

Relationship between the subjective and objective parameters for accurate force generation and relaxation

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Abstract

Relationships between subjective and objective parameters for accurate force generation and relaxation were examined using graded isometric force control tasks with the upper and lower limbs. Participants were instructed to accurately control their force under the simple reaction condition as follows: generation task, wherein they increased from 0% to 20%, 40%, or 60% maximum voluntary force (MVF) and relaxation task, in which they decreased from 60% to 40%, 20%, or 0% MVF. The produced force was recorded, and the relative values were calculated based on each participant's MVF. The log-log relationship and the exponent of the power functions between the subjective and objective parameters were evaluated. As a result, significant positive correlations and log-log relations were observed between subjective and objective magnitudes in both tasks and limbs. Furthermore, the exponent of power function in relaxation task was greater than the generation task. These results indicated that functional relationships existed between subjective and objective parameters, and the degree of difference was greater in force relaxation than in generation.

Keywords: voluntary force control, subjective, objective, power function, relaxation

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Introduction

All voluntary movements comprise changing one's objective amplitudes and velocities based on the psychological scale as a subjective sensorimotor parameter. To move as intended with smoothness and accuracy, particularly in situations requiring fine motor control, well-coordinated control of both force generation (muscle contraction) and relaxation (muscle relaxation) is essential. Grading ability refers to the accuracy in precisely controlling one's movements according to the purpose and situation. It is vital to minimize the differences between subjective sensorimotor parameters (subjectivity) and results of performance (objectivity) to accurately perform movements as intended.

A previous study has evaluated the functional relationships among the subjective and objective parameters using various external stimuli (e.g., loudness, brightness, and temperature) ²⁰⁾. A functional relationship means that, in two parameters that depend on each other, one parameter is fixed and the other one depends on the former. The author explored the exponents of power functions using methods of magnitude estimation and magnitude production. In the methods of magnitude estimation, for example, in an experiment on loudness, the experimenter presents a "standard" sound of moderate intensity and tells the participants to consider its loudness to have the value 10. The experimenter then presents, in an irregular order, a series of intensities above and below the standard and instructs the participants to assign a number to each stimulus, proportional to the

apparent loudness. The participants are asked to judge each stimulus by using numbers as they hear it ²⁰⁾. Using this method, participants estimate the intensity in terms of numerals. During magnitude production, the participants are told to judge each stimulus as they recognize it by grading it according to a consecutive parameter. In this method, the observers estimate the intensity by adjusting with a switch or dial. In the study mentioned above, functional relationships (power function) between subjective and objective parameters were found for each type of external stimulus, although the degree of the difference between the subjective and objective parameters varied according to the type of external stimulus.

Moreover, regarding the subjectivity of sensorimotor functions for voluntary movements, functional relationships were found between the subjective parameters and the physical magnitudes of the mechanical forces utilized in the tasks of grading hand grip ¹⁹⁾ and jumping movement ¹⁶⁾. These studies analyzed the degree of the differences between the subjective and objective parameters, comparing the magnitude of the exponents of the power function. Other studies reported a relationship between subjectivity and objectivity by analyzing only the results of performance focusing on dynamic discrete ^{1), 5), 7), 13), 22), 23)} or rhythmic ^{3), 6)} movements.

The aforementioned studies were focused on the phase of force generation. However, to control voluntary movements as intended, accurately controlling force relaxation is as important as accurately controlling force generation. In terms of kinetics, force relaxation is a contrasting

phenomenon to force generation. Interestingly, regarding the neural mechanisms underlying muscle relaxation, neuroimaging studies using functional magnetic resonance imaging (fMRI) have showed that muscle relaxation occurs as a consequence of excitation of corticospinal projection neurons or intracortical inhibitory interneurons, rather than a passive cessation of muscle contraction ²¹⁾. In addition, the underlying neural mechanisms in controlled force contraction and relaxation are significantly different ¹⁸⁾.

To the best of our knowledge, however, no studies have examined the relationship between the subjective and objective parameters during force relaxation. Based on these research backgrounds, the present study investigated the power function between subjective and objective parameters during force generation and relaxation. We calculated the difference between the target force level (subjectivity) and the measured force value (objectivity), utilizing the grading tasks to adjust several different target force levels. We hypothesized that the gap between the subjective and objective values was greater in force relaxation than in force generation since it has been reported that force relaxation is more difficult to control (with respect to accuracy) than force generation; all these studies focused on the accuracy of grading against several target force levels ^{4), 10), 12), 14), 15)} or controlling the force by following a preset ramp template ^{9), 17)}.

