Original Article

# Force control characteristics for generation and relaxation compared between the upper and lower limbs

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**ABSTRACT**

We investigated the characteristics for force generation and relaxation compared between upper and lower limb. Participants were instructed to control the force of isometric elbow flexion or knee extension as quickly and accurately as possible. They performed the following two tasks: 1) Generation task, they increased their force from 0% maximum voluntary force (MVF) to 20%, 40%, or 60% MVF, 2) Relaxation tasks, they decreased their force from 60% MVF to 40%, 20%, or to 0% MVF. As a result, variable error of upper limb was greater than that of lower limb at all magnitudes in generation task. The peak rate of force development was greater in lower limb than in upper limb at all magnitudes in both tasks. The results indicate that it is more difficult to control relaxation of force accurately by upper limb than by lower limb under conditions that involve forces with low magnitude of control.

**Keywords:** Motor control; Biomechanics; Grading ability; Isometric.

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## INTRODUCTION

In daily life and sports activities, we perform various types of movements ranging from fine movements of the hands or upper limbs to dynamic movements of the lower limbs and the entire body. Accordingly, both the generation and relaxation of the forces must be accurately controlled such that one can move their body as intended. However, particularly in unfamiliar movements, adequately relaxing the force is often more difficult than generating it. Therefore, controlling force generation and relaxation accuracy is considered to be a basic and crucial requirement (Kato et al., 2014; Li, 2013; Spraker et al., 2009).

From the aspect of force generation, previous studies have reported on the relation between the magnitudes of the control force and motor strategies (Freund and Budingen, 1978; Gordon and Ghez, 1987; Gottlieb et al., 1989; Ono et al., 1997). In addition, the functional relation between the subjective and the physical magnitudes of the generated force was studied through graded handgrip tasks (Stevens and Mack, 1959) or distance jumping (Sadamoto and Ohtsuki, 1977). Furthermore, a previous study applied functional magnetic resonance imaging (fMRI) to compare force generation and relaxation and showed that different neural substrates were activated for muscle contraction and relaxation (Spraker et al., 2009). Some studies on isometric contraction also reported that force relaxation showed higher variability compared with force generation variability in the control of force level (Harbst et al., 2000; Masumoto and Inui, 2010; Moritou et al., 2009; Spiegel et al., 1996) and control of timing (Masumoto and Inui, 2010; Moritou et al., 2009). Therefore, quickness and strategy of control are critical factors in force generation. In addition, accurately controlling force relaxation is more difficult than generating the force. However, the characteristics of quickness and accuracy as well as the reason for the inaccuracies in the force relaxation were not clarified for several magnitudes of force control (hereinafter referred as ‘magnitude’).

Accordingly, Ohtaka and Fujiwara (2016) comprehensively studied the characteristics of force generation and relaxation by comparing the differences in the upper limbs at several magnitudes. They observed that at a target force level, the force relaxation demonstrated lower accuracy than force generation, particularly at smaller magnitudes. Regarding the quickness of adjustment and reaction, their times depended on the magnitude of both force generation and relaxation. Furthermore, the strategies employed for force relaxation differ from those for force generation, thereby further affecting the overall force control. As for the lower limbs, they reported the characteristics of force generation and relaxation by employing the same tasks as those of the upper limbs (Ohtaka and Fujiwara, 2019). The control strategy was markedly different for force relaxation and generation. This tendency was particularly evident for the lower limbs. Although previous studies showed the characteristics of force generation and relaxation in the upper and lower limbs, the difference in the characteristics of force control between the upper and lower limbs has not been directly investigated. Both limb types have basic functions of operation, movement, and support. The upper limbs play a part in high operability in daily life and sports activities. Moreover, the lower limbs play essential roles in moving or supporting the entire body. The force levels to be controlled are relatively higher at the lower limb than at the upper limb.

Therefore, this study aims to investigate the differences in the characteristics of force generation and relaxation focusing on the difference between the upper and lower limbs via conduction of further analyses utilizing the data of previous studies on the upper (Ohtaka and Fujiwara, 2016) and lower limbs (Ohtaka and Fujiwara, 2019). The differences are simultaneously evaluated for the upper and lower limbs considering force control (generation and relaxation) at several magnitudes (20%, 40%, and 60%). The following hypotheses are considered based on functional characteristics.

Hypothesis 1: For accuracy, the error of force generation and relaxation will be higher in the lower limbs than in the upper limbs at all magnitudes.

Hypothesis 2: For quickness, the reaction time will be shorter for the upper limbs than for the lower limbs, with the adjustment time being constant between both types of limbs for force generation and relaxation at all magnitudes.

## MATERIALS AND METHODS

The participants, measures, procedure, and analysis involved in this study were the same as those of previous studies (Ohtaka and Fujiwara, 2016; 2019). To accomplish the aim of our study, we did an original statistical analysis involving a comparison of the limbs (upper and lower), force control (generation and relaxation), and magnitudes (20%, 40%, and 60%) simultaneously.

### *Participants*

Fifteen healthy right-handed and right-footed women (*M* age = 20.2 years; *SD* = 1.1 years) participated in the study. All subjects were undergraduate or graduate students. They were all right-handed according to the criteria of the Edinburgh handedness inventory (Oldfield, 1971) and right-footed according to the criteria of the foot-preference inventory (Chapman et al., 1987). The participants had no record of physical disorder. The procedures were approved by the academic ethics committee of the Nara Women's University, where this study was conducted. Prior to the experiments, all participants were fully informed about the purpose of the study and its procedures in detail. Subsequently, written informed consent was obtained from all participants.

