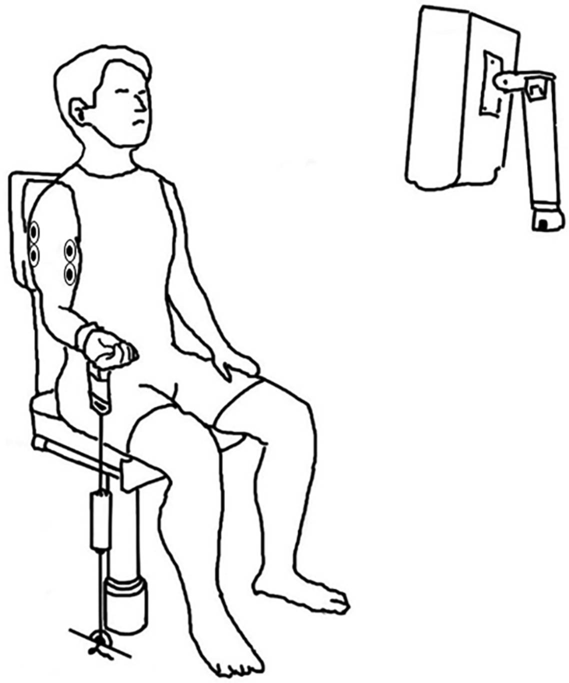

**Fig. 1.** Schematic of experimental setup. The monitor presented feedback of upward force applied on the right wrist when the participant contract their elbow flexors.

### *2.3. Trajectory tracking task*

A maximal voluntary contraction (MVC) force of the isometric elbow flexion was measured prior to the experimental task and used to construct a series of normalized experimental tasks. We simulated three sequential force control phases (Fig. 2). In the first phase, the participants were instructed to instantly generate the isometric force and maintain a reference magnitude (REF) of 40% MVC force for 7 s. During the next phase of force release, a ramp with varying rates was presented to guide force release from the

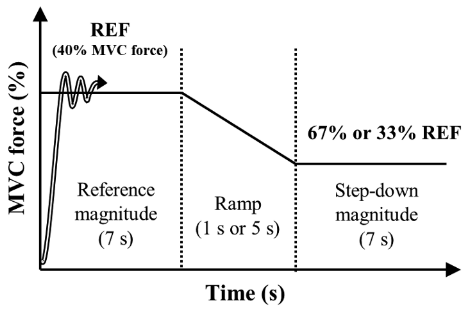


**Fig. 2.** Schematic diagram of the trajectory tracking task with three sequential phases. The arrow represents real-time force control feedback.

reference magnitude to step-down magnitude. Finally, participants were asked to maintain the step-down magnitude for 7 s. The simulation phases were sequentially presented on the monitor as a target trajectory of three line segments (reference magnitude - ramp - step-down magnitude). Real-time force control feedback on actual tracking performance was presented simultaneously. Participants were instructed to track the target trajectories as accurately as possible by adjusting the isometric force of their elbow flexion. Graphical visualization of the simulation was provided using LabChart 7.

### 2.4. Experimental conditions

For each trial, the ramp duration for guiding force release was set to be either 1 s or 5 s. The step-down magnitude, which followed the ramp involved maintaining 67% REF (67% × 40% MVC force = 26.8% MVC force) or maintaining 33% REF (33% × 40% MVC force = 13.2% MVC force). Therefore, the release phase involved one out of four ramp-downs: (1) ramp of 1 s to 67% REF (rate: −13.2% MVC force/s), (2) ramp of 1 s to 33% REF (−26.8%/s), (3) ramp of 5 s to 67% REF (−2.6%/s), and (4) ramp of 5 s to 33% REF (−5.4%/s). The elapsed time for one trial was either 15 s or 19 s, depending on the ramp duration.

### 2.5. Procedure

Each participant conducted one experimental session. The session sequentially comprised (1) physical measurement and electrode placement, (2) The MVC trials, (3) task familiarization, and (4) main experiment. During task familiarization, each participant practiced the trajectory tracking task for about 10 min. The trials of main experiment were conducted in a randomized order across participants and two additional conditions involving a false set were intermingled among the real sets to reduce task predictability. Therefore, the main experiment consisted of 12 trials in total (6 conditions (4 real + 2 false) × 2 repetition). 60 s of rest were provided between the trials and one session lasted about 2 h.

### 2.6. Measurements

Electromyography (EMG) measurements of the biceps brachii (BB) and triceps brachii (TB) were recorded with bipolar disposable surface electrodes (N-00-S, Ambu Inc., MD, USA). Electrode sites were palpated and cleaned by scrubbing with alcohol, then the electrodes were placed, maintaining an inter-electrode distance of 25 mm. We followed the SENIAM recommendations for sensor location (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000); the electrodes for the BB were placed on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit, and the electrodes for the TB were placed on the line between the posterior crista of the acromion and the olecranon. Reference electrodes were attached over the head of the right radius and the right acromion. EMG signals were sampled at a frequency of 1 kHz, amplified (×1,000) using Bio-amp ML 132 (ADInstruments), and filtered using a band pass finite impulse response filter (15–500 Hz) for amplitude analysis. Then, the signals were full-wave rectified to determine muscle activity onset. The isometric force of dominant-arm elbow flexion was also recorded using the tensile sensor, with a sampling rate of 1 kHz. All the EMG and force data were transmitted to the A/D converter and stored on a personal computer.