Methods

The apparatus, experimental tasks, and procedure in this study were the same as in previous studies ^{14), 15)}, because further analysis was intended to be performed on the data regarding the upper ¹⁴⁾ and lower limbs ¹⁵⁾.

Participants

Fifteen healthy right-handed and right-footed women (mean age = 20.2 years, SD = 1.1) participated in the present study. The procedures were approved by the academic ethics committee of the university where this study was conducted. Prior to the experiment, all participants were fully informed about the purpose of the study and its procedures, and written informed consent was obtained.

Apparatus

The output force of the participants was measured using a force measuring device (Takei Scientific Instrument Co., Ltd., Japan). For assessing the upper limb, the participants were seated in the force measuring device, with the right arm fixed to an arm holder that was connected to a force plate with the elbow joint fixed at 90° of flexion (180° is full elbow extension); this elbow angle was selected based on a previous research ¹⁴⁾. The left arm was held on the left side of the body. Both legs were straightened and positioned on the cylindrical pole to exclude the effect of the strength exerted by the lower limbs. For assessing the lower limb, 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 ¹⁵⁾. 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 (VJ22LL-D, NEC Co., Ltd., Japan). The target force level line, along with three light-emitting diode (LED) lights controlled by the time-programmer (Takei Scientific Instrument Co., Ltd., Japan), was placed at a distance of approximately 1.5 m from the participants' eyes to act as a visual stimulus.

Experimental tasks

The participants were instructed to produce an isometric force to match the target force level as quickly and accurately as possible. They produced an elbow flexion force by using their right arm in case of the upper limb, and knee extension force by using their right leg in case of the lower limb. For each limb, the participants were required to perform the motor tasks described below.

Participants were asked to perform two discrete tasks: 1) a generation task: to increase their applied force and 2) a relaxation task: to decrease their applied force. Given the following target force levels: 0%, 20%, 40%, and 60% maximum voluntary force (MVF), they were asked to perform force control repetitions of three magnitudes, as shown in Table 1.

1) Generation task

At 20% magnitude: to increase their force from 0% to 20% MVF

At 40% magnitude: to increase their force from 0% to 40% MVF

At 60% magnitude: to increase their force from 0% to 60% MVF

2) Relaxation task

At 20% magnitude: to decrease their force from 60% to 40% MVF

At 40% magnitude: to decrease their force from 60% to 20% MVF

At 60% magnitude: to decrease their force from 60% to 0% MVF.

Table 1 shows the relationship between the task and magnitude. In the generation task, magnitudes mean each target force level. In the relaxation task, magnitudes are defined as the subtraction each target force level from 60% MVF.

Table 1. The relationship of tasks and magnitudes, and the abbreviations used

Task	Force level (%MVF)		Magnitude (%)
	Start level	Target level	
Generation	0	20	20
		40	40
		60	60
Relaxation	60	40	20
		20	40
		0	60

The participants performed the tasks under the simple reaction condition. Each trial began with a 500-ms visual warning signal, and the subsequent go signal was presented for 500 ms. The foreperiod (i.e., the interval between the warning signal and the go

signal) was 2 s. The participants were informed of the magnitude before the beginning of each trial along with the visual warning signal and instructed to control their force in response to the go signal accurately and as quickly as possible. For the relaxation task, the participants were instructed to maintain the force level of 60% MVF prior to the warning signal while looking at the line of the 60% MVF. After maintaining the 60% MVF for 1 s, the participants were informed to turn their eyes toward the warning LED, the warning LED was lit, and the subsequent 2-s go signal was presented.

To measure and contrast the two tasks, the participants were instructed to adjust the target force level as quickly as possible under both tasks. As soon as they achieved the target force level, they were instructed to relax their force for the generation task. In the relaxation task, by contrast to the generation task, the participants adjusted the target force level in an instant, subsequently increasing their voluntary force level.

