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**RESEARCH ARTICLE**

**Force Control Characteristics for Generation and Relaxation in the Lower Limb**

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**Summary.** We investigated the characteristics for force generation and relaxation using graded isometric contractions of the knee extensors. Participants performed the following tasks as quickly and accurately as possible. For the force generation task, force was increased from 0% to 20%, 40% and 60% of the maximal voluntary force (MVF). For the force relaxation task, force was decreased from 60% to 40%, 20%, and 0%. The following parameters of the recorded force were calculated: error, time, and rate of force development. The error was consistently greater for force relaxation than generation. Reaction and adjustment times were independent of the tasks. The control strategy was markedly different for force relaxation and generation, this tendency was particularly evident for the lower limb compared to the upper limb.

**Keywords:** Voluntary force control, Relaxation, Accuracy, Quickness

**Introduction**

Performance of smooth, accurate and well-coordinated movement requires control over both force generation (muscle contraction) and force relaxation (muscle relaxation). Therefore, the ability to accurately control both force generation and relaxation, quickly, is essential to the skillful performance of various movements (Kato, Muraoka, Higuchi, Mizuguchi, & Kanosue, 2014; Li, 2013; Spraker, Corcos, & Vaillancourt, 2009). However, when performing unfamiliar movements, force relaxation is typically more difficult to accurately control than force generation (Sakurai & Ohtsuki, 2000; Sewa & Kizuka, 2006).

Various studies have investigated the control of force using different paradigms, including the control of pulse height and width (Freund & Büdingen, 1978; Ghez, 1979; Gordon & Ghez, 1987). It has been reported that as the magnitude of force to be controlled increases, the strategy changes from one of controlling pulse height (control of the rate of force development) to controlling pulse width (control of the timing of the force) (Bahill, Clark, & Stark, 1975). Gottlieb, Corcos, and Agarwal (1989) described the control of pulse height and width as a strategy for the control of force for single joint movements. Strategies of force generation and relaxation have also been investigated through the measurement of muscle activation using electromyography and functional magnetic resonance imaging. Using functional magnetic resonance imaging, Spraker et al. (2009) demonstrated that different neural substrates were activated for muscle contraction and relaxation during an isometric pinch task. Harbst, Lazarus, and Whitall (2000) used a periodic isometric bimanual self-paced pinch task, performed at two force magnitudes, 10%–30% of maximal voluntary force (MVF) and 20%–40% of MVF, to investigate force-time control in adults and children. They reported greater variability in the timing and force level for force relaxation than force generation. This finding of a higher variability in force relaxation than force generation has been supported by several other researchers (Masumoto & Inui, 2010; Moritou, Inui, & Masumoto, 2009; Spiegel, Stratton, Burke, Glendinning, & Enoka, 1996). However, these findings have been reported only for isometric motor tasks involving small muscles and relatively small force levels, such as finger-grasping movements, with no reports of control strategies for whole limb, with tasks requiring a relatively high level of force. Other studies have evaluated the characteristics underlying the accuracy and quickness of force control for various muscle groups (ranging from the small muscles of the hand and digits to the large muscles of the thigh), using different force levels and tasks. Therefore, it is difficult to systematically compare results from these various studies. Moreover, in these studies, the control of force generation and relaxation was evaluated as components of one task, with relaxation analyzed as the relaxation phase during a periodic force generation (Harbst et al., 2000; Masumoto & Inui, 2010; Moritou et al., 2009; Spiegel et al., 1996). As such, the characteristics of force relaxation have not been systematically evaluated as a discrete component of force control.

Based on the above, Ohtaka and Fujiwara (2016) systematically investigated the characteristics and motor strategies for force generation and relaxation in the upper limb, demonstrating that for tasks requiring accurate control of force, the magnitude of error was greater for force relaxation than force generation, especially under conditions of low magnitude of force. They also demonstrated that although the timing of force adjustments was dependent on the magnitude of the target force level for both force generation and relaxation, the reaction time was consistently shorter for force relaxation than for force generation. They concluded that force generation and relaxation are controlled by two different strategies, with the need to control both the timing and the peak rate of force development increasing the difficulty of the control of force relaxation.

As mentioned above, the characteristics of force control in the upper limb were clarified, but there have been no reports of the characteristics of force generation and relaxation in the lower limb. While the upper limbs play a part of relatively high
operability, the lower limbs support the upper body, as well as move the body, such in walking and running. In addition to having different functions, the force levels to be controlled are also relatively larger at the lower than at the upper limbs.