The MVCs of the BB and TB were obtained along with MVC force during isometric elbow flexion prior to the main experiment. MVC for the BB was measured by instructing participants to maximally pull the strap towards their body, contracting their BB. Then, the strap and tensile sensor were temporarily removed, and a firm pad was installed under the forearm to support MVC trials for the TB at 90° of elbow flexion. Participants were instructed to maximally push the pad away from their body, contracting the TB with the supinated forearm. Each MVC trial lasted for 7 s and was repeated at least twice. The mean rectified amplitude over the middle 3 s of MVC trials was quantified for the BB and TB muscle and used as values for EMG normalization (%MVC). The MVC force (N) was sampled over the same interval of MVC trials for the BB and averaged value was used for force normalization (%MVC force). 60 s of rest were provided between the trials to minimize muscle fatigue. The rating of perceived exertion (RPE) for each trial were also explored using the RPE on the Borg's CR-10 scale (Borg, 1982), immediately after the completion of one trial.

### 2.7. Data analysis

This study mainly explored the latter two phases of the trajectory tracking task, force release and maintenance. Based on the normalized EMG and force data for the force control simulation, in-depth variables of muscle co-contraction and motor performance were calculated for those phases. The data were processed and stored in Excel (Microsoft, Redmond, WA, USA).

#### 2.7.1. Muscle co-contraction

*2.7.1.1. Co-contraction ratio.* A relative involvements of the agonist and the antagonist muscles during elbow flexion were estimated by Eq. (1) (Arellano et al., 2016).

$$\text{Co-contraction ratio (\%)} = \frac{\%\text{MVC of TB}}{\%\text{MVC of BB}} \times 100 \tag{1}$$

#### 2.7.2. Motor performance

*Force variability:* Force variability generated during the isometric force control was calculated using the coefficient of variation, according to Eq. (2) (Baweja, Patel, Martinkewiz, Vu, & Christou, 2009; Tracy, Dinenno, Jorgensen, & Welsh, 2007; Welsh, Dinenno, & Tracy, 2007).

$$\text{Force variability (\%)} = \frac{\text{Standard deviation of forces}}{\text{Mean of forces}} \times 100 \tag{2}$$

*Overshoot ratio:* The degree of overshoot, which may arise in the process of top-down force control from the REF (top) to step-down magnitude, was quantified: the difference between the actual and target force changes was normalized by the target force change. Only the maximum of the normalized differences was adopted according to Eq. (3) (Potter, Kent, Lindstrom, & Lazarus, 2006; Shemmell et al., 2005), where $AC_i$ was the actual force change, $TC_i$ the target force change, and N the number of observations for the analyzed phases.

$$\text{Overshoot ratio (\%)} = \max_{i \in N} \frac{AC_i - TC_i}{TC_i} \times 100 \tag{3}$$

### 2.8. Statistical analysis

A two-way Analysis of Variance (ANOVA) with repeated measures was conducted for the two factors-ramp duration (1 s and 5 s) and step-down magnitude (67% REF and 33% REF)—to examine whether there were any significant differences based on the described variables. Statistical significance of the experimental conditions was determined by $\alpha = 0.05$. SPSS Statistics 23.0 (IBM, Research Triangle Park, NC, USA) was utilized for the statistical analyses. All values are reported as mean ± SD.

## 3. Results

### 3.1. Force output and muscle activity

The normalized isometric force (%MVC force) was released in accordance with the four conditions of guided trajectory during the simulation (Fig. 3a). The activities of the BB and TB muscles (%MVC) showed trends similar to those for force output (Fig. 3b & c). The BB was more involved as the agonist muscle during elbow flexion than the TB. The last 3 s of the simulation (12 s–15 s for the conditions involving ramp duration of 1 s; 16 s–19 s for the conditions involving ramp duration of 5 s) were explored to confirm whether the muscular force was correctly released and stabilized for each targeted level of magnitude.

The ANOVA results for force during the last 3 s showed that the main effect of step-down magnitude was significant ($F(1,11) = 27183.62$, $p < 0.01$) (67% REF: 26.2 ± 0.3% MVC force; 33% REF: 12.9 ± 0.3% MVC force), while no significant main effect was found for the ramp duration and the interaction between ramp duration and step-down magnitude. For the BB, the main effects of step-down magnitude ($F(1,11) = 40.22$, $p < 0.01$) and ramp duration were significant ($F(1,11) = 7.18$, $p < 0.05$) (Fig. 4). The mean comparison showed that a longer ramp duration lowered BB muscle activity during the final seconds (1 s: 19.0 ± 8.4% MVC; 5 s: 17.9 ± 7.5% MVC). No significant interaction between ramp duration and step-down magnitude was observed for the BB. The TB results were analyzed for 11 participants because the data for one participant were excluded after outlier detection. The results showed that the step-down magnitude had a significant main effect ($F(1,10) = 26.69$; $p < 0.01$) (67% REF: 5.1 ± 2.2% MVC; 33% REF: 3.2 ± 1.1% MVC), while the ramp duration and the interaction between the two factors did not.