Procedure

The participants were initially instructed to produce an isometric force of maximum effort for 1 s, three separate times. The maximum force value of the three trials was set as each participant's MVF. All the participants practiced controlling their force by looking at the line of the target force level before the data collection for each task. Visual feedback of the force level produced was provided during the practice trials. Thereafter, one practice session was conducted. The participants were instructed to perform practice trials with visual feedback by looking at the line of the target force level so that

they could learn to control the target force levels rapidly¹⁰⁾. The participants were allowed to repeat the practice trial ten times for each magnitude before data collection for each task.

Participants then began the data collection without looking at the line of the target force level or using any visual feedback. The participants received feedback regarding their results after each session by looking at the summary of their force waves in one session. They performed three sessions of ten trials for each of the three magnitudes in a random order. Data collection was conducted with a 1-min rest interval between each session and with a 5-min rest interval between each task. The order of the tasks was counterbalanced, with 7/15 of participants performing the force generation prior to the force reduction task; therefore, 8/15 of the participants performed the relaxation task first. With regard to the magnitude of force, we used a blocked randomized design, with the ten trials at a given level performed as a block, with the order of the 'force level' blocks randomized across participants. The participants were instructed to perform the tasks as accurately and quickly as possible. After completion of the two tasks, participants again produced three MVFs to exclude effects of fatigue. They conducted the tasks of the upper limb and lower limb on different dates.

Data analysis

The produced force was recorded. All recordings were digitized at 1000 Hz using a Biopac MP150 data acquisition system (Biopac Systems, USA). Data of Trials that exceeded $\pm 2SD$ of the reaction

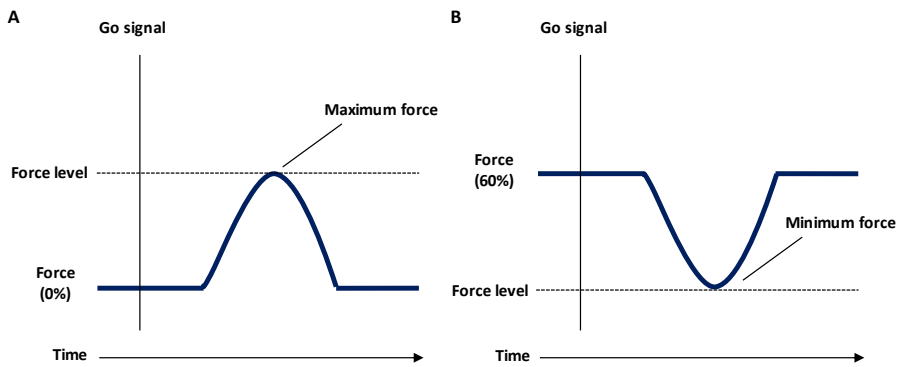


Figure 1. Definition and measurement of force for (A) generation task and (B) relaxation task

time were excluded and the number of trials among all participants were unified; therefore, eight trials from each magnitude were chosen. The force data were passed through a digital filter with a 100-Hz low-pass cut off, producing a mean value for further analysis; this value was selected based on previous research ^{14), 15)}.

The force level (% MVF) was defined as the relative value of the maximum force (generation task) or minimum force (relaxation task) of each participant's MVF (Figure 1). In the generation task, the force level equaled the objective magnitude (% MVF). In the relaxation task, the objective magnitude (% MVF) was defined as the value that was subtract the force level from 60% MVF.

The exponent of the power functions was calculated between the subjective and objective magnitudes in each task under each limb based on previous research ¹⁶⁾, as described below.

Objective magnitude was set on the axis of abscissa, and the subjective magnitude was set on the axis of ordinate. From these, the log-log relationship between the subjective and the objective for both tasks and limbs were graphed.

The power exponent was defined as the value of inclination on the regression line in the log-log relation graph. In the cases wherein the log-log relationship is significant, the inclination of the line shows the exponent, which indicates a linear relationship between the subjective and objective magnitudes; for example, when the objective magnitude increases by a factor of 2, the subjective magnitude also increases by the factor of 2.

Statistical analysis

Prior to applying the evaluating differences between subjective and objective magnitudes, we tested for normal distribution using the Kolmogorov-Smirnov test. In all cases, a normal distribution was maintained; therefore, the Pearson correlation coefficient was calculated between each subjective and objective magnitude in each task under each limb. Differences between pre-task and post-task maximum voluntary forces were evaluated using one-way repeated measures analysis of variance (ANOVA) conducted for each limb. The level of statistical significance was set at $p < 0.05$.