Our aim in this study was to evaluate if the control of force generation and relaxation for the lower limb uses the same characteristics and strategies as identified for the upper limb. A priori, we hypothesized the following based on previous studies of force control for the upper limbs and the points of commonality and difference in the function of the upper and lower limbs.

**Hypothesis 1:** Force generation (a). The accuracy of force generation will be lower under conditions of low than high force magnitudes. This tendency will be particularly evident for the lower than upper limb. (b) Reaction time will be shorter for higher than lower magnitudes of force generation, with the adjustment time varying as a function of the magnitude of force generation.

**Hypothesis 2:** Force relaxation (a). The accuracy of force relaxation will be lower under conditions of low than high force magnitudes, and these differences will be more conspicuous in the lower than upper limb. (b) Reaction time of force relaxation will be shorter for higher than lower magnitudes of force, and the adjustment time will again depend on the magnitude of force.

**Hypothesis 3:** Comparing force generation and relaxation (a). The magnitude of error will be significantly higher for force relaxation than for force generation, and the relationship between the magnitude of error for force generation and for force relaxation will be different than those previously identified for the upper limb. (b) Reaction time will be significantly shorter for force relaxation than for force generation, with no differences in the adjustment time for force generation and relaxation. (c) Motor strategies controlling force generation and relaxation will be different between the lower and upper limbs.

**Method**

**Participants**

Fifteen healthy women of right foot dominance (mean age, 32.2 years; standard deviation, 1.1 years) formed our study group. The procedures were approved by the Academic Ethics Committee in Nara Women’s University, Japan. Prior to the experiment, all participants were fully informed of the purpose of the study and its procedures, and written informed consent was obtained.

**Apparatus**

The experimental set-up is shown in Fig. 1. The output force was measured using a force-measuring device (Takei Inc., Japan). Participants were seated in the force-measuring device, with the right knee in 120° of extension (180° is full knee extension) and the foot placed on the force plate; this knee angle was selected based on previous research that reportedly the highest magnitude of maximal isometric voluntary contractions around 120° of knee extension (Lindahl, Movin, & Ringqvist, 1969; Tsunoda, Watanabe, & Hori-kawa, 1987). The left leg was maintained in a relaxed position, with the foot resting on a cylindrical bar, and the arms were held along each side of the body. The output of the force-plate and the target line of the force level were displayed on a personal computer (NEC, VJ22LL-D). The target force level line, along with three light-emitting diodes (LED) used to indicate the warning signal and “go” signal, was controlled by a time-programmer (Takei Inc., Japan). The display of force levels was placed at a distance of approximately 1.5 m from participants, providing visual feedback for knowledge of performance.

**Experimental Tasks**

Participants were instructed to produce an isometric knee extension force to match the target force level, as quickly and accurately as possible. This required that force be either generated or decreased through relaxation. Four target force levels were used (0%, 20%, 40%, and 60% MVF), with three conditions presented for force generation and relaxation, as follows: force generation task (20% magnitude, increase force from 0% to 20% MVF; 40% magnitude, increase force from 0% to 40% MVF; and 60% magnitude, increase force from 0% to 60% MVF) and force relaxation task (20% magnitude, decrease force from 60% to 40% MVF; 40% magnitude, decrease force from 60% to 20% MVF; and 60% magnitude, decrease force from 60% to 0% MVF). The relationship between the tasks and magnitudes, as well the abbreviations used, are defined in detail in Table 1. Each trial began with a 500 ms visual warning signal, with the 500 ms “go” signal presented 2 s following the warning signal. Participants were informed of the magnitude before each trial. For the force generation tasks, participants generated the required force level from baseline resting (0%). For the relaxation task, participants were instructed to generate a force level of 60% MVF prior to the warning signal, with visual feedback of the force level presented. After maintaining the 60% MVF for 1 s, the warning and “go” signals were...
presented. Once the target force level had been achieved, the participants were informed to turn their eyes towards the warning signal. In order to measure and contrast the two tasks, participants were instructed to adjust the target force level in an instant under both tasks. As soon as they achieved the target force level, participants were instructed to relax their force for the generation task. In the relaxation task, as a contrast to the generation task, the participants adjusted the target force level in an instant, subsequently increasing their voluntary force level.

