Ability of Adjusting Grip Strength From Childhood to Adulthood

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Purpose: This cross-sectional study aimed to investigate the ability to adjust grip strength by comparing the characteristics of force generation and relaxation from childhood to adulthood. Method: This study included 225 participants aged 6, 11, 17, and 19–23 years (adults) who performed isometric hand-grip force as follows: maximum, half generation, and half relaxation. The force was recorded, and relative values and errors were calculated for half tasks. Results: The maximum task values increased with age, but there was no significant age difference between 17-year-olds and adults. The difference between sexes was significant; males were stronger than females in both 17-year-olds and adults. Both sexes in all age groups had greater errors in half relaxation than in half generation tasks. Females had negatively greater constant error than males in half tasks. The errors of 6-year-olds were greater than the other age groups in half tasks. Conclusion: There is a developmental trend for producing maximal strength that is similar across sexes until adolescence when males are stronger and females plateau. The ability of force relaxation was more difficult to accurately control than force generation for all age groups and was adult-like by middle childhood.

Keywords: motor control, force control

Evaluating human movement, particularly when assessing physical strength, often requires analyzing the results of the strength and speed performance when exerting one’s power with maximum effort. Meanwhile, in daily life, several situations require adjusting one’s force or movement within the level of maximum effort in response to changing conditions or other people. Thus, it is meaningful to estimate how skillful an individual is in accurately and smoothly controlling movement. To smoothly move as intended, good control of both force generation (muscle contraction) and relaxation (muscle relaxation) is crucial. Decreasing force as intended, that is, to relax well when performing unfamiliar movements or when performing movements that require various skills, such as sports or playing a musical instrument, can be especially difficult (Furuya et al., 2009; Sakurai & Ohtsuki, 2000). The ability to relax by deliberately decreasing force below maximum effort is also essential. Although the term “relaxation” may imply a
complete force release, in this study, both relaxation and decreasing of force were defined as a declining control of force to a specific level.

Previous studies have compared the difference in accuracy and quickness between force generation and relaxation utilizing an isometric force control task, movement in the fingers or hand (Harbst et al., 2000; Masumoto & Inui, 2010), and the upper (Ohtaka & Fujiwara, 2016) and lower limbs (Ohtaka & Fujiwara, 2019). These studies have clarified that force relaxation demonstrated higher inaccuracy and variability than force generation by evaluating the error between the actual and target force levels.

As for the characteristics of force control, the aforementioned studies have focused predominantly on adults, and only a few studies have examined individuals in childhood (Harbst et al., 2000). Although the development of physical strength from childhood to adulthood has been investigated in many previous studies (Bohannon et al., 2017; Budziareck et al., 2008; Cohen et al., 2010), studies on the development of skills in accurately controlling one’s movements are limited, especially regarding force relaxation. As studies on early childhood motor performance have not searched for any relationship between physical strength, such as motor performance by maximum effort, and motor control ability, this confirmation of the developmental process of the relationship is desirable, including that in other age groups.

Throughout childhood, the nervous system and the ability to control one’s movements improve remarkably. In particular, the nervous system develops rapidly around the age of 10 years. Age-related fractional anisotropy, in the white matter of the brain, increases during childhood and plateaus at approximately 10 years old (Budday & Kuhl, 2020; Dennis & Thompson, 2013). In view of this, the “skill of accurately controlling one’s movements” may be acquired at this time. In addition, acquiring and experiencing various movements will heavily influence the preference or attitude of human movements in later life.

Accordingly, Ohtaka et al. (2019) investigated the characteristics of force control using the grip strength force control task for a target level of 50% of the maximum strength in 6-year-old boys and girls. They observed that force relaxation was significantly more difficult to accurately control than force generation in young children. Furthermore, the mechanism of force control development and acquisition with age remains unclear. Thus, it is essential to focus on the developmental characteristics during force control based on self-perceived effort using proprioception, including the aspect of force relaxation across ages from childhood to adulthood. Therefore, this study can provide new indications regarding developmental characteristics during force relaxation, with the unique concept of utilizing self-perceived 50% maximum effort in a force control task from childhood to adulthood.