The data were analyzed using SPSS for Windows (SPSS Inc., USA).

Results

The maximum voluntary forces were 153 ± 12 N (pre-task) and 166 ± 30 N (post-task) for the upper limbs and 945 ± 318 N (pre-task) and 1157 ± 354 N (post-task) for the lower limbs. In the upper limbs, there were no differences between the pre and post-tasks. In the lower limbs, however, the differences were significantly greater for the post-tasks than the pre-tasks, which were influenced by a main effect ($F_{1, 14} = 10.459$, $p < 0.05$). These results showed no effects of fatigue on these tasks.

Figure 2 shows the log-log relation between the subjective and the objective magnitudes for both tasks in both limbs. Both in the upper limb and the lower limb, the correlation coefficient and the exponent of the power functions were calculated between each subjective magnitude and objective magnitude in each task.

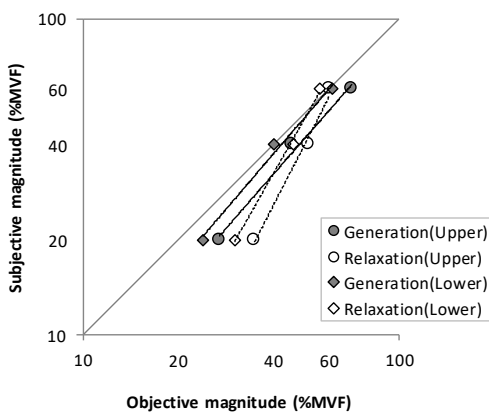


Figure 2. The log-log relation between the subjective magnitude and the objective magnitude for both tasks and limbs

In the upper limb, there were significant positive correlations between the subjective and objective magnitudes in both tasks, and straight lines in log-log relations (generation task: $r = 0.844$, the exponent = 1.093; relaxation task: $r = 0.814$, the exponent = 1.831). In the lower limb, significant positive correlations were also found between the subjective and the objective magnitudes in both tasks, and straight lines in log-log relations (generation task: $r = 0.924$, the exponent = 1.157; relaxation task: $r = 0.855$, the exponent = 1.685) were shown. In both limbs, the results of both tasks approximated the power functions between subjective and the objective magnitudes.

Furthermore, as for the relation between the upper and lower limbs, Table 2 shows the results of the Pearson correlation coefficient and exponent of the power functions in both tasks of both limbs.

Table 2. The results of Pearson product-moment correlation coefficient and the exponent of the power functions in both tasks of both limbs

Task	Limb	r	Power exponent
Generation	Upper	0.844	1.093
	Lower	0.924	1.157
Relaxation	Upper	0.814	1.831
	Lower	0.855	1.685

Discussion

In the upper limb, we observed significant positive correlations between subjective and the objective magnitudes in both tasks and straight lines in log-log relations (Figure 2 and Table 2). This indicates functional relationships between

subjective and the objective magnitudes in both tasks.

Previous studies have investigated the characteristics of subjective and objective magnitudes in the context of various kinds of external stimuli²⁰⁾ and grading tasks for handgrip¹⁹⁾ and standing broad jump¹⁶⁾. The results of these studies approximated power functions by utilizing the motor tasks without visual feedback. In the present study, although participants practiced trials with visual feedback by looking at the line of the force level and target force level after they finish adjusting their force, they performed official trials without looking at the line of the target force level or using any visual feedback. This suggests that the results of the present study are consistent with previous findings^{16), 19), 20)}, and that a constant log-log relationship between subjective and objective parameters exists in force control for generation and relaxation.

Importantly, the functional relationship of force control to force relaxation was found to be the same as that of force generation, from the point of view of existing functional relationships.