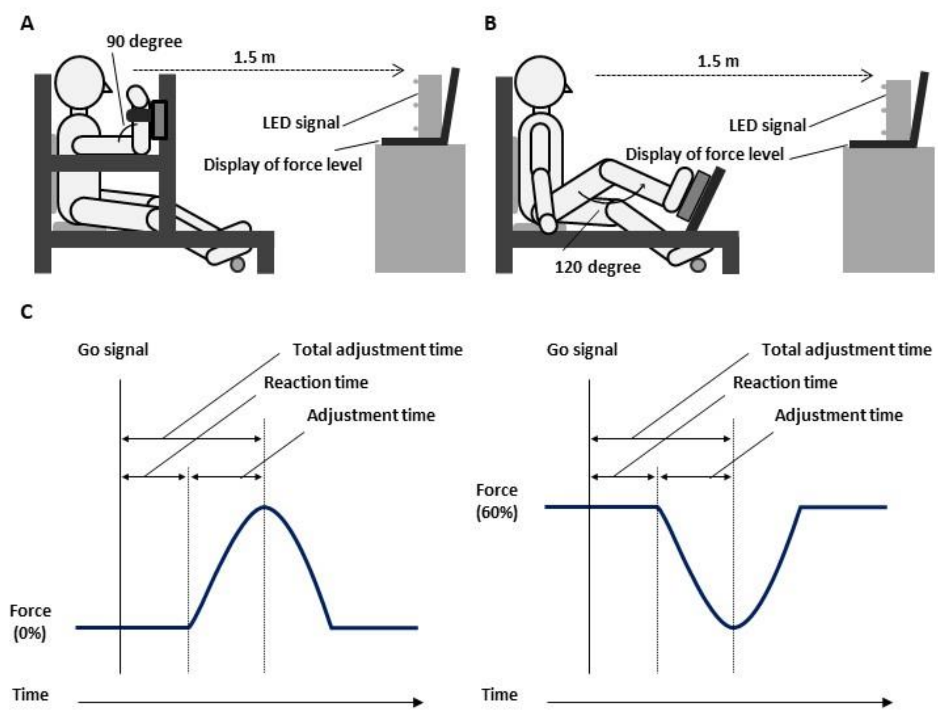



Figure 1. Experimental setup for the (A) upper and (B) lower limbs from Ohtaka & Fujiwara 2016, 2019. (C) Definition and measurement of the force for the force generation (left) and force relaxation (right) tasks adapted from Ohtaka & Fujiwara 2020.

***Measures***
Figure 1 shows the experimental setup adapted from Ohtaka and Fujiwara (2016, 2019, 2020). The output force of the participants was measured using a force-measuring device (Takei Scientific Instrument Co., Ltd., Japan). The participants were seated in the force-measuring device according to the position of the utilizing arm (Ohtaka and Fujiwara, 2016). The right arm was fixed to an arm holder connected to a force plate with the elbow joint fixed at 90° of flexion (180° corresponds to full elbow extension). The left arm was held on the left side of the body. Both legs were straightened and positioned on a cylindrical pole.

Regarding the condition of the utilizing leg (Ohtaka and Fujiwara, 2019), the participants were seated in the force-measuring device, with their right leg placed on the force plate fixed with the knee joint at an extension of 120° (180° corresponds to full knee extension). This knee angle was selected based on previous research that reported the highest magnitude of the maximal isometric voluntary contractions at a knee extension of approximately 120° (Lindahl et al., 1969; Tsunoda et al., 1987). The left leg was straightened and positioned on a cylindrical pole. Both arms were held at the 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, controlled by a time programmer (Takei Scientific Instrument Co., Ltd., Japan) were placed approximately 1.5 m from the participants' eyes to act as visual stimuli.

***Procedures***
The participants were instructed to produce isometric elbow flexion or knee extension force to match the target force level as rapidly and accurately as possible by using their right arm or leg. They were asked to perform two discrete tasks: (1) a force generation task, which comprised increasing their force and (2) a force relaxation task, which comprised decreasing their force. For target force levels of 0%, 20%, 40%, and 60% of the maximum voluntary force (MVF), they were asked to perform three magnitudes of force control repetitions.

*1) Force generation task*
20% magnitude: increase their force from 0% to 20% MVF.
40% magnitude: increase their force from 0% to 40% MVF.
60% magnitude: increase their force from 0% to 60% MVF.

*2) Force relaxation task*
20% magnitude: decrease their force from 60% to 40% MVF.
40% magnitude: decrease their force from 60% to 20% MVF.
60% magnitude: decrease their force from 60% to 0% MVF.

The participants performed the task under a simple reaction condition. Each trial began with a 500-ms visual warning signal. The subsequent 'go' signal was presented for 500 ms. The fore-period (i.e., the interval between the warning and 'go' signals) was 2.0 s. The participants were informed about the magnitude before each trial along with the visual warning signals and instructed to control their force in response to the 'go' signal. For the force generation task, the participants generated the required force level from the baseline resting (0%). Meanwhile, for the force relaxation task, the participants were instructed to maintain a force level of 60% MVF prior to presenting the warning signal with visual feedback of the force level. After maintaining 60% MVF for 1 s, the participants were informed to turn their eyes toward the warning signal. Subsequently, the warning signal and subsequent 2 s 'go' signal were presented. The participants were instructed to immediately adjust the target force level under both tasks to measure and provide a contrast between the two tasks. In the generation task, as soon as the participants achieved the target force level, they were instructed to relax their force. Conversely, in the relaxation task, the participants instantly adjusted the target force level, after which their voluntary force level was increased. The participants were initially instructed to produce an isometric force of maximum effort for 1 s for three separate trials. The maximum force value of the three trials was set as each participant's MVF. Subsequently, the participants practiced controlling their force to the target level, with visual feedback provided to facilitate learning (Masumoto and Inui, 2010). Up to 10 trials were offered at each target force level. One practice session using the warning and 'go' signals was conducted after the participants could accurately control their force output.