This cross-sectional study aimed to investigate the developmental characteristics of force control ability, focusing on the relationship between force generation and relaxation from childhood to adulthood, including the ability of estimating, based on self-perceived effort. This is performed according to muscle sensation and the evaluation of the accuracy of the actual participant performance relative to the estimate. Based on previous study findings, the following hypotheses were tested: (a) The developmental trend for both sexes will be shown in grip strength with maximum effort (Bohannon et al., 2017; Budziareck et al., 2008;
Cohen et al., 2010), with increased grip strength with age, and with sex differences after adolescence; (b) considering adult characteristics (Harbst et al., 2000; Masumoto & Inui, 2010; Ohtaka & Fujiwara, 2016, 2019), force relaxation will be significantly more difficult to accurately control than force generation in all age groups; (c) given that the skill of accurately controlling one’s movements appears to be acquired at approximately 10 years old (Budday & Kuhl, 2020; Dennis & Thompson, 2013), force control ability, both generation and relaxation, will develop significantly from early childhood to school age, at approximately 10 years old, reporting less accuracy with 6-year-olds; and (d) as there is reportedly no association between motor performance by maximum effort and motor control ability in early childhood (Ohtaka et al., 2016, 2019), the physical strength with maximum effort and the skill of accurately controlling one’s movements will show no relationship in all age groups in this study.

**Methods**

**Participants**

Altogether, 225 participants, comprising 6-year-olds in the final year of kindergarten (mean age = 6.1 ± 0.3 years; male, 24; female, 21), 11-year-olds (mean age = 11.4 ± 0.4 years; male, 25; female, 26), 17-year-olds (mean age = 17.3 ± 0.3 years; male, 29; female, 31), and adults ranging from 19 to 23 years of age (mean age = 19.7 ± 1.0 years; male, 34; female, 35), were included in this study. For 6-year-old participants, data from a previous study (Ohtaka et al., 2019) were included. In the 11-, 17-, and 19–23-year-olds, hand dominance was verified by the criteria of the Edinburgh Handedness Inventory (Oldfield, 1971). The inventory revealed laterality quotients of +100 in all age groups except the 6-year-olds. For 6-year-olds, hand dominance was verified through the use of chopsticks, scissors, and crayons, and those that used all three objects with their right hand were included as participants in our analysis. All procedures were approved by the Academic Ethics Committee of Nara Women’s University, Japan. Prior to study initiation, written informed consent was obtained from all adult participants and the guardians of all the participants aged <19 years. Experiments were conducted in accordance with the Declaration of Helsinki.

**Apparatus**

Participants were asked to stand and grip the handle of the device using their dominant hand with the elbow flexed at 90° (Figure 1). The width of the handle was set with the proximal interphalangeal joint of the index finger at 90°. The output force of participants was measured using a force-measuring device (T.K.K.5710b, Takei Inc.).

**Procedures**

Participants were instructed to produce an isometric hand grip force to perform the following three motor tasks: maximum task, wherein the grip was performed with
maximum effort; half generation task, wherein the control grip strength was increased to the target level of 50% of the maximum task with self-perceived effort; and half relaxation task, wherein the control grip strength started at maximum effort and decreased to the target level of 50% of the maximum task. Hereafter, the half generation and half relaxation tasks are collectively referred to as “half tasks.”

Participants initially performed all tasks, the maximum task, half generation task, and half relaxation task, in that order with two repetitions for each task. As for half tasks, participants were instructed to adjust their force to what they considered to be “half” the force quickly and maintain that force as constant as possible for 2 s. Subsequently, they were instructed to relax their force. For the 6-year-olds, the examiner held a sponge and showed how force changes its shape to illustrate to them the image of each motor task. We used the expression “half” to describe “50%.”