Regarding the exponent of the power functions, the exponent in the generation task was approximately 1.1 (Table 2). By contrast, the exponent in the relaxation task was approximately 1.7 (Table 2). Stevens and Mack¹⁹⁾ investigated the functional relationships between subjective and physical magnitudes of mechanical forces by utilizing grading task for handgrip. They demonstrated that the apparent magnitude of handgrip grew exponentially, and that the exponent of the function was from 1.7 to 1.9. Moreover,

Sadamoto and Ohtsuki¹⁶⁾ also showed similar relationships by using grading tasks for the Sargent and standing broad jumps under the eyes open and closed conditions. Apart from the standing broad jump task with eyes open, the exponents of these tasks were over 1.0: the Sargent jump with eyes open was 2.5; the Sargent jump with eyes closed was 3.1; and the standing broad jump with eyes closed was 1.6.

The results of the relaxation task in this study are similar to these previous findings, in that the exponent of the function was over 1.0, near 1.7 and 1.8. This means that the relationship between the subjective and objective parameters is not uniform, although the intention was to maintain the same magnitude, the objective parameter for the higher subjective parameter was smaller than that for the lower subjective parameter. To match the subjective and objective parameters, it is very important to perceive the magnitude of efforts accurately by oneself. This is known as “sense of effort”, subjective effort depends on the sensory of perceived in heaviness¹¹⁾. Thus, in case of a higher objective magnitude, the subjective magnitude for efforts does not increase; conversely, in the case of a lower objective magnitude, it is necessary to control the magnitude more modestly than efforts.

The exponents of the relaxation task were greater than those of the generation task (Table 2). This result was consistent with the results from previous studies that showed the difficulty in force relaxation by evaluating the error of performance^{10), 12), 14), 15)} and suggests that the magnitude of difference between the subjective and objective parameters is greater in force relaxation than in force generation.

Specifically, the present study provides new important evidence of the difficulty in force relaxation from the point of view of the functional relationships. One reason for the difficulty of accurate control of force relaxation is supported by Henneman's size principle (see review by Bawa et al. ²⁾), that describes differences between force generation and relaxation in motor unit recruitment and derecruitment. According to this principle, for force generation, smaller motor units are recruited before larger ones; conversely, motor units are derecruited in reverse order, from the largest to the smallest motor units ⁸⁾. This reverse size order would cause lower accuracy for force relaxation than generation, because the early derecruitment of large motor units would not allow accurate adjustments, though it is rapid. As mentioned above, although there have been some previous reports describing the accuracy of grading in force control ^{10), 12), 14), 15)}, this study is the first report to clarify the difficulty in force relaxation focusing on functional relationships.

In the lower limb, there were significant positive correlations between subjective and objective magnitudes in both tasks, and straight lines in log-log relations (Figure 2). This suggests functional relationships between subjective and objective magnitudes in both tasks. In addition, focusing on the inclination of the log-log graph, the inclination of the relaxation task was sharp rather than that of the generation task in both upper and lower limbs; that is, the exponent of the function was greater in the relaxation task than in the generation task. Therefore, the relation in the lower limb was found to be the same as that in the upper limb; the

magnitude of difference between the subjective and objective parameters was greater in force relaxation. Moreover, the degree of the difference between the subjective and objective magnitudes was greater in force relaxation than in force generation, especially with the control of lower magnitude. In the case of force relaxation with a lower magnitude, it would be necessary to adjust the magnitude more than previously thought.

When comparing the upper and lower limbs, the horizontal value that represented the objective magnitude was larger for the upper limb than for the lower limb at all magnitudes (Figure 2). In other words, adjustments in the upper limb results in an underestimation of the output compared to adjustments in the lower limb, and the objective magnitude overshoots each target magnitude. These results suggest that the degree of the difference between subjective and objective magnitude was greater in the upper limb than in the lower limb.

A few methodological limitations of the present study are: 1) We focused only on the force data not on the data analyzing electromyography; 2) we compared the motor tasks at the same magnitude of force, but starting or targeting force level was different; 3) we summarized whole data without considering the learning effectiveness from the early to final stages. We should consider further studies to overcome these limitations.

In conclusion, as the control force increases, the sensory effort to control the force for force generation also increases in the upper and lower limbs. On the other hand, the relationship between the subjective and objective parameters was not

uniform in force relaxation. The findings of the present study indicate that the degrees of the differences between the subjective and objective parameters are greater in force relaxation than in force generation and are greater in the upper limb than in the lower limb. These results show the difficulty of accurate control of force relaxation from the point of view of functional relationships. Accordingly, controlling the degree of the psychological scale on the magnitude of generation or relaxation would lead to skillful performance.

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