Procedure

Prior to the presentation of the test conditions, participants were instructed to produce three maximum isometric force efforts, with the MVF held for 1 s, and the maximum value obtained used as the reference MVF for each participant. Participants then practiced controlling their force to the target level, with visual feedback provided to facilitate learning (Masumoto & Inui, 2010). Up to 10 trials were offered at each target force level. Once participants were able to accurately control their force output, one practice session using the warning and “go” signals was conducted.

For the test conditions, participants were instructed about the target force level prior to each trial. Participants did not receive visual feedback of their performance during the trial, but did receive knowledge of their performance using a summary of their force waves after completion of the 10 trials at each of the three target force levels. A 1-min rest period was provided between each force level, with a 5-min rest interval between the two tasks (force generation and force relaxation). The order of the tasks was counterbalanced, with 7/15 of participants performing the force generation prior to the force-reduction task and, therefore, 8/15 of participants performed the relaxation task first. With regard to the magnitude of force, we used a blocked randomized design, with the 10 trials at a given level performed as a block, with the order of the “force level” blocks randomized across participants. After completion of the two tasks, participants again produced three MVFs to exclude effects of fatigue.

Data Analysis

Force measurements were acquired using a Biopac MP150 data acquisition system (1000 Hz sampling rate; Biopac Systems, United States). From each set of 10 trials at each of the three target force levels, 8 trials were randomly selected for analysis. The force data were low-pass filtered (cutoff, 100 Hz) and a mean force curve calculated from which the variables of interest were measured as shown in Fig. 2, and described as follows.

The calculation of adjustment time was performed as follows. Baseline force was calculated as the average force produced over a 300 ms period prior to the “go” signal. The average rate of force development (N/s) was then calculated over a 10 ms period following the “go” signal. Subsequently, the force onset was defined as the first time point within this first 10 ms period during which the average rate of force development exceeded 50% of baseline force for the force generation task, or decreased below this 50% threshold for the force relaxation task (Ohtaka & Fujiwara, 2016). The reaction time was defined as the time interval between the “go” signal and the force onset. The adjustment time could then be defined as the time between the force onset and the maximum force (generation task) or the minimum force (relaxation task). The total adjustment time was defined as the time between the “go” signal and the maximum force (generation task) or the minimum force (relaxation task).

The calculation of accuracy was performed as follows. The force level (%MVF) was defined as the relative value of the maximum or minimum force of each participant’s MVF. The difference in the accuracy of the force level between the peak force and each target force level was calculated to evaluate the constant, absolute and variable error.

The peak rate of force development of force control was calculated as follows. The peak rate of force development (peak RFD) was defined as the peak value of the rate of

<table>
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<th>TABLE 1. The relationship of tasks and magnitudes, and abbreviations used</th>
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force development over the adjustment time, with the time to reach peak RFD (time to peak RFD) also calculated.

**Statistical Analysis**

Prior to applying the evaluating differences between tasks and force levels, we tested for homoscedasticity in the data set. Differences in measured variables (error, time, and peak RFD) between the magnitudes (20%, 40%, and 60% magnitudes) and the two tasks (force generation and force relaxation) were evaluated using a two-way repeated measures analysis of variance (ANOVA). The within-participant factors were the magnitude of force (20%, 40%, and 60%) and task (force generation and relaxation). When significant effects were identified, pairwise comparisons were carried out, using a Bonferroni post hoc test. Differences in the slope of the force wave (RFD) between target force levels for the two force tasks were evaluated using one-way repeated measures ANOVA. All analyses were performed using SPSS for Windows (SPSS Inc.). Statistical analysis was conducted at the 0.05 level of significance.

**Results**

**Accuracy**

The means and standard deviations of the force levels for the force-generation and force-relaxation tasks for all participants are summarized in Fig. 3. For the force generation task, the difference between the force level and the target force level was influenced by a main effect of force magnitude ($F_{2, 18} = 2640.753, \ p < .001$) and an interaction between force level and the target force level ($F_{1, 9} = 5.698, \ p < .05$). The force level increased as a function of an increase in the target force level,
from magnitudes of 20% through to 60% \( (p < .001) \), with the force level being significantly higher than the target force level at the 20% magnitude \( (p < .05) \).