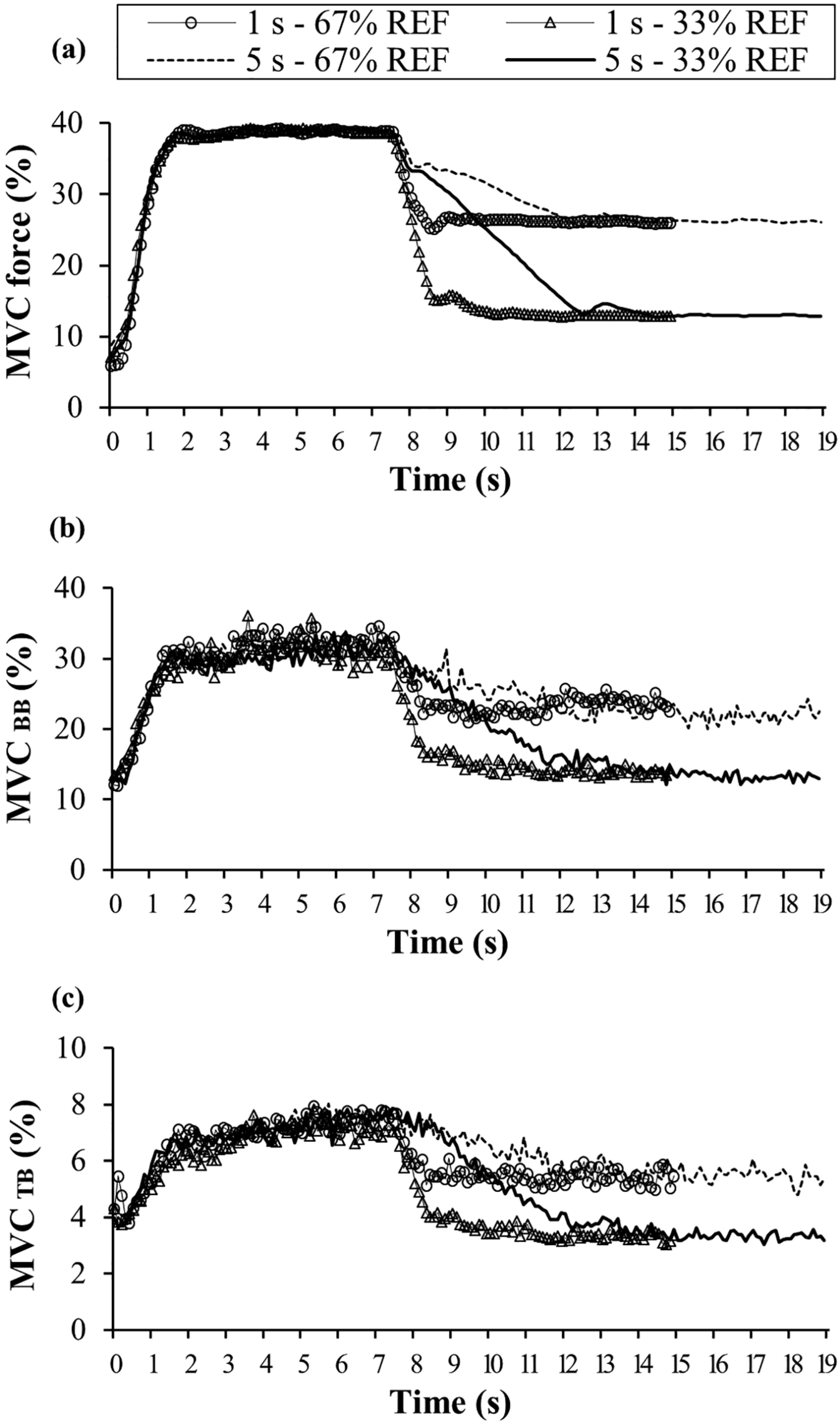


**Fig. 3.** The averaged trends of (a) normalized force output and muscle activity of the (b) BB and (c) TB over time (n = 12). In these graphs, sampling frequency was set as 10 Hz for convenient visualization.

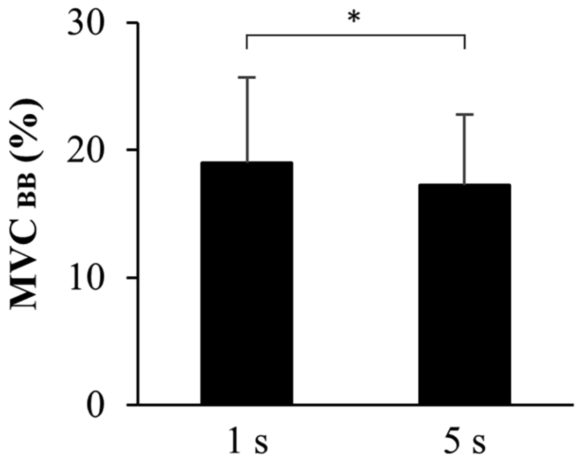


**Fig. 4.** Mean activity of the BB by ramp duration (* $p < 0.05$).

### *3.2. Co-contraction ratio*

The results of the ANOVA for co-contraction ratio during the phases of force release and followed maintenance showed that the main effect of ramp duration was significant ($F(1,10) = 6.82$, $p < 0.05$). Specifically, a longer ramp duration resulted in an elevated co-contraction than did a relatively short ramp duration (1 s: 22.8 ± 10.2%; 5 s: 23.4 ± 10.3%) (Fig. 5). However, the main effect of step-down magnitude and the interaction between ramp duration and step-down magnitude showed no significant effects.