For the test conditions, the participants were instructed about the target force level before each trial. The visual feedback of their performance was not provided during the trial; however, knowledge on their performance was provided as a summary of their force waves after completing 10 trials. A rest period of 1 min was provided between each force level, with a 5-min rest interval between the two tasks (i.e., force generation and relaxation). The task order was counterbalanced: 7/15 participants performed the force generation task prior to the force reduction task; therefore, 8/15 participants performed the relaxation task first. Concerning the force magnitude, we used a blocked randomized design with 10 trials at a given level performed as a block. The order of the 'force level' blocks was randomized across all participants. The participants were instructed to perform the task as rapidly and accurately as possible. After completing the two tasks, the participants again produced three MVFs to exclude the effects of fatigue. The upper- and lower-limb tasks were performed on separate days. The order of the limbs was counterbalanced: 7/15 participants performed upper limb tasks prior to the lower limb tasks. Therefore, 8/15 participants performed the lower limb tasks first.

### *Analysis*

The produced force was recorded. All recordings were digitized at 1000 Hz using a Biopac MP150 data acquisition system (Biopac Systems, USA). Eight trials were randomly selected for analysis from each set of 10 trials at each of the three target force levels. The force data were passed through a digital filter with a 100-Hz low-pass cut-off frequency, producing a mean value for further analysis. *Time* was calculated as follows (Figure 1C): the baseline force was calculated as the average force produced over a 300-ms period prior to the 'go' signal; the average rate of the force development (N/s) was calculated over a 10-ms period following the 'go' signal; and subsequently, the force onset was defined as the first time point during which the average rate of force development exceeded 50% of the baseline force in the force generation task or decreased below the 50% threshold in the force relaxation task (Ohtaka and Fujiwara, 2019). The *reaction time* is 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 is defined as the time between the 'go' signal and the maximum force (generation task) or the minimum force (relaxation task).

The *accuracy* was calculated as follows: the force level (%MVF) is 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 maximum or minimum force and each target force level was calculated to evaluate the following three errors: *constant error* defined as the difference between the signed values of the peak force and each target force level; *absolute error* defined as the absolute value of the constant error; and *variable error*, which measures the reproduction within the participants, is defined as the average of the difference between the signed values of the peak force and each participant's average of each force level.

The *peak rate of force development* (peak RFD) is defined as the peak value of the rate of force development during the adjustment time. The *time to reach peak RFD* (time to peak RFD) was calculated in addition to the peak RFD.

### *Statistical analysis*

To consider the hypothesis, we compared the tasks, magnitudes, and limbs simultaneously utilizing the statistical analysis as follows. The data set was tested for homoscedasticity prior to evaluating the differences between tasks, magnitudes, and limbs. A three-way repeated measure analysis of variance (ANOVA) was conducted for the error, time, and peak RFD parameters to test the differences in the mean values for each magnitude and limb. The intra-participant factors were task (generation and relaxation tasks), magnitude (20%, 40%, and 60% magnitudes), and limbs (upper and lower limbs). Pairwise comparisons were performed using Bonferroni post-hoc tests when significant effects were found. Regarding the repeated measures, we tested whether Mauchly's sphericity assumption was violated. If the result of Mauchly's test was significant, and the assumption of sphericity was violated, the Greenhouse–Geisser adjustment was used to correct sphericity by altering the degrees of freedom using the correction coefficient epsilon. Sphericity was maintained in all cases; thus, the Greenhouse–Geisser correction was not used. The one-way repeated measures ANOVA was conducted for both tasks and limb types to test the difference in inclinations (RFD) of the force signal among the magnitudes. The data were analysed using SPSS software (SPSS Inc.). The statistical analysis was conducted at $p < .05$ significance level.

## RESULTS

### *Maximum voluntary force*

The maximum voluntary forces were 152.8 ± 11.9 N (pre-task) and 166.1 ± 29.3 N (post-task) for the upper limbs and 944.5 ± 318.1 N (pre-task) and 1157.4 ± 353.6 N (post-task) for the lower limbs. These results did not show the effect of fatigue on the exertion strength.

### *Accuracy*

*Force level (% MVF)*

Figure 2 presents the mean and the standard deviation of the force level for the generation and relaxation tasks of all participants.