Data Analysis

Force produced by participants was recorded by a strain gauge built in a force-measuring device. All recordings were digitized at 1000 Hz using a BIOPAC MP150 data acquisition system (BIOPAC Systems). A digital filter with a 100-Hz low-pass cutoff frequency was used to produce a mean value for further analysis;
this value was selected based on a previous study (Ohtaka et al., 2019). The absolute values were defined as the average force during the 500-ms interval after maintaining the force of participants in all tasks. We selected this analysis interval following previous studies that evaluated the accuracy of force control (Ohtaka & Fujiwara, 2019, 2022) to extract a stable interval immediately after the adjustment and minimize the variability of force. As for half tasks, the relative values were calculated as the ratio of the value of the half task to that of the maximum task. To comprehensively evaluate accuracy, two error values were calculated, indicating the direction and magnitude of the error. The difference between the accuracy of the relative values and each target level (50%) was calculated to evaluate constant error, which is the difference between the achieved values of the force level and each target force level, taking direction into account. This measure is mathematically and conceptually related to the measure of relative value by a factor of 1:2 as the target is exactly half of the maximum value. Absolute error is the absolute value of the constant error, the difference between the achieved values of the force level and each target force level without regard to the direction. The data of the two trials were averaged in each task.

**Statistical Analysis**

Prior to applying the evaluating differences among tasks, ages, and sex, we tested for homoscedasticity in the data set. For the maximum task, differences in the measured variables among age and sex were evaluated using a two-way repeated-measures analysis of variance. As for half tasks, differences in the measured variables among tasks (generation and relaxation), age, and sex were evaluated using a three-way repeated-measures analysis of variance. The within-participant factors were the tasks (generation and relaxation), age, and sex. When significant effects were identified, pairwise comparisons were performed using a Bonferroni post hoc test. Regarding the repeated-measures analysis of variance, we tested whether the sphericity assumption was violated. If the assumption was violated, the Greenhouse–Geisser adjustment was used to correct sphericity by altering the degrees of freedom using the correction coefficient epsilon. The Pearson correlation coefficient was calculated between the maximum and the two types of error in half tasks. All analyses were performed using SPSS software for Windows (version 28.0). A p value < .05 was considered significant, and significant tendency was set at .1.

**Results**

**Absolute Value of the Maximum Task Grip**

Figure 2 presents the mean and the SD of the absolute value of the maximum task. The interaction, $F(3, 225) = 46.699$, $p < .001$, main effects of age, $F(3, 225) = 348.039$, $p < .001$, and sex, $F(1, 225) = 77.002$, $p < .001$, were significant. In 17-year-olds and adults, male participants demonstrated significantly greater values than female participants ($p < .001$, respectively). In the male participants, the value increased with age: 6-year-olds < 11-year-olds < 17-year-olds < adults ($p < .001$, respectively). In the female participants, the value increased as follows: 6-year-olds < 11-year-olds < 17-year-olds and adults ($p < .001$, respectively).
Relative Value and Error of Half Tasks

Figure 3 presents the mean and the $SD$ of the relative value of half tasks. The main effects of task, $F(1, 16) = 139.038, p < .001$; age, $F(3, 48) = 6.965, p < .01$; and sex, $F(1, 16) = 6.526, p < .05$, were significant, although no interaction was observed. The value in the half generation task was significantly greater than that in the half

Figure 2 — Means and $SD$s of the absolute value for the maximum task. Significant difference among age groups: $***p < .001$. Significant difference between sexes: $^\dagger p < .05$.

Figure 3 — Means and $SD$s of the relative value for half tasks. Significant difference among the age groups: $(*)p < .1; *p < .05$. Significant difference between tasks: $***p < .001$. Significant difference between sexes: $^\dagger\dagger p < .05$. 

(Ahead of Print)
relaxation task ($p < .001$), and male participants had greater values than female participants ($p < .05$). The 6-year-olds had significantly or trending lower values than the remaining age groups (11- and 17-year-olds: $p < .05$; adults: $p < .1$). Similar results were obtained for constant error. These results are mathematically and conceptually related to the relative value analysis, as mentioned earlier. The main effects of task, $F(1, 16) = 139.051, p < .001$; age $F(3, 48) = 6.966, p < .01$; and sex, $F(1, 16) = 6.525, p < .05$, were significant, although no interaction was observed. The half relaxation task demonstrated significantly greater negative values than the half generation task ($p < .001$). Female participants had significantly greater negative values than male participants ($p < .05$). Six-year-olds demonstrated significantly or trending greater negative values than the remaining age groups (11- and 17-year-olds, $p < .05$; adults, $p < .1$). Given that the relative value and constant error provided the same results, we will refer only to constant error hereafter.