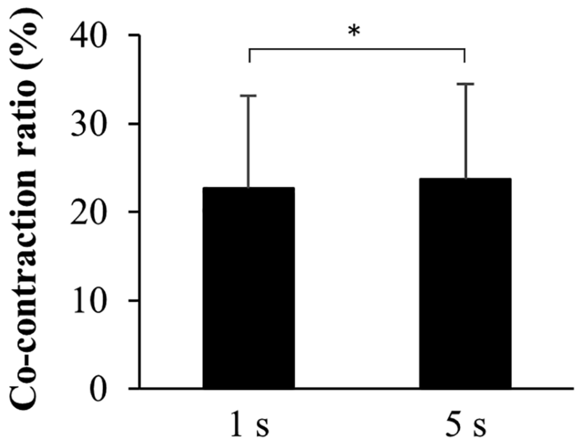


**Fig. 5.** Mean co-contraction ratio by ramp duration (* $p < 0.05$).

### *3.3. Force variability*

The results for force variability also demonstrated significant main effects of ramp duration and step-down magnitude ($F(1,11) = 29.89$, $p < 0.01$; $F(1,11) = 8621.79$, $p < 0.01$), along with a significant interaction between ramp duration and step-down magnitude ($F(1,11) = 17.84$, $p < 0.01$). A longer ramp duration followed by a step-down magnitude of 33% REF markedly lowered the variability (1 s: 47.8 ± 2.1%; 5 s: 44.2 ± 1.5%), compared with that of 67% REF (1 s: 14.4 ± 0.7%; 5 s: 13.8 ± 0.7%) (Fig. 6a).

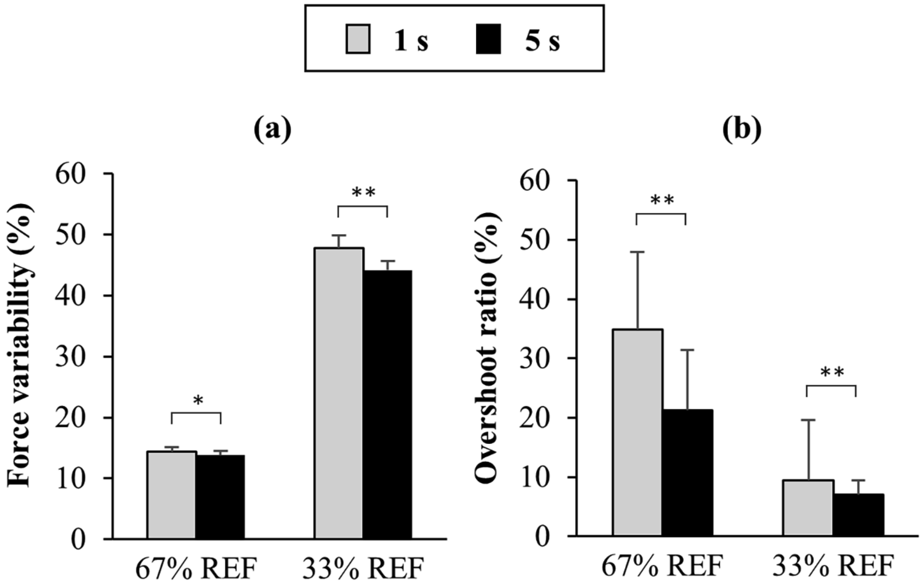


**Fig. 6.** Mean (a) force variability and (b) overshoot ratio for each ramp duration by step-down magnitude (*$p < 0.05$; ** $p < 0.01$).

### 3.4. Overshoot ratio

The main effects of ramp duration and step-down magnitude on the overshoot ratio were significant (F(1,11) = 29.64, $p < 0.01$; F(1,11) = 48.26, $p < 0.01$). In addition, a significant interaction between ramp duration and step-down magnitude was found (F(1,11) = 10.89, $p < 0.01$), showing that the overshoot ratio was far greatly reduced at the step-down magnitude of 67% REF (1 s: 34.8 ± 13.1%; 5 s: 21.2 ± 10.2%) than that at the other magnitude (1 s: 9.4 ± 4.5%; 5 s: 7.1 ± 2.4%), when the ramp duration was extended to 5 s (Fig. 6b).

### 3.5. RPE

The main effects of ramp duration and step-down magnitude were significant for the RPE (F(1,11) = 25.11, $p < 0.01$; F(1,11) = 19.48, $p < 0.01$). The ramp duration of 5 s resulted in significantly greater perceived exertion than the ramp duration of 1 s (1 s: 4.9 ± 1.3; 5 s: 5.3 ± 1.4), and the step-down magnitude of 67% REF resulted in greater RPE than that of magnitude 33% REF (67% REF: 5.6 ± 1.4; 33% REF: 4.7 ± 1.1) (Fig. 7a & b). The interaction between ramp duration and step-down magnitude did not show a significant effect on the RPE.