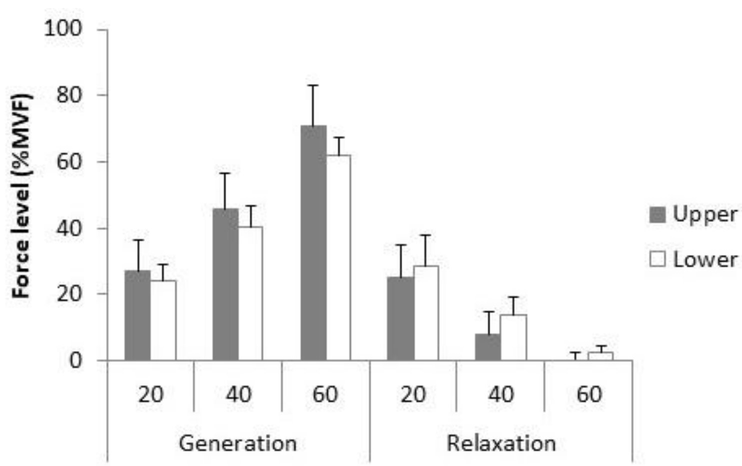
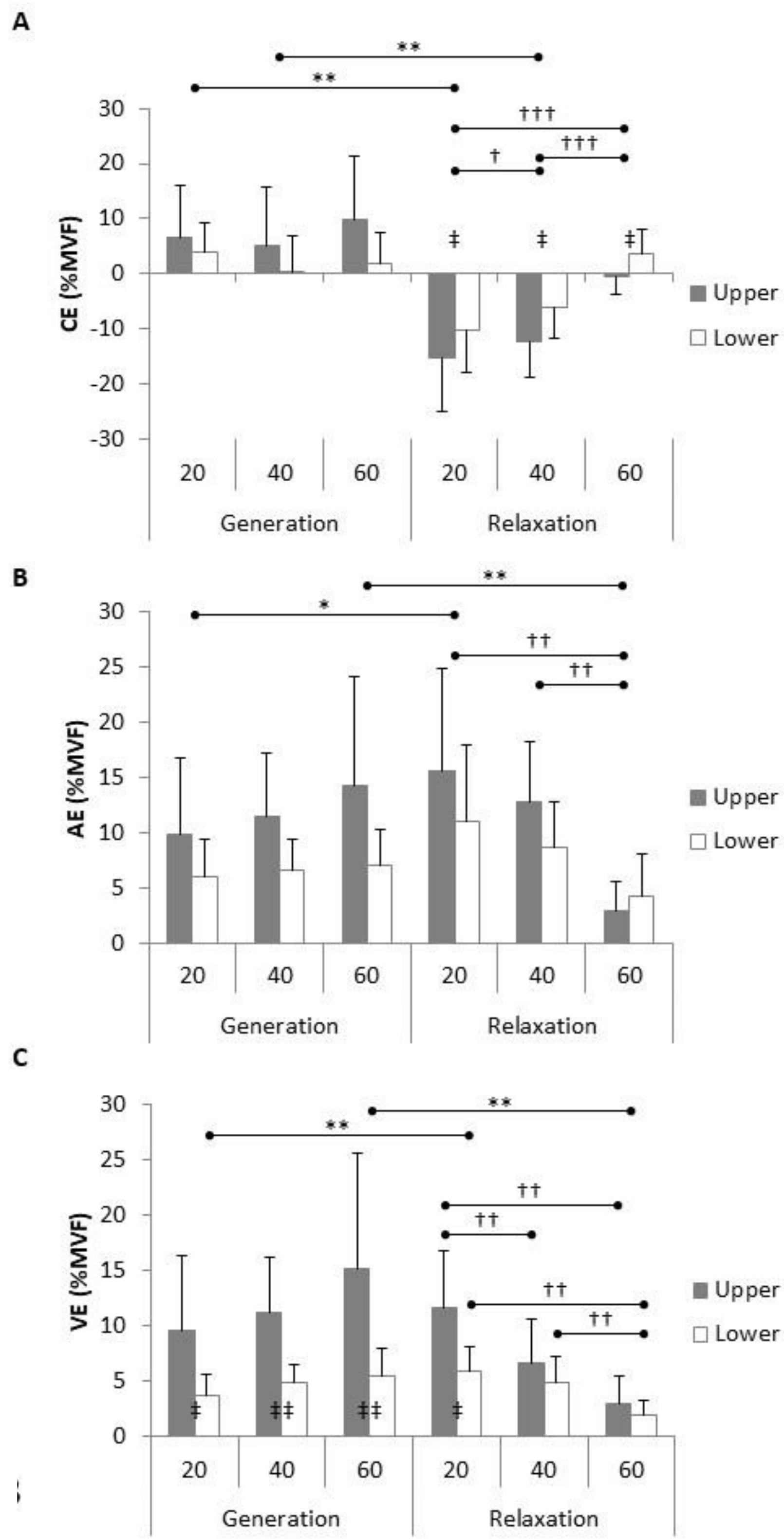