For the force relaxation task, the difference between the force level and the target force level was influenced by a main effect of force magnitude \( (F_{2, 18} = 546.113, p < .001) \) and level \( (F_{1, 9} = 7.172, p < .001) \), as well as by an interaction between the force level and the target force level \( (F_{2, 18} = 26.721, p < .001) \). Again, the force level decreased as a function of the target force level, from magnitudes of 20% through to 60% \( (p < .001) \), with the force level being significantly lower than the target force level for the 20% and 40% magnitudes \( (p < .01) \), and higher at the target force level of 60% magnitude \( (p < .05) \). Therefore, for the force generation task, the force level was significantly higher than the target force level at the 20% magnitude. By comparison, for the force relaxation task, the force level was significantly lower than the target force level at the 20% and 40% magnitudes.

**Error**

The means and standard deviations of the constant, absolute, and variable error for all participants and for both tasks are shown in Fig. 4. The constant error was influenced by a significant interaction \( (F_{2, 18} = 18.620, p < .001) \) as well as by significant main effects of the magnitude of force \( (F_{2, 18} = 30.722, p < .001) \) and task \( (F_{1, 9} = 8.224, p < .01) \). The constant error was significantly higher at the 20% magnitude than the 40% magnitude for the force generation task \( (p < .05) \), and higher at the 60% magnitude than the 20% and 40% magnitudes for the force relaxation task \( (p < .05) \). Moreover, the constant error was significantly higher for the force generation than relaxation task at the 20% and 40% magnitudes \( (20\%: p < .01; 40\%: p < .05) \).

In terms of the absolute error, a significant interaction was identified \( (F_{2, 18} = 6.327, p < .01) \), with the magnitude of the absolute error being significantly higher for the force relaxation than force-generation task at the 20% magnitude \( (p < .05) \), but with the magnitude of the absolute error being significantly higher for the force generation than relaxation task at the 60% magnitude \( (p < .05) \).

In terms of the variable error, the interaction \( (F_{2, 18} = 13.467, p < .001) \) and the main effect of the magnitude \( (F_{2, 18} = 4.360, p < .05) \) were again significant factors. For the force-relaxation task, the variable error was significantly greater at the 20% and 40% magnitudes than at the 60% magnitude \( (p < .01) \). The variable error was also greater for the force relaxation than generation task at the 20% magnitude \( (p < .01) \). In contrast, the variable error was greater for the generation than force-relaxation task at the 60% magnitude \( (p < .01) \).

Overall, for the force-generation task, no differences in absolute and variable error values were observed across the three levels of force magnitude \( (20\%, 40\%, \text{and} 60\%) \), with the constant error being higher at the 20% magnitude than at the 40% magnitude. For the force-relaxation task, the constant error was lower at the 20% and 40% magnitudes than at the 60% magnitude, and with the variable error being higher at the 20% and 40% magnitudes than at the 60% magnitude. Moreover, when comparing the force generation and relaxation tasks at the same magnitude, the constant error was lower for force relaxation than generation at the 20% and 40% magnitudes, and the absolute and variable errors were greater for force relaxation than generation at the 20% magnitude. However, the absolute and variable

![Figure 4](image-url)
errors were lower for force relaxation than generation task at the 60% magnitude.

Quickness

The means and standard deviations of the reaction time, adjustment time and total adjustment time are shown for all participants for the two tasks in Fig. 5. Reaction time was influenced mainly by the magnitude of force \( (F_{2,18} = 21.931, p < .001) \), with significantly longer reaction time at the 20% and 40% magnitudes than at the 60% magnitude for both tasks \( (20\%: p < .001; 40\%: p < .01) \). Adjustment time was influenced mainly by the magnitude \( (F_{2,18} = 106.999, p < .001) \) and the task \( (F_{1,9} = 26.620, p < .01) \). The adjustment time was increasingly longer from the 20% through to the 60% magnitudes \( (20\%: p < .001; 40\%: p < .01) \). Similarly, total adjustment time was influenced mainly by the magnitude of force \( (F_{2,18} = 95.971, p < .001) \) and the task \( (F_{1,9} = 11.331, p < .01) \). The total adjustment time was increasingly longer from the 20% through to the 60% magnitudes \( (20\%: p < .001; 40\%: p < .01) \) and being longer for force generation than relaxation at all magnitudes \( (p < .01) \).

Overall, the adjustment time increased as the magnitude of force increased for both tasks, whereas the reaction time tended to decrease as the magnitude increased. Comparing the two tasks, the adjustment time and the total adjustment time were consistently shorter for force relaxation than generation at all magnitudes.