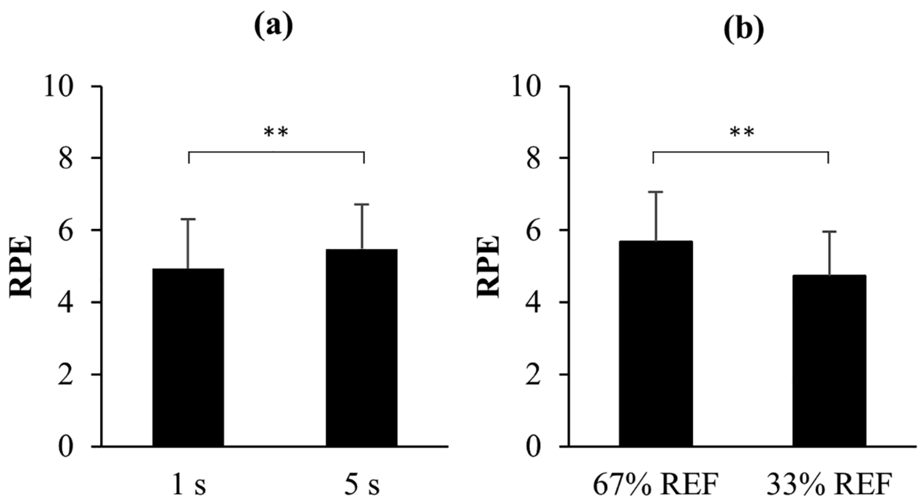


**Fig. 7.** Mean RPE by (a) ramp duration and (b) step-down magnitude (b) (** $p < 0.01$).

## 4. Discussion

This study aimed to determine whether motor performance and EMG responses were affected by varying ramp durations and by followed step-down magnitudes. The results of the last 3 s of force output indicated that force was released and maintained as it was guided by the experimental task; however, relatively short ramp duration (1 s) increased BB activity in the last seconds of force maintenance. We also found that both force variability and overshoot ratio decreased when ramp duration was extended to 5 s, which accompanied the increased co-contraction ratio and RPE. Those parameters of motor performance showed the opposite results based on the level of step-down magnitude as force variability increased while overshoot ratio decreased under the magnitude of 33% REF, compared to the one of 67% REF. These results provide insight that the control strategy required for force release differs not only with the ramp rates, but also with the targeted step-down magnitude of force maintenance.

### *4.1. Force variability*

Our results showed that force variability increased when force was markedly released to the step-down magnitude of 33% REF and maintained. This supports previous findings that indicated increased force variability when force was greatly released (Masumoto & Inui, 2010) and when relatively low force magnitude was maintained (Galganski et al., 1993; Griffin et al., 2009; Kumar et al., 2017; Orizio et al., 2010). Further, the decreased firing rate of motor units in the lower range of force release might also contribute to increased force variability (Andrzejewska et al., 2014; Moon et al., 2014; Onushko et al., 2013).

We also discovered that increased force variability, which appears during force release to relatively low step-down magnitude (33% REF), can be greatly reduced when ramp duration is extended to 5 s (Fig. 6a). These results are in line with previous findings of reduced force variability under the gradual force release to complete relaxation (Naik et al., 2011; Orizio et al., 2010). Specifically, sufficient time to adjust the planned and executed movements might stabilize motor output of target-directed movements (Elliott et al., 2004; Srinivasan, Samani, Mathiassen, & Madeleine, 2015).

### *4.2. Relationship between overshoot and BB activity*

Contrary to force variability, the overshoot ratio was reduced under the step-down magnitude of 33% REF, even though the magnitude was closer to complete relaxation compared to the magnitude of 67% REF. Specifically, a clear difference was found under the ramp duration of 1 s (Fig. 6b). It is noteworthy that distinct strategies of top-down force control were revealed based on these results and on the increased BB activity during the last 3 s of maintaining step-down magnitude (Fig. 3).

At the step-down magnitude of 67% REF, the underlying motor control strategy to release force seems to be risky as it showed greater overshoot ratio, and which might be costly. The cause of such a greater overshoot is likely due to feed-forward models of motor control, which predicted consequences of planned movement based on estimates of the force required (Kawato, 1999; Shadmehr, Smith, & Krakauer, 2010). Such estimation is known to depend on motor memory from prior experiences (Huang, Haith, Mazzoni, & Krakauer, 2011; Ostry & Feldman, 2003). As most of human movements involve rapid termination (complete relaxation) of ongoing muscle contraction in order to switch to another sets of muscle contraction (Buccolieri, Abbruzzese, & Rothwell, 2004), the force change may have been overestimated, leading to an increased overshoot that is closer to complete relaxation. Furthermore, the increased BB activity after force release may be associated with this strategy, denoting agonist muscle contraction as a sub-movement to overcome inertia caused by the overshoot and to recover from the targeted magnitude (Elliott et al., 2004).

On the other hand, the control strategy used during force release to the step-down magnitude of 33% REF seems to be conservative, showing lower overshoot ratio. We expected that the overshoot ratio would increase for the greater force change, not only because of the accumulated experience from releasing muscular force to complete relaxation but also due to the overestimation of externally induced force during movement planning (Walsh, Taylor, & Gandevia, 2011; Wolpert, Ghahramani, & Jordan, 1995). Nonetheless, movements required for releasing force to the step-down magnitude of 33% REF appears to be corrected conservatively so that force is released gradually to the targeted magnitude. This implies that the resistance against the external forces, reported in previous studies (Feldman, 2011; Ostry & Feldman, 2003), also occurs especially during intentional regulation of greater force release, reserving a certain level of muscle activity for postural stabilization and countermeasure against unexpected accidents (Gibson, Lambert, & Noakes, 2001; Lay, Sparrow, Hughes, & O'Dwyer, 2002; McGill, Grenier, Kavcic, & Cholewicki, 2003). Therefore, compared to the risky control strategy for relatively small changes in force release, the increased BB activity might be the result of a conservative strategy for greater force change, which maintains the agonist contraction to gradually release the muscular force.

To sum up, it can be concluded that top-down target-directed movements share similar characteristics with bottom-up target-directed movements, in terms of greater overshoot under the relatively small and rapid change of force (Dideriksen et al., 2017; Hu et al., 2011). Nonetheless, the difference between those control strategies appears to be reduced if duration for force release is extended. Similar to the results of force variability, the provision of a sufficient time might have decreased the unpredictability during target-oriented movements (Elliott et al., 2004; Srinivasan et al., 2015), making up for the performance gap between the two strategies.