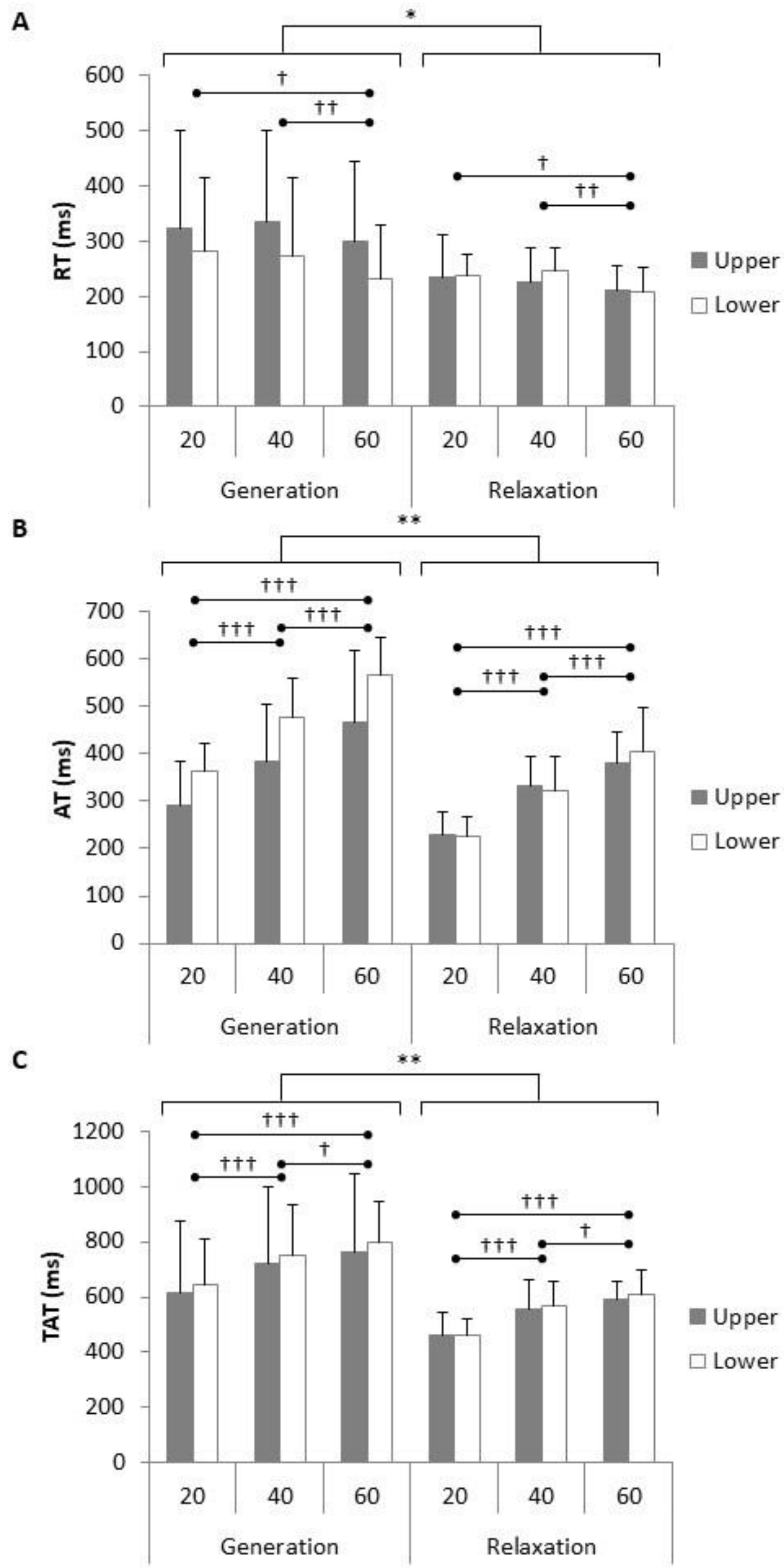

Figure 2. Mean values and standard deviations for each force level.




*Note: *: Significant difference between the tasks, *: p < .05, **: p < .01. †: Significant difference among the magnitudes of force control, †: p < .05, ††: p < .01, †††: p < .001. ‡: Significant difference between the limbs, ‡: p < .05, ‡‡: p < .01.*

Figure 3. Mean values and standard deviations of the (A) constant, (B) absolute, and (C) variable errors.




*Note: *: Significant difference between the tasks, *: p < .05, **: p < .01. †: Significant difference among the magnitudes of force control, †: p < .05, ††: p < .01, †††: p < .001.*

Figure 4. Mean values and standard deviations of the (A) reaction, (B) adjustment, and (C) total adjustment times.

*Error*

Figure 3 presents the mean and the standard deviation of the constant, absolute, and variable errors of all participants. The Task–Limb interaction ($F_{1,9}$ = 6.795, $p$ < .05), Task–Magnitude interaction ($F_{2,18}$ = 13.863, $p$ < .001), and main effects of Task ($F_{1,9}$ = 21.030, $p$ < .01) and Magnitude ($F_{2,18}$ = 50.800, $p$ < .001) were significant regarding the constant error. The post-hoc test for the Task–Limb interaction indicated that the generation task error was significantly higher than that of the relaxation task for both limb types (upper limb: $p$ < .01; lower limb: $p$ < .05). For the relaxation task, the upper limb showed significantly greater negative values than the lower limb ($p$ < .05). For the Task–Magnitude interaction, the generation task showed significantly higher error than the relaxation task ($p$ < .01) at 20% and 40% magnitudes. For the relaxation task, the error significantly increased from 20% to 60% magnitudes (20%, 40%, and 60%: p < .001; 20% and 40%: p < .05).

The Task–Magnitude interaction ($F_{2,18}$ = 30.415, p < .001) and the main effects of the Limb ($F_{1,9}$ = 9.038, $p$ < .05) and Magnitude ($F_{2,18}$ = 4.923, $p$ < .05) were significant regarding the absolute error. The post-hoc test for Task indicated that the relaxation task had a significantly higher error than the generation task at 20% magnitude ($p$ < .05), whereas the generation task had a significantly higher error than the relaxation task at 60% magnitude ($p$ < .01). Regarding Magnitude, the errors of the relaxation task at 20% and 40% magnitudes were significantly higher than those at 60% magnitude ($p$ < .01).