Regarding absolute error (Figure 4), the main effects of task, $F(1, 16) = 114.779, p < .001$, and age, $F(3, 48) = 27.027, p < .001$, were significant. No interaction or main effect was observed in terms of sex. The half relaxation task demonstrated significantly greater values than the half generation task ($p < .001$), and 6-year-olds had significantly greater values than the remaining age groups ($p < .001$).

### Relationship Between Maximum and Half Tasks

The Pearson correlation coefficient, which was calculated as the difference between the value of the maximum task and that of constant and absolute errors in each age and sex group, did not reveal any significant correlation.

### Discussion

The present study examined the developmental characteristics and sex differences in force strength and control ability, specifically the relationship between force

![Figure 4](image-url) — Mean values and $SD$s of the absolute error. Significant difference among the age groups: $*** p < .001$. Significant difference between the tasks: $††† p < .001$. 

(Ahead of Print)
generation and relaxation, in multiple age groups from childhood to adulthood (6-, 11-, 17-, and 19–23-year-olds). The main finding was that producing self-perceived 50% maximum effort was more accurate during force generation than force relaxation for all age groups and plateaued by middle childhood.

**Characteristics of the Grip Strength With Maximum Effort**

The first hypothesis involved motor performance with maximum effort; the developmental trend for both sexes would be shown in grip strength with maximum effort (Bohannon et al., 2017; Budziareck et al., 2008; Cohen et al., 2010). The absolute value of handgrip strength increased with age, yet no significant age difference was observed between 17-year-olds and adults among female participants (Figure 2). The muscle strength level of the 17-year-old boys in this study was slightly below the national average but within an SD. Furthermore, the average values for the age groups in previous studies (Japan Sports Agency, 2021; Ohtaka et al., 2019) were similar to the absolute values of handgrip strength for 6-year-olds, 11-year-olds, and adults ranging from 19 to 23 years of age in the present study. Therefore, the participants of this study had muscle strength levels comparable with the national average for both males and females in all age groups. As an overall trend, consistent with the findings of many previous studies (Bohannon et al., 2017; Budziareck et al., 2008; Cohen et al., 2010; Spiegel et al., 1996), the results of this study suggest that the characteristics of grip strength improve with age in both sexes during development.

Sex differences were observed after the age of 17 years (Figure 2). Specifically, compared with female participants, male participants demonstrated improvement from the ages of 17 years into adulthood. Sex differences in grip strength have been reported for ages around 4–15 years old (Cohen et al., 2010; Molenaar et al., 2010; Ploegmakers et al., 2013; Román et al., 2017). Therefore, the handgrip strength of boys has been demonstrated to be significantly greater than that of girls in early childhood and school age. In addition, the difference between sexes has also been observed after the age of 13 years (Bohannon et al., 2017). Furthermore, the degree of increase in grip strength differs with age between boys and girls (Cohen et al., 2010), and aging changes have been shown to be greater in boys than in girls (Cohen et al., 2010; McQuiddy et al., 2015).

In light of the findings regarding the sex differences in aging changes (Bohannon et al., 2017; Cohen et al., 2010; Japan Sports Agency, 2021; McQuiddy et al., 2015), sex differences were observed from the age of 13 years and above, and aging changes were greater in boys than in girls. Therefore, based on previous study results and those of this study, sex differences may be more pronounced after school age, that is, between 11- and 17-year-olds in this participant group and for this specific task.