The means and standard deviations of the peak RFD and the time to peak RFD for all participants during both tasks are shown in Fig. 6. Peak RFD was influenced by a significant main effect of the magnitude of force \( (F_{2,18} = 52.141, p < .001) \) and the task \( (F_{1,9} = 23.110, p < .01) \). For both tasks, peak RFD significantly increased from the 20% through to the 60% magnitudes \( (20\%, 40\%, \text{and} 60\%: p < .001; 20\% \text{and} 40\%: p < .01) \), with a significantly higher peak RFD for force relaxation than generation at all magnitudes \( (p < .01) \). Time to peak RFD was influenced by a significant interaction \( (F_{2,18} = 11.930, p < .001) \) and a main effect of the magnitude \( (F_{2,18} = 27.239, p < .001) \) and of the task \( (F_{1,9} = 36.622, p < .001) \). Time to peak RFD was significantly longer for the 40% and 60% than the 20% magnitudes for the force-generation task \( (40\%: p < .001; 60\%: p < .01) \). As well, the time to peak RFD was significantly longer for force generation than force relaxation at all magnitudes \( (20\%: p < .01; 40\% \text{and} 60\%: p < .001) \).

Overall, for the force-generation task, peak RFD increased as the magnitude increased, which was associated with an increase in the time to peak RFD. In contrast, for the force-relaxation task, as the magnitude increased, although the peak RFD increased, the time to peak RFD remained constant. Comparing the two tasks, the relaxation task showed greater peak RFD than the generation task, while the generation task showed longer time to peak RFD compared to the relaxation task at all magnitudes.

![FIGURE 5. Mean values and standard deviations of (A) the reaction time, (B) adjustment time, and (C) total adjustment time. *: Significant difference between the magnitude of the force controlled, **: \( p < .05, \text{***}: p < .01, \text{****}: p < .001 \). †: Significant difference between the tasks, ††: \( p < .01 \).](image)
A) having a different slope for each of the three magnitudes (Fig. 7A), with the slopes being comparable at all three magnitudes in the second pattern (pattern B; Fig. 7B). Based on these findings, and using a one-way repeated measures ANOVA for both tasks, we classified the force waves into these two patterns for both tasks (Ohtaka & Fujiwara, 2016). For the force-generation task, pattern A was consistently identified for all participants. By comparison, for the force-relaxation task, pattern A was identified in 2/10 participants, with pattern B identified in the other 8 participants. Therefore, the ratio of pattern A to pattern B was 10:0 for force generation, compared to 1:4 for force relaxation.

Discussion

With a focus on force control, we describe the characteristics for the control of force generation and relaxation for the lower limb. Moreover, we compared the characteristics of force control for the lower limb to those previously described for the upper limb (Ohtaka & Fujiwara, 2016).

The Accuracy of Force Control

In terms of force generation, at the 20% magnitude, force level overshot the target level (Fig. 3A), with the magnitude of error being significantly higher than at the 40% magnitude (Fig. 4A). This finding is indicative of a lower accuracy of force generation at lower than mid-levels of magnitude, which is opposite to the control characteristics for the upper limb. However, our findings were consistent with previous studies which have reported an increase in self-reported sensation of effort (and hence greater error) to control higher magnitudes of mechanical force during a graded handgrip task (Stevens & Mack, 1959) or an increase in jump distance task (Sadamoto & Ohtsuki, 1977). Therefore, the error in generated force (objective) is influenced by the magnitude of force to be controlled (subjective).

In terms of force relaxation, for the 20% and 40% magnitudes, force level undershot the target force level greatly (Fig. 3B), with the magnitude in force error being significantly higher than at the 60% magnitude (Fig. 4A). Moreover, the variability of force relaxation was also significantly higher at the 20% and 40% magnitudes than at the 60% magnitude (Fig. 4C). Consistent with previous findings for the upper limb, we demonstrated greater difficulty in accurately controlling force relaxation than generation at low magnitude in the lower limb. Therefore, the error in force control (objective) is influenced by the magnitude of force to be controlled by muscle relaxation (subjective).