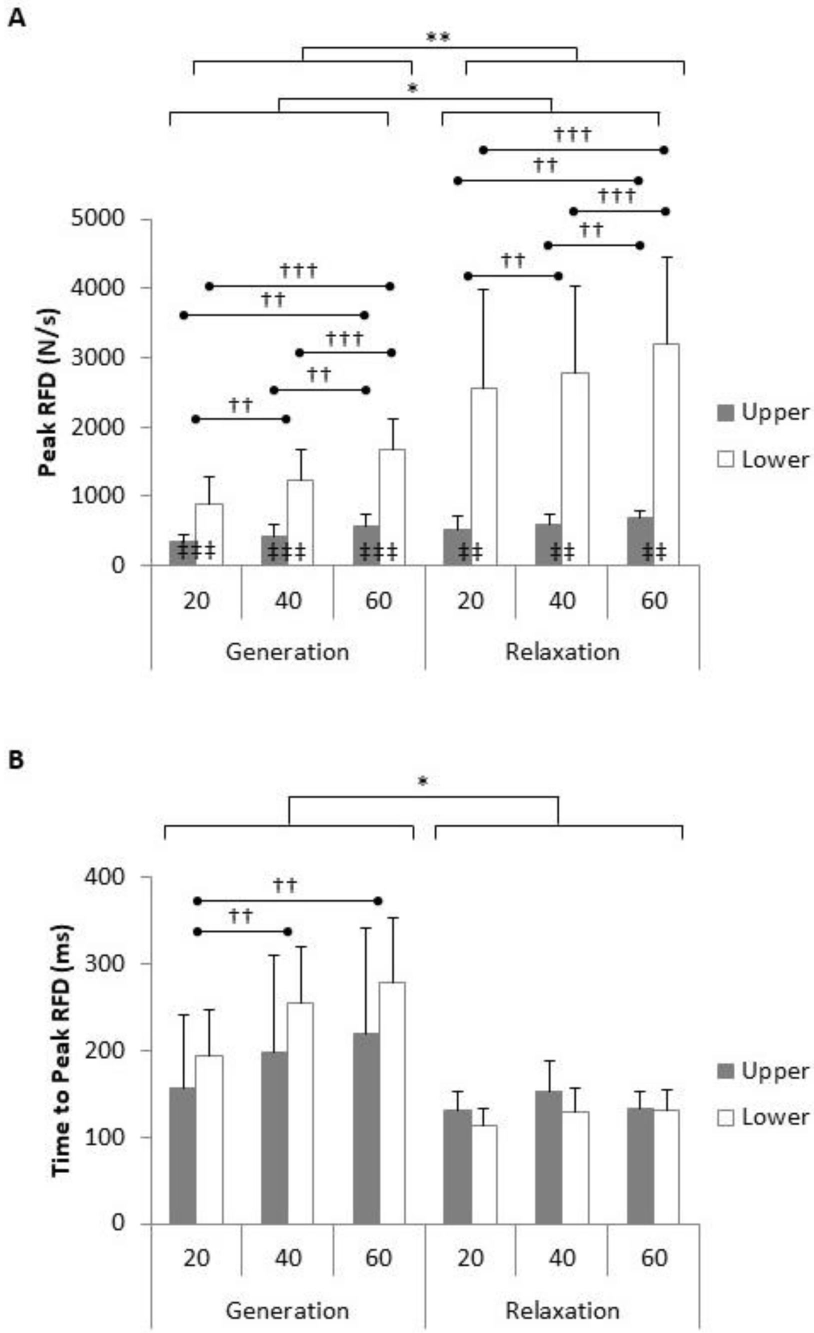
Regarding the variable error, the Task–Magnitude-Limb ($F_{2,18}$ = 3.965, $p$ < .05) and Task–Magnitude ($F_{2,18}$ = 31.569, $p$ < .001) interactions and the main effects of Limb ($F_{1,9}$ = 34.849, $p$ < .001) and Task ($F_{1,9}$ = 5.523, $p$ < .05) were significant. The post-hoc test for Task indicated that the generation task had a significantly higher error than the relaxation task at 60% magnitude for both limb types ($p$ < .01). In contrast, the relaxation task showed significantly higher error than the generation task at 20% magnitude for the lower limb ($p$ < .01). For Magnitude, the error of the relaxation task was significantly higher at 20% magnitude than at 40% and 60% magnitudes in the upper limb ($p$ < .01) and higher at 20% and 40% magnitudes than at 60% magnitude in the lower limb ($p$ < .01). Regarding Limb, the upper limb showed significantly higher values than the lower limb for all magnitudes in the generation task (20%: $p$ < .05, 40% and 60%: $p$ < .01) and for 20% magnitude in the relaxation task ($p$ < .05).

Overall, when comparing tasks, the constant and absolute errors of the relaxation task were both higher than those of the generation task at 20% magnitude for both limb types. In contrast, at 60% magnitude, the absolute and variable errors of the generation task were both higher than those of the relaxation task for both limb types. When comparing magnitudes, no significant differences were observed among the 20%, 40%, and 60% magnitudes for both limb types in the generation task. In the relaxation task, the errors were higher at 20% magnitude than at 60% magnitude for both limb types. Comparing the limbs, the variable error of the upper limb was higher than that of the lower limb in the generation task.

***Quickness***

*Time*

Figure 4 shows the mean and the standard deviation of the reaction and adjustment time for all the participants. The reaction, adjustment, and total adjustment times had no interaction. The main effects of Task ($F_{1,9}$ = 6.357, $p$ < .05) and Magnitude ($F_{2,18}$ = 12.951, $p$ < .001) were significant regarding the reaction time. The generation task was significantly longer than the relaxation task ($p$ < .05). The tasks at 20% and 40% magnitudes were significantly longer than those at 60% magnitude (20%: $p$ < .05, 40%: $p$ < .01). The main effects of Task ($F_{1,9}$ = 16.119, $p$ < .01) and Magnitude ($F_{2,18}$ = 128.490, $p$ < .001) were significant regarding the adjustment time. The generation task was significantly longer than the relaxation task ($p$ < .01) and became increasingly longer the magnitudes from 20% through 40% to 60% ($p < .001$). Meanwhile, the main effects of Task ($F_{1,9} = 13.245$, $p < .01$) and Magnitude ($F_{2,18} = 79.467$, $p < .001$) were significant regarding the total adjustment time. The generation task was significantly longer than the relaxation task ($p < .01$). The time increased with the magnitudes from 20% through 40% to 60% (40% and 60%: $p < .05$, other pairs: $p < .001$).




*Note: *: Significant difference between the tasks, *: p < .05, **: p < .01. †: Significant difference among the magnitudes of force control, ††: p < .01, †††: p < .001. ‡: Significant difference between the limbs, ‡: p < .05, ‡‡: p < .01, ‡‡‡: p < .001.*

Figure 5. Mean values and standard deviations of the (A) peak rate of force development and the (B) time to peak rate of force development.

Overall, the reaction and adjustment times of the generation task were both longer than those of the relaxation task in both limb types for all magnitudes. The reaction time tended to become shorter, while the adjustment time tended to become longer as the magnitude increased in both tasks and limb types.