### *4.3. RPE*

As expected, the step-down magnitude of 33% REF, which was relatively close to complete relaxation, resulted in decreased RPE (Fig. 7), showing the absolute reduction of force and muscle activity is consistent with the perceived exertion. On the other hand, ramp duration of 5 s resulted in greater RPE than that of 1 s. This can be associated with increased co-contraction of BB and TB with extended ramp duration (Fig. 5). The co-contraction strategy during joint movements is used for increased joint stiffness against instability (Franklin, Osu, Burdet, Kawato, & Milner, 2003; Lewis, MacKinnon, Trumbower, & Perreault, 2010) and for higher degrees of precision (Selen, Beek, & Van Dieën, 2006). Although the ramp duration of 5 s contributed to lower force variability and overshoot ratio, the higher precision demand might have contributed to mental stress and ineffectively increased co-contraction during joint movements (Au & Keir, 2007; Mehta & Agnew, 2012; Mehta, Nussbaum, & Agnew, 2012; Van Loon, Masters, Ring, & McIntyre, 2001; Visser et al., 2003). Furthermore, muscle relaxation in a regulated manner is known to require extensive control by the central nervous system (Hasegawa, Kasai, Tsuji, & Yahagi, 2001; Yoshida et al., 2015). Therefore, it is possible that force release is perceived to be more demanding if its duration is extended, also raising co-contraction ratio.

### *4.4. Implications and limitations*

These findings are particularly important for improving target-directed movements in the activities of daily living and rehabilitation, which often require muscle relaxation and force release. Results obtained from the current study may have limitations in that it tested linearly guided force release with unilateral movements under restricted experimental conditions. Further research is warranted for how these results are altered through extended conditions using linear or non-linear guidance with bilateral or ipsilateral movements.

## 5. Conclusion

This study focused on the force and EMG responses in the process of force release to a certain magnitude and its maintenance during isometric elbow flexion. Although force release guided by longer ramp duration lowered the force variability and overshoot ratio than that guided by shorter ramp duration, it also accompanied increased RPE and co-contraction ratio. When force was greatly released, force variability increased while overshoot ratio decreased. Specifically, the results of overshoot ratio and BB activity implied that distinct control strategies could be employed according to the levels of step-down magnitude.

## Acknowledgements

The authors would like to thank Yuanyuan Wang and Angelie Revilla for their assistance in conducting our experiment. This work was supported by JSPS KAKENHI Grant Number JP17H01454.

## References

Andrzejewska, R., Jaskólski, A., Jaskólska, A., Gobbo, M., & Orizio, C. (2014). Electromyogram features during linear torque decrement and their changes with fatigue. *European Journal of Applied Physiology, 114*(10), 2105–2117. https://doi.org/10.1007/s00421-014-2928-4.

Arellano, C. J., Caha, D., Hennessey, J. E., Amiridis, I. G., Baudry, S., & Enoka, R. M. (2016). Fatigue-induced adjustment in antagonist coactivation by old adults during a steadiness task. *Journal of Applied Physiology, 120*(9), 1039–1046. https://doi.org/10.1152/japplphysiol.00908.2015.

Au, A. K., & Keir, P. J. (2007). Interfering effects of multitasking on muscle activity in the upper extremity. *Journal of Electromyography and Kinesiology*. https://doi.org/10.1016/j.jelekin.2006.06.005.

Baweja, H. S., Patel, B. K., Martinkewiz, J. D., Vu, J., & Christou, E. A. (2009). Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Experimental Brain Research, 197*(1), 35–47. https://doi.org/10.1007/s00221-009-1883-5.

Borg, G. (1982). Physiological bases of percieved exertion. *Medicine & Science in Sports & Exercise, 14*(5), 377–381.

Buccolieri, A., Abbruzzese, G., & Rothwell, J. C. (2004). Relaxation from a voluntary contraction is preceded by increased excitability of motor cortical inhibitory circuits. *Journal of Physiology, 558*(2), 685–695. https://doi.org/10.1113/jphysiol.2004.064774.

Choi, J., Loh, P. Y., & Muraki, S. (2018). *Simulation study on the effects of adaptive time for assist considering release of isometric force during elbow flexion. Proceedings of the 20th Congress of the International Ergonomics Association*347–350. https://doi.org/10.1007/978-3-319-96083-8_46.

Daikoku, R., & Saito, Y. (2008). Differences between Novice and Experienced Caregivers in Muscle Activity and Perceived Exertion while Repositioning Bedridden Patients. *Journal of Physiological Anthropology, 27*(6), 333–339. https://doi.org/10.2114/jpa2.27.333.

Dideriksen, J. L., Feeney, D. F., Almuklass, A. M., & Enoka, R. M. (2017). Control of force during rapid visuomotor force-matching tasks can be described by discrete time PID control algorithms. *Experimental Brain Research, 235*(8), 2561–2573. https://doi.org/10.1007/s00221-017-4995-3.

Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior, 36*(3), 339–351. https://doi.org/10.3200/JMBR.36.3.339-351.

Feldman, A. G. (2011). Space and time in the context of equilibrium-point theory. *Wiley Interdisciplinary Reviews: Cognitive Science, 2*(3), 287–304. https://doi.org/10.1002/wcs.108.

Franklin, D. W., Osu, R., Burdet, E., Kawato, M., & Milner, T. E. (2003). Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model. *Journal of Neurophysiology, 90*(5), 3270–3282. https://doi.org/10.1152/jn.01112.2002.