Furthermore, at the 20% magnitude, the error was significantly greater for force relaxation than for force generation (Fig. 4). In other words, accurate control at low magnitude of force is more difficult for force relaxation than for force generation. Several studies have demonstrated that decreasing isometric force results in greater variability in force and timing than for increasing isometric force (Harbst et al., 2000; Masumoto & Inui, 2010; Moritou et al., 2009; Spiegel et al., 1996). Harbst et al. (2000)) investigated how children and adults control force and timing using periodic isometric bimanual self-paced pinch tasks of 10–30% MVF and 20–40% MVF. Masumoto and Inui (2010) also examined the control of force and timing utilizing a periodic isometric force task of the right index finger in adults. They related the variability in force and timing to the isometric condition of the task itself. Specifically, as force is produced without an overt change in muscle length during an isometric contraction, the proprioceptive feedback of force is reduced, which would contribute to the variability in maintaining a consistent force output. That this variability is greater in the force relaxation than force generation task reflects the further decrease in tactile cues on the index and thumb as the magnitude of force of the pinch is decreased under force relaxation. Although these studies used relatively small force levels, our findings were consistent with the outcomes of these studies, as well as for larger forces at
the upper limb (Ohtaka & Fujiwara, 2016), confirming the greater difficulty in controlling force relaxation than generation. However, we did identify a specific difference between force control between the upper and lower limbs. Specifically, at the 60% magnitude, errors in force generation were significantly higher compared to those for force relaxation, with errors being comparatively higher for force relaxation than generation at the 20% magnitude (Fig. 4B, Fig. 4C). Therefore, the magnitude of error and variability in force control decreases as the target force level approaches 0%, regardless of the direction of force control, which likely reflects the better estimation of effort that enhances force reproducibility.

The Quickness of Force Control

The reaction time was shorter for the 60% magnitude than for the 20% and 40% magnitudes, for both force generation and relaxation (Fig. 5A). Using an isometric pinch grasp task, Haagh, Spijkers, Boogaart, and Buxtel (1987) reported a negative correlation between the premotor reaction time and the peak amplitude of force. Our findings were consistent with this previous finding, indicative that the quickness of force control improves as the magnitude of force to be controlled increases for the lower limb. This inverse association between reaction time and the magnitude of force to be controlled was significant for force relaxation. This might reflect differences in the complexity of control for high and low magnitude forces. Specifically, for high magnitudes of force, the control of force is first initiated, with adjustments to the target level following. However, for low magnitudes of force, the control of force and the final adjustment to the target level must occur concurrently, which would increase the reaction time as attention must be paid to both components of force control. However, we did not identify differences in reaction time between force generation and relaxation at high force magnitudes (Fig. 5A). This finding is in contrast to the findings of Buccolieri, Avanzino, Trompetto, and Abbruzzese (2003) who reported reaction time to be shorter for force relaxation than for force generation for the proximal muscles of the arm (biceps brachii and triceps brachii). In contrast, for the lower limb, the quickness of force control was comparable for both force generation and relaxation. This difference between the upper and lower limb might reflect differences in absolute force capacity, with the MVF being greater for the lower limb than upper limb.

The adjustment time for both force generation and relaxation increased from the 20% through to the 60% magnitude as well as being positively associated to the magnitude of force to be controlled (Fig. 5B). This finding is consistent with those of previous studies (Bahill et al., 1975; Gottlieb et al., 1989; Ono, Okada, Kizuka, & Tanii, 1997), and is indicative of a common effect of force magnitude on adjustment time for the upper and lower limbs and this for both force generation and relaxation. As well, the
adjustment time was consistently shorter for force relaxation than generation at all magnitudes, this consistency in the lower limb being different than for the upper limb. When we consider that peak RFD was greater for force relaxation than generation at all magnitudes, we confirm a quicker control of force relaxation than generation, with a greater control of force per unit time than for force generation.