**The Characteristics of Force Control, Generation, and Relaxation**

The second hypothesis predicted that force relaxation would be significantly more difficult to accurately control than force generation in all age groups. As for errors
(Figure 4), both tasks were undershooting the target level, and the error was greater in the relaxation task than in the generation task. Furthermore, the errors were greater among 6-year-olds than in the remaining age groups. Previous studies that reported the difficulty of force relaxation in adults and children have compared the phase of generation and relaxation utilizing periodic isometric force control tasks. As a result, the accurate control of target values was more difficult in the relaxation phase than in the generation phase (Harbst et al., 2000; Masumoto & Inui, 2010). The previous studies used periodic isometric control tasks, whereas the present study used discrete isometric force control tasks. Although the motor tasks and analysis phases were different, the common result showed that accurate force relaxation was difficult. In other previous studies using a discrete task similar to the present study, force control characteristics were reported at several force control magnitudes in adults (Ohtaka & Fujiwara, 2016, 2019). Focusing on the difference between generation and relaxation, force relaxation showed lower accuracy than force generation, particularly at smaller magnitudes of force control. Furthermore, in a study utilizing the same task as this study and comparing the difficulty of accurately performing force relaxation in 6-year-old boys and girls, errors of the relaxation task were larger than those of the generation task (Ohtaka et al., 2019). Thus, for comparisons between force generation and relaxation, this study has a novel finding in that it suggests that in all ages, from children to adults, the accuracy of force relaxation may be difficult to control compared with that of force generation based on self-perceived effort rather than a visually guided target.

The third hypothesis, regarding the comparisons among age groups, predicted that force control ability would develop significantly from early childhood to school age, at approximately 10 years old, reporting less accuracy with 6-year-olds. Commonly in both force generation and relaxation groups, the error was greater among 6-year-olds than in the remaining age groups and plateaued after the age of 11 years (Figure 4). Previous studies on the characteristics of force control in children suggest that approximately 5–6 years of age may be one of the milestones of force control development (Deutsch & Newell, 2004; Forssberg et al., 1991; Westenberg et al., 2004). For instance, 5- to 12-year-old children and adults performed a unimanual and a bimanual isometric force task; there were six different levels, ranging from 0% to 60% maximum voluntary contraction (MVC) (Westenberg et al., 2004). Consequently, for variability, a developmental trend in differences between the unimanual and bimanual tasks was identified; with age, the coefficient of variation in force decreased, and 5- and 6-year-old children demonstrated significantly greater differences between the unimanual and bimanual tasks than the older children. To examine the coordination of force output in children, 6-, 8-, and 10-year-olds and adults (18–22 years) performed isometric pinch grip force tasks as a function of force level (5%, 15%, 25%, and 35% MVC); the error decreased significantly as age increased (Deutsch & Newell, 2002). Accuracy can be improved with practice, although 6-year-olds did not reach the level of that of adults, even at the end of a 5-day practice (Deutsch & Newell, 2004).

Focusing on comparisons between the phase of controlling generation and controlling relaxation, Harbst et al. (2000) examined the characteristics of accuracy of force and timing control by utilizing the periodic isometric pinch tasks performed by 6-, 8-, 10-, and 12-year-olds and adults. Lower accuracy and greater variability resulted when the force was decreased. Moreover, the constant and...
variable errors were more difficult for 6- and 8-year-olds than for older participants and more difficult for 10- and 12-year-olds than for adults. Particularly, 6-year-olds demonstrated greater errors and adopted the letting go strategy in which they relaxed well below the target level. Thus, decreasing the force to a certain level rather than completely relaxing may be difficult, and this is an ability acquired during development. Regarding the visually guided force control, characteristics were also reported in a power and precision grip task to target a level of 30% MVC in 3- to 6-year-old children (Potter et al., 2006). Children increased the force to the target level, held the force for 3 s, and then relaxed completely until the force reached 0%. From 3 to 5 years of age, the initial overshoot immediately after the start of adjustment decreased, and the coefficient of variation decreased. This indicates that the stability of force control increases with age.

Forssberg et al. (1991) investigated the grip and load force control while using fingertips to lift a small object between the thumb and index finger in children and adults. As a result, adults lifted the object with the minimum force required, whereas children used more grip force than required to lift the object, showing a significant difference between adults and children under 6 years of age. Furthermore, during the static phase, 6- and 8-year-old children and adults were able to hold force stably, whereas children under 4 years of age showed a high variability in grip force. These results indicated the change toward anticipatory strategy with age from feedback control to feedforward control. The characteristics of anticipatory control have been examined utilizing the same task during precision grip with different object sizes and weights (Forssberg et al., 1992; Gordon et al., 1992).