Galganski, M. E., Fuglevand, A. J., & Enoka, R. M. (1993). Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. *Journal of Neurophysiology, 69*(6), 2108–2115. https://doi.org/10.1152/jn.1993.69.6.2108.

Gibson, A. S. C., Lambert, M. I., & Noakes, T. D. (2001). Neural control of force output during maximal and submaximal exercise. *Sports Medicine, 31*(9), 637–650. https://doi.org/10.2165/00007256-200131090-00001.

Griffin, L., Painter, P. E., Wadhwa, A., & Spirduso, W. W. (2009). Motor unit firing variability and synchronization during short-term light-load training in older adults. *Experimental Brain Research, 197*(4), 337–345. https://doi.org/10.1007/s00221-009-1920-4.

Hasegawa, Y., Kasai, T., Tsuji, T., & Yahagi, S. (2001). Further insight into the task-dependent excitability of motor evoked potentials in first dorsal interosseous muscle in humans. *Experimental Brain Research, 140*(4), 387–396. https://doi.org/10.1007/s002210100842.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*(5), 361–374. https://doi.org/10.1016/S1050-6411(00)00027-4.

Hu, X., Loncharich, M., & Newell, K. M. (2011). Visual information interacts with neuromuscular factors in the coordination of bimanual isometric force. *Experimental Brain Research, 209*(1), 129–138. https://doi.org/10.1007/s00221-010-2528-4.

Huang, V. S., Haith, A., Mazzoni, P., & Krakauer, J. W. (2011). Rethinking motor learning and savings in adaptation paradigms: Model-free memory for successful actions combines with internal models. *Neuron, 70*(4), 787–801. https://doi.org/10.1016/j.neuron.2011.04.012.