*Peak rate of force development*
Figure 5 depicts the mean and the standard deviation of the peak RFD and the time to peak RFD for all participants for the two tasks. The Task–Limb ($F_{1, 9} = 18.003$, $p < .01$) and Limb-Magnitude ($F_{2, 18} = 35.644$, $p < .001$) interactions and the main effects of Task ($F_{1, 9} = 27.654$, $p < .01$), Limb ($F_{1, 9} = 31.635$, $p < .001$), and Magnitude ($F_{2, 18} = 58.518$, $p < .001$) were regarding the peak RFD. The post-hoc test for the Task–Limb indicated that the lower limb had a significantly higher peak RFD than the upper limb in both tasks (Generation task: $p < .001$, Relaxation task: $p < .01$). For both limb types, the relaxation task had a significantly higher peak RFD than the generation task (upper limb: $p < .05$; lower limb: $p < .01$). For the Limb-Magnitude, the lower limb had a significantly higher peak RFD than the upper limb at all magnitudes (20%: $p < .01$, 40% and 60%: $p < .001$). In both limbs, the peak RFD increased with magnitudes from 20% through 40% to 60% magnitudes (upper limb: $p < .01$, 20% and 40% in the lower limb: $p < .01$, and other pairs in lower limb: $p < .001$).

Regarding the time to peak RFD, the Task–Magnitude interaction ($F_{2, 18} = 13.590$, $p < .001$), and the main effects of Task ($F_{1, 9} = 21.255$, $p < .01$) and Magnitude ($F_{2, 18} = 21.812$, $p < .001$) were significant. The post-hoc test for Task–Magnitude indicated that the generation task required a significantly longer time to peak RFD than the relaxation task at all magnitudes ($p < .05$). For Magnitude, the time to peak RFD of the generation task was significantly longer at 40% and 60% magnitudes than at 20% magnitude ($p < .01$).

Overall, for the generation task, the peak RFD increased as the magnitude increased, and the time to peak RFD increased in both limb types. In contrast, for the relaxation task, although the peak RFD increased, the time to peak RFD remained constant in both limb types as the magnitude increased. On comparing the tasks, the peak RFD was observed to be higher for the relaxation task than the generation task. However, the time to peak RFD was longer for the generation task than for the relaxation task. When comparing the limbs, the lower limb showed a higher peak RFD than the upper limb at all magnitudes in both tasks.

## DISCUSSION

In the comprehensive discussion on the characteristics of force generation and relaxation, we particularly focused on the difference between the upper and lower limbs.

### *Accuracy of force control*
When comparing the limbs, although no difference was observed between the limbs regarding the constant error in the force generation task, the upper limb showed a significantly higher variable error than the lower limb (Figure 3). This result indicates that the accuracy of force generation is similar between the limbs, irrespective of magnitudes. However, the limb type affected the variability (reproducibility) of force generation, and constant control of force generation was more challenging to maintain in the upper limbs than in the lower limbs. These results suggest that the adjustment in the lower limb is more suited toward stably controlling the force than the adjustment in the upper limb. The lower limb plays an important role in daily life, such as walking and standing. Conversely, we performed delicate or fine control by utilizing the upper limb. Owing to the high operability and high flexibility of the upper limb that allows for fine adjustment, the variability of the upper limb was assumed to be relatively high in force generation.

In the force relaxation task, in the downward direction, the upper limb showed constant errors higher than those of the lower limb at 20% and 40% magnitudes and a variable error higher than that in the lower limb at 20% magnitude (Figure 3). These results indicate that the force relaxation in the upper limb tended to significantly exceed the target force level in the downward direction than in the lower limb when controlling low magnitude. When comparing the magnitudes, the relaxation task at 20% and 40% magnitudes showed higher errors than at 60% magnitude for both limb types. These results are consistent with the findings of previous force control studies confirming that demonstrate controlling force relaxation at low magnitude is tremendously difficult rather than at high magnitudes (Ohtaka and Fujiwara, 2016, 2019). Moreover, at 20% magnitude, the upper limb showed a higher variable error than the lower limb. In particular, at low magnitudes, force relaxation was more challenging to control with high reproducibility accurately in the upper limb than in the lower limb.

Comparing force generation and relaxation, the force relaxation task at 20% magnitude showed higher constant and absolute errors than the force generation task for both limb types. These results agree with those of the previous studies on force control confirming the higher difficulty in controlling isometric force relaxation than generation (Harbst et al., 2000; Masumoto and Inui, 2010; Moritou et al., 2009; Ohtaka and Fujiwara, 2016, 2019). According to studies on precise multi-finger isometric ramp force control, the errors for matching the line were also amplified, and a higher variability was observed for force relaxation (ramp-down phase) than for force generation (ramp-up phase) (Li, 2013; Shim et al., 2005). These findings suggest a possible mechanism for relaxation, where an increased dorsolateral prefrontal cortex activation could impose general inhibition to the motor system, resulting in a decreased primary motor cortex (M1) excitability with proportionally decreased intracortical inhibitory and facilitatory activities (Li, 2013). Moreover, increased anterior cingulate cortex deactivation is associated with decreased error detection ability (Garavan et al., 2002). Another study reported that the firing rates of motor units (MUs) at the same force levels were lower during muscle relaxation than muscle contraction for slow isometric control of the elbow flexor (Denier van der Gon et al., 1985). Different MU firing rates at the same force level between generation and relaxation imply that the elbow flexor cannot perform a similar control with identical subjective sensorimotor parameters, which might explain force relaxation difficulty.