The aforementioned previous studies evaluated the performance of force control in terms of variability or stability using coefficient of variation, especially studies utilizing the tasks with visual feedback. On the other hand, the evaluation in terms of accuracy used the errors from a certain target level. In the present study, accuracy based on self-perceived effort was evaluated using constant error and absolute error. Unlike previous studies that predominantly used visual cues and feedback, this study investigated a unique perspective using perceived estimate of effort. Here, the accuracy of 6-year-olds of both sexes was lower than that of the age group of more than 11 years of age; this result supports those of previous studies showing the characteristics of variability and accuracy (Deutsch & Newell, 2002, 2004; Harbst et al., 2000). Thus, for comparisons among ages, children under 10 years of age are in the middle of a developmental stage in force control, and their development of force accuracy both in generation and relaxation is not yet complete.

Although previous studies have reported the developmental characteristics of variability and accuracy in force generation, this study has a novel finding in that it suggests that there is also a marked improvement in accuracy of force relaxation based on self-perceived effort between early childhood (6-year-olds) and school age (11-year-olds), with no significant change after that time. The force control task used in this study was performed according to muscle sensation, and the evaluation of the performance accuracy relative to the self-perceived effort of the target level was possible. In Scammon’s growth curve, the development of the nervous system is almost complete around the age of 10, which is called the golden age because this is when the nervous system is almost approaching adulthood. Furthermore, as the...
development of inhibitory control of motor output is also largely involved around the age of 10 years (Harbst et al., 2000), the development of inhibitory control of force becomes more pronounced, and self-perceived 50% effort control has also reached adult-like levels by 11 years.

For comparisons between sexes, a previous study on the characteristics of force control in children aged 5–6 years, 7–8 years, 9–10 years, and 11–12 years and adults performed a unimanual isometric force control task with five different levels, ranging from 0% to 60% MVC with online visual feedback (Smits-Engelsman et al., 2003). No sex differences in force control parameters were observed in any of the age groups, although sex differences were identified in the MVC. Thus, the accuracy of the sex differences regardless of force generation or relaxation appeared only in constant error. Both sexes had negative errors, but female participants had less accurate values than male participants, supporting our findings.

**Relationship Between Physical Strength and Skill of Accurately Controlling Force**

The last hypothesis on the relationship between physical strength and the skill of accurate force control predicted that grip strength with maximum effort and the skill of accurately controlling force would show no relationship in all age groups. As hypothesized, no significant correlations between the value of the maximum task and the absolute error of half tasks were observed in all age groups and sexes. Hence, superior physical strength with a maximum effort does not necessarily indicate superior accuracy in controlling movements. A previous study examining force control tasks with jumping movements in 6-year-old children also indicated that there was no relationship between jumping ability and the ability to adjust to jumping distance, showing results similar to this study (Ohtaka et al., 2016). In summary, no relationship exists between physical strength with a maximum effort and the skill of accurately controlling one’s movements at any age for our task.

**Limitations**

The strategy that participants adjusted the target level was not analyzed. Previous studies on force control in adults have reported that different strategies are adopted depending on the combination of time and speed to control strength in force generation or relaxation (Ohtaka & Fujiwara, 2016, 2019). In addition, in the present study, participants performed each task twice without practice. We did not examine the effect of practice by increasing the number of trials or days. Thus, further studies are required to examine the differences in age and sex in terms of detailed strategies or variability in force control. Furthermore, there was no assessment to confirm that the youngest age group understood the cognitive concept of 50% maximum effort, as was previously investigated (Ohtaka et al., 2016). We were unable to determine whether errors were due to a mismatch in estimates, in force control, or in both. Finally, we relied on trends to make the case that the 6-year-olds were different from adults in our half tasks. This is not a statistically solid approach.
Conclusion

Both sexes in all age groups had greater difficulty in self-perceived estimation and control of force when relaxing than while generating force. These two skills develop from early childhood and appear adult-like by 11 years old despite further changes in maximum force production ability that support previous studies. Future research will establish whether these skills can be trained with practice.

References