The Force Control Strategy

Applying findings of force control process and peak RFD for the upper limb (Ohtaka & Fujiwara, 2016), we identified two control strategies that were differentially used for force generation and relaxation (Fig. 8). For force generation, a single strategy was observed, in which timing and RFD are controlled for different magnitudes (Fig. 7A, Fig. 8A). In other words, the force is controlled by changing the RFD from the beginning of the adjustment for each magnitude. This pattern is similar to the pulse height control strategy which has previously been described (Freund & Büdingen, 1978; Ghez, 1979; Gordon & Ghez, 1987; Gottlieb et al., 1989), and is comparable to the control strategy of force generation of the upper limb (Ohtaka & Fujiwara, 2016). In contrast, for force relaxation, two strategies were observed, namely, the control of timing and RFD, as for force generation, and control of only timing, irrespective of the magnitude (Fig. 7B, Fig. 8B). Thus, the force is controlled by a fixed RFD, which is determined from the onset of the adjustment time for each magnitude. The concomitant control of timing and RFD is similar to the pattern of control for force relaxation which has previously described (Bahill et al., 1975; Gottlieb et al., 1989), and is comparable to the strategy for the upper limb (Ohtaka & Fujiwara, 2016). Of note, however, was the obvious difference in the pattern of control for force generation and relaxation in the lower limb, which was quite different than previously reported findings for the upper limb. Specifically, all participants selected to control both the timing and RFD of force generation, while controlling only timing for force relaxation. The control of both timing and RFD would provide a quicker and more accurate control of force generation, compared to force relaxation. It might be that as force relaxation is more difficult to control at the level of the muscle, opting for a strategy that controls only timing (rather than control of both timing and RFD) might lower the attentional demand required. The effect of the difference in control strategy for force generation and relaxation on peak RFD and time to peak RFD is clearly evident in Fig. 6, with peak RFD being greater for force relaxation than force generation (Fig. 6A), with the time to peak RFD being almost twice as short for force relaxation than force generation (Fig. 6B). The fact that a higher RFD is organized more quickly likely explains the decrease in accuracy of force relaxation as magnitude was decreased to 20% (requiring a greater change in force per unit of time). This finding is comparable to the strategies that have previously been reported for the upper limb, and agree with the mechanism of a speed-accuracy trade-off that has previously been well described (Fitts, 1954; Schmidt, 1982). Therefore, although participants can

![FIGURE 8](image-url)

FIGURE 8. Motor strategies for force generation and force relaxation focused on the force wave and peak RFD of (A) a strategy to control both the time and RFD and (B) a strategy to control only the time. “Peak RFD” in the figure shows the time at which peak RFD occurred. The peak RFD occurred in the latter half of the adjustment time for all magnitude in the force-generation task, but occurred during the early stage of the adjustment time for all magnitudes in the force-relaxation task.
quickly control force relaxation at higher RFD, this comes at a cost of lower accuracy due to the short time available to organize the force response.

With regard to the issue of lower accuracy with force relaxation than generation, differences in motor unit recruitment and derecruitment must also be considered. According to Henneman’s size principle (Henneman, Somjen, & Carpenter, 1964), during ramped force generation, smaller motor units are recruited before larger ones. In contrast, during force relaxation, motor units are derecruited in reverse order, from the largest to the smallest motor units (Latash, 1998). This reverse order would further contribute to the lower accuracy for force relaxation than generation, as the early derecruitment of large motor units would not allow rapid adjustments in force level. Several studies have previously reported greater variability in the force and timing of force relaxation than generation (Harbst et al., 2000; Masumoto & Inui, 2010; Moritou et al., 2009), but without providing insight onto possible mechanisms. We provide evidence for the lower limb that this variability likely reflects a trade-off of control speed during force relaxation, compared to force generation, with this effect being greater for the lower than upper limb.

The following limitations of this study are recognized. Foremost, we did not consider the effect of providing feedback of force and of visual feedback of the target force levels on the characteristics of force generation and relaxation. In future studies, we also should compare force control characteristics for the upper and lower limb at the same magnitude of force in each force direction to reliably evaluate differences in accuracy, quickness and strategy.

In conclusion, the findings of the present study indicate marked differences in the accuracy, quickness, and motor control for force generation and relaxation for the lower limb, which were not evident for the upper limb.

**Verification of the Hypotheses**

**Force Generation**

Accuracy of force generation is lower for low than high magnitudes of force output. Moreover, quickness and reaction time are negatively associated with the magnitude of force output, with the adjustment time being dependent on the control strategy selected. Accuracy can be improved by controlling both timing and RFD, which is a strategy that is consistently used for force generation.

**Force Relaxation**

Again, accuracy decreased as the magnitude of force decreased. With regard to quickness, reaction time was negatively associated with force magnitude. Again, adjustment time varied depending on the control strategy used. A strategy in which only time was controlled (with RFD remaining constant) was principally used for force relaxation.

**Comparison between Force Generation and Relaxation**

The magnitude of error in controlling the target force level was significantly higher for force relaxation than force generation, especially at low magnitudes of force. Reaction time and adjustment time (which together characterize quickness) were independent of the direction of force control (generation or relaxation). However, the control strategy was markedly different for force relaxation and generation, with consequent differences in peak RFD and the time to peak RFD. This tendency was particularly evident for the lower limb compared to the upper limb.

**REFERENCES**


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