In summary, the above-mentioned studies indicated that muscle relaxation is not easy to control and can hinder the adequate control of other body parts. The results of the present study confirmed that force relaxation is more challenging to control precisely than force generation. We elucidated these phenomena as the overall characteristics of the upper and lower limbs, particularly when controlling force at low magnitudes.

***Quickness of force control***

No differences were observed in the reaction and adjustment times between the upper and lower limbs (Figure 4). In this study, we set the grading task using the relative magnitudes against MVF for each limb, which is assumed as one of the reasons for the lack of difference between the limbs. The absolute force level when control was higher in the lower limb than in the upper limb. Moreover, the adjustment time is known to depend on the force control magnitude (Ohtaka and Fujiwara, 2016, 2019). Consequently, further studies are required to clarify the quickness between the upper and the lower limbs by focusing on this issue. The characteristics of using the grading task of absolute magnitudes should also be considered because different parameters are required to compare tasks among relative magnitudes.

When comparing force generation and relaxation reaction times, the relaxation task presented a significantly shorter reaction time than the generation task in both limb types, that were consistent with the previous studies using the grading task reported that reaction time was shorter for force relaxation than for force generation (Buccolieri et al., 2003; Ohtaka and Fujiwara, 2016). This indicated that the force levels at the beginning of the control that is called the function of preliminary muscular tension (Clarke, 1968; Schmidt and Stull, 1970), irrespective of maintaining force before adjustment, affected the quickness to begin adjusting the force. Moreover, the reaction time was shorter at high magnitudes than at low magnitudes for both force generation and relaxation. Regarding force generation, the reaction time tended to be shorter, with higher the magnitude of force control (Haagh et al., 1987; Ohtaka and Fujiwara, 2019). Concerning the force relaxation, Ohtaka and Fujiwara (2019) clarified that the reaction time tended to be negatively related to the magnitude of force control, whereas Yotani et al. (2014) showed that reaction time became longer as the magnitude increased. The difference between these studies is that in the former, the task comprised force grading to a specified target level, whereas in the latter, the task comprised complete relaxation. Therefore, our findings were consistent with those of previous studies on force grading, suggesting that, as an overall characteristic of the upper and lower limbs, the reaction time was affected by the direction (generation or relaxation) and magnitudes of force control.

For quickness to adjustment, the findings of this study on the overall characteristics of the upper and lower limbs (Figure 4) were consistent with those in previous studies for both force generation (Gottlieb et al., 1989; Ohtaka and Fujiwara, 2016, 2019; Ono et al., 1997) and relaxation (Ohtaka and Fujiwara, 2016, 2019). The adjustment time was affected by the direction (generation or relaxation) and magnitudes of force control; the time was long during force generation and increased with the magnitude of force control. When considering the relation of the peak RFD and the time to peak RFD, as for force relaxation, the peak RFD was greater and time to peak RFD was shorter in both limb types, although peak RFD of lower limb was greater than those of upper limb. In contrast, in force generation, the peak RFD was lower and the time to peak RFD was longer in both limb types (Figure 5). Moreover, focusing on the magnitudes of force control, for force generation, the peak RFD occurred at the end of the adjustment at every magnitude, whereas for force relaxation at all magnitudes, the peak RFD occurred at the beginning of the adjustment and was higher than that of force generation. These characteristics are consistent with those reported in previous studies (Ohtaka and Fujiwara, 2016, 2019). In particular, owing to the higher peak RFD for the lower limb than the upper limb, a more marked tendency of the characteristics of the lower limb is obtained due to that the absolute force level when control was higher in the lower limb than in the upper limb. The results indicate the difficulty of performing force relaxation, which involves that the higher peak RFD exists at once after beginning the adjustment in both limb types.

## CONCLUSIONS

In this study, the force control characteristics were clearly depicted by systematically comparing the same magnitudes between the limbs and tasks. In a future study, we intend to consider the effect of start or target level differences on the force generation and relaxation characteristics. In this study, we used the grading motor tasks to control a specific target level. The neural mechanisms for muscle relaxation present in the active process similar to those of muscle contraction were revealed using fMR. These mechanisms are related to M1 and supplementary motor area (SMA) activation and do not promote contraction cessation (Toma et al., 1999). Moreover, motor-related cortical potentials (MRCPs) were observed in the region of the SMA (Terada et al., 1995; 1999) and M1 (Rothwell et al., 1998; Pope et al., 2007) preceding muscle relaxation. As previously described, the neural mechanisms for relaxation have been mostly studied for complete relaxation (Kato et al., 2019). Although Vogt et al. (2018) investigated the MRCPs in M1 during the sequential relaxation for magnitudes decreasing from 40% to 20%, the mechanism for force grading is still unclear. Hence, more information regarding the mechanism for force relaxation must be obtained, for instance, the difference between relaxing completely and relaxing to a specific target level.

In conclusion, our study clarified that unexpected differences exist in the accuracy of force control between the upper and the lower limbs; however, there were no unexpected differences in quickness. Moreover, accurately decreasing force in the upper limb is more challenging than in the lower limb under low-magnitude conditions.

***Verification of the proposed hypothesis***

*Accuracy*

When comparing the upper and lower limbs, the latter showed a variable error higher than that of the former in the generation task at all magnitudes. The upper limb showed a constant error negatively higher than that of the lower limb in the relaxation task at low magnitudes.

*Quickness*

When comparing the upper and lower limbs, the reaction time for the upper limb was shorter than that for the lower limb; however, the adjustment time was constant between both limb types at all magnitudes for both force generation and relaxation. The peak RFD of the lower limb was higher than that of the upper limb at all magnitudes for both force generation and relaxation.

## AUTHOR CONTRIBUTIONS

Conceptualization and methodology, C.O. and M.F. Investigation and writing-original draft preparation, C.O. Writing-Review and editing, and supervision, M.F.

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## DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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