Kato, K., Muraoka, T., Higuchi, T., Mizuguchi, N., & Kanosue, K. (2014). Interaction between simultaneous contraction and relaxation in different limbs. *Experimental Brain Research, 232*(1), 181–189. https://doi.org/10.1007/s00221-013-3730-y.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology, 9*(6), 718–727. https://doi.org/10.1016/S0959-4388(99)00028-8.
Kesar, T., Chou, L. W., & Binder-Macleod, S. A. (2008). Effects of stimulation frequency versus pulse duration modulation on muscle fatigue. *Journal of Electromyography and Kinesiology, 18*(4), 662–671. https://doi.org/10.1016/j.jelekin.2007.01.001.
Kumar, A., Tanaka, Y., Grigoriadis, A., Grigoriadis, J., Trulsson, M., & Svensson, P. (2017). Training-induced dynamics of accuracy and precision in human motor control. *Scientific Reports, 7*(1), 1–10. https://doi.org/10.1038/s41598-017-07078-y.
Lay, B. S., Sparrow, W. A., Hughes, K. M., & O'Dwyer, N. J. (2002). Practice effects on coordination and control, metabolic energy expenditure, and muscle activation. *Human Movement Science, 21*(5–6), 807–830. https://doi.org/10.1016/S0167-9457(02)00166-5.
Lewis, G. N., MacKinnon, C. D., Trumbower, R., & Perreault, E. J. (2010). Co-contraction modifies the stretch reflex elicited in muscles shortened by a joint perturbation. *Experimental Brain Research, 207*(1–2), 39–48. https://doi.org/10.1007/s00221-010-2426-9.
Masumoto, J., & Inui, N. (2010). Control of increasing or decreasing force during periodic isometric movement of the finger. *Human Movement Science, 29*(3), 339–348. https://doi.org/10.1016/j.humov.2009.11.006.
McGill, S. M., Grenier, S., Kavcic, N., & Cholewicki, J. (2003). Coordination of muscle activity to assure stability of the lumbar spine. *Journal of Electromyography and Kinesiology, 13*(4), 353–359. https://doi.org/10.1016/S1050-6411(03)00043-9.
Mehta, R. K., & Agnew, M. J. (2012). Influence of mental workload on muscle endurance, fatigue, and recovery during intermittent static work. *European Journal of Applied Physiology, 112*(8), 2891–2902. https://doi.org/10.1007/s00421-011-2264-x.
Mehta, R. K., Nussbaum, M. A., & Agnew, M. J. (2012). Muscle- and task-dependent responses to concurrent physical and mental workload during intermittent static work. *Ergonomics, 55*(10), 1166–1179. https://doi.org/10.1080/00140139.2012.703695.
Moon, H., Kim, C., Kwon, M., Chen, Y. T., Onushko, T., Lodha, N., & Christou, E. A. (2014). Force control is related to low-frequency oscillations in force and surface EMG. *PLoS ONE, 9*(11), 1–9. https://doi.org/10.1371/journal.pone.0109202.
Muraki, S., Hayashi, K., Nasir, N., & Loh, P. Y. (2018). *Motor control with assistive force during isometric elbow flexion. Proceedings of the 20th Congress of the International Ergonomics Association*191–194. https://doi.org/10.1007/978-3-319-96083-8_24.
Naik, S. K., Patten, C., Lodha, N., Coombes, S. A., & Cauraugh, J. H. (2011). Force control deficits in chronic stroke: Grip formation and release phases. *Experimental Brain Research, 211*(1), 1–15. https://doi.org/10.1007/s00221-011-2637-8.
Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4.
Onushko, T., Baweja, H. S., & Christou, E. A. (2013). Practice improves motor control in older adults by increasing the motor unit modulation from 13 to 30 Hz. *Journal of Neurophysiology, 110*(10), 2393–2401. https://doi.org/10.1152/jn.00345.2013.
Orizio, C., Baruzzi, E., Gaffurini, P., Diemont, B., & Gobbo, M. (2010). Electromyogram and force fluctuation during different linearly varying isometric motor tasks. *Journal of Electromyography and Kinesiology, 20*(4), 732–741. https://doi.org/10.1016/j.jelekin.2010.03.005.
Ostry, D. J., & Feldman, A. G. (2003). A critical evaluation of the force control hypothesis in motor control. *Experimental Brain Research, 153*(3), 275–288. https://doi.org/10.1007/s00221-003-1624-0.
Park, S. H., Kwon, M., Solis, D., Lodha, N., & Christou, E. A. (2016). Motor control differs for increasing and releasing force. *Journal of Neurophysiology, 115*(6), 2924–2930. https://doi.org/10.1152/jn.00715.2015.
Potter, N. L., Kent, R. D., Lindstrom, M. J., & Lazarus, J. A. C. (2006). Power and precision grip force control in three-to-five-year-old children: Velocity control precedes amplitude control in development. *Experimental Brain Research, 172*(2), 246–260. https://doi.org/10.1007/s00221-005-0322-5.
Rosen, J., & Perry, J. (2007). Upper limb powered exoskeleton. *International Journal of Humanoid Robotics, 04*(03), 529–548. https://doi.org/10.1142/S021984360700114X.
Sakurai, S., & Ohtsuki, T. (2000). Muscle activity and accuracy of performance of the smash stroke in badminton with reference to skill and practice. *Journal of Sports Sciences, 18*(11), 901–914. https://doi.org/10.1080/026404100750017832.
Selen, L. P. J., Beek, P. J., & Van Dieën, J. H. (2006). Impedance is modulated to meet accuracy demands during goal-directed arm movements. *Experimental Brain Research, 172*(1), 129–138. https://doi.org/10.1007/s00221-005-0320-7.
Shadmehr, R., Smith, M. A., & Krakauer, J. W. (2010). Error correction, sensory prediction, and adaptation in motor control. *Annual Review of Neuroscience, 33*(1), 89–108. https://doi.org/10.1146/annurev-neuro-060909-153135.
Shemmell, J., Forner, M., Tresilian, J. R., Riek, S., Barry, B. K., & Carson, R. G. (2005). Neuromuscular adaptation during skill acquisition on a two degree-of-freedom target-acquisition task: Isometric torque production. *Journal of Neurophysiology, 94*(5), 3046–3057. https://doi.org/10.1152/jn.00670.2004.
Sparrow, W. A., & Newell, K. M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin and Review, 5*(2), 173–196. https://doi.org/10.3758/BF03212943.
Srinivasan, D., Samani, A., Mathiassen, S. E., & Madeleine, P. (2015). The size and structure of arm movement variability decreased with work pace in a standardised repetitive precision task. *Ergonomics, 58*(1), 128–139. https://doi.org/10.1080/00140139.2014.957736.
Sugawara, K., Tanabe, S., Suzuki, T., Saitoh, K., & Higashi, T. (2016). Modification of motor cortex excitability during muscle relaxation in motor learning. *Behavioural Brain Research, 296*, 78–84. https://doi.org/10.1016/j.bbr.2015.09.001.
Suzuki, T., Sugawara, K., Takagi, M., & Higashi, T. (2015). Excitability changes in primary motor cortex just prior to voluntary muscle relaxation. *Journal of Neurophysiology, 113*(1), 110–115. https://doi.org/10.1152/jn.00489.2014.
Tracy, B. L., Dinenno, D. V., Jorgensen, B., & Welsh, S. J. (2007). Aging, visuomotor correction, and force fluctuations in large muscles. *Medicine and Science in Sports and Exercise, 39*(3), 469–479. https://doi.org/10.1249/mss.0b013e31802d3ad3.
Van Loon, E. M., Masters, R. S. W., Ring, C., & McIntyre, D. B. (2001). Changes in limb stiffness under conditions of mental stress. *Journal of Motor Behavior, 33*(2), 153–164. https://doi.org/10.1080/00222890109603147.
Visser, B., de Looze, M. P., Veeger, D., Douwes, M., Groenesteijn, L., de Korte, E., & van Dieën, J. H. (2003). The effects of precision demands during a low intensity pinching task on muscle activation and load sharing of the fingers. *Journal of Electromyography and Kinesiology, 13*(2), 149–157. https://doi.org/10.1016/S1050-6411(02)00108-6.
Wada, T., & Yoshida, K. (2016). Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars. *Ergonomics, 59*(8), 1050–1059. https://doi.org/10.1080/00140139.2015.1109713.
Walsh, L. D., Taylor, J. L., & Gandevia, S. C. (2011). Overestimation of force during matching of externally generated forces. *Journal of Physiology, 589*(3), 547–557. https://doi.org/10.1113/jphysiol.2010.198689.
Welsh, S. J., Dinenno, D. V., & Tracy, B. L. (2007). Variability of quadriceps femoris motor neuron discharge and muscle force in human aging. *Experimental Brain Research, 179*(2), 219–233. https://doi.org/10.1007/s00221-006-0785-z.
Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 269*(5332), 1880–1882. https://doi.org/10.1126/science.7569931.
Yoshida, N., Yamaguchi, T., Saitou, K., Tanabe, S., & Sugawara, K. (2015). Increasing corticospinal excitability in the antagonist muscle during muscle relaxation with a tracking task. *Somatosensory and Motor Research, 32*(1), 39–43. https://doi.org/10.3109/08990220.2014.958215.