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Features of Index-Ring Finger Pair's Force Contribution in Multi-Finger Force-Following Tasks

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Abstract: New types of cylindrical handles such as pushrims with force signal sensors under four fingers (excluding the thumb) enable real-time gripping-status assessment. The mirrored change phenomenon of the index and ring fingers observed in linear grip tasks offers a new perspective on finger grouping. To evaluate the force contribution of index-ring finger pair in multi-finger force, 10 right-handed male participants with similar hand sizes were recruited to participate in sinusoidal function force-following tasks involving a cylindrical handle. The real-time signal of the grip force and individual finger force were recorded to analyze real-time changes in the finger force contribution (FC). Subsequently, the time-FC curves of individual and paired fingers were analyzed. Results show are as follows: (1) When the FC of the index-ring finger pair exceeded that of the middle-little finger pair, the gripping load was relatively low, and a smaller difference between the FCs of the index-ring finger pair and the middle-little finger pair indicated a smaller following error. (2) The FC of index-ring finger pair is a better (higher-linearity) parameter to assess gripping status. These findings show that the paired-finger FC is an adequate parameter for the gripping-status assessment.

Keywords: analysis and evaluation; process control; biomechanics; physical ergonomics; coordinated action

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1. Introduction

The operation of cylindrical handles or controllers (such as pushrims in a wheelchair) is common in modern technology [1,2]. Real-time working status assessment of the operator and rehabilitation assessment of finger function is becoming increasingly important because misoperation can lead to significant losses. In the operation of traditional pushrims, the thumb is used is to press several buttons on the top of the joystick, and the other four fingers work together with the palm to control the direction. Understanding the mechanism of four-finger force distribution and adjustment in dynamic gripping tasks will help in gripping status assessment of pushrims with sensors inside and the rehabilitation assessment of people who suffer from finger injuries. Numerous studies have been performed on the coordination mechanism of individual fingers, yielding useful results. Some focused on the individual finger forces. The middle finger and little finger have the strongest and weakest force outputs, respectively, according to several studies [3–6]. Other studies focused on the functions of individual fingers. Zatsiorsky et al. [7], Li [8], and Martin et al. [9] reported that the index finger has greater independence than the other fingers in multi-finger tasks, indicating that the enslaving effect has a smaller impact on the index finger than on the other fingers. Studies have also been performed on the difference in finger-force exertion between single- and multi-finger tasks. The studies of Latash et al. [10] and Scholz et al. [11] revealed that a single finger has a limited effect on grip-force exertion, and the variance of an individual finger force exceeds that of combined fingers. Research has also been conducted on the coordination mechanisms of combined fingers. A motor unit investigation based on the forearm (flexor digitorum profundus and flexor pollicis longus) electromyography analysis [12] indicated that the little finger has the strongest synchrony with the other fingers, and the index-ring pair has the weakest synchrony in multi-finger tasks. However, these studies did not reveal the relationship between the individual finger force and the gripping status.

It is known that the signal of the individual finger force changes rapidly [11] and has a strong correlation (correlation differs among fingers) with the grip force [13] during multi-finger tasks. The force contribution (FC) of an individual finger (quotient of the individual finger force and grip force) is a more appropriate parameter to reflect finger status. If we know the common mechanism of finger force distribution and adjustment in multi-finger gripping tasks, we can use it as a standard to evaluate finger status or function with pushrims or grip dynamometers.

Many studies have been performed on the FCs of individual fingers in static-load (load does not change in single trials) grip tasks. For example, in one study, although the FCs of the individual fingers changed with respect to the load level in the gripping task, they changed within relatively fixed ranges [5]. Grouping fingers into different pairs is a popular method for evaluating the coordination between fingers. In some studies, fingers were grouped into pairs according to the total moment; however, the results have been inconsistent. Zatsiorsky et al. [14] reported that grouping fingers into an index–middle pair and a ring-little pair is convenient for analysis of the total moment. Kuo et al. [15] reported that the index-middle and middle-ring pairs both have a reasonable correlation with regard to force exertion; however, in their study, the correlation was calculated using force vectors. In other studies, researchers grouped fingers into a peripheral pair and a central pair in analyzing the total moment [16–18]. In these studies, the fingers were grouped into pairs to analyze the forces and moments in grip tasks with static loads. The mechanism under dynamically changing load levels needs to be investigated further.

Luo et al. [13] discovered a mirrored change phenomenon in linear force-following tasks. In their experiments, the change in the FC of the index finger was always opposite to that for the ring finger, with similar amplitude and velocity. When the grip force changed linearly, the FC of each finger changed differently, but the mirrored adjustment kept the FC of the index-ring finger pair stable; in other words, the linearity of time-FC curve of index-ring finger pair should be better than other finger pairs. Thus, the finger FC of the index-ring finger pair may be an adequate parameter for assessing the gripping status. According to Dragan et al. [19], force exertion with different velocities and accuracy may cause the change of mechanism of the agonist-antagonist coactivation. However, in the study, the grip force was changed with a constant slope (linear).

Although the study of Luo et al. [13] provided new ideas regarding the assessment of the gripping status and finger function, three questions must be determined before using the force data of index-ring finger to assess the gripping status: (1) whether the mirrored change phenomenon also occurs when the slope of the grip force changes, (2) whether the FC of the index-ring finger pair can indicate features of the gripping status, and (3) whether the index-ring pair outperforms other pairs or individual fingers as an assessment parameter. To solve these problems in the present study, the authors designed a series of force-following tasks wherein the following target varied nonlinearly (sinusoidal function) and assume the answers to the three questions are all positive. Then, an enhanced understanding of the force adjustment mechanism of the index-ring finger pair will help in griping status and finger function assessment.

2. Methods

2.1. Participants

There have been plenty of studies on mechanisms of finger force distribution. In most experiments, the number of subjects has been 4–12, as shown in Table 1. The results of these experiments had been proved to be valid. This indicates that in research of finge force distribution, a small number of subjects will not affect the validity of results.

Table 1. Number of subjects in reference.

Reference	Number of Participants
[3]	Twenty-five, 12, and 9 subjects were assigned into small, middle, and large hand size groups
[4]	Fifteen male right handed subjects
[5]	Seventy-two male graduate and undergraduate students participated in the study.
[6]	Fourteen healthy right-handed males participated in the experiment.
[7]	Ten right-handed university male students participated in the experiment.
[8]	Twelve healthy volunteers participated in the experiment.
[9]	Twelve subjects (six men and six women) participated in the experiment.
[10]	Six unpaid, healthy volunteers took part as subjects in the experiments.
[11]	Six unpaid, healthy male volunteers participated as subjects in the experiments.
[12]	A total of eight subjects took part in the experiments.
[13]	Ten right-handed male subjects participated in the experiments.
[14]	Eight right-handed healthy university students served as subjects.
[15]	Twenty-four healthy participants with no history of hand injuries or sensory deficits were recruited in this study.
[16]	Ten right-handed university male students served as the subjects.
[17]	Four right-handed male subjects took part in the experiments.
[18]	Eighteen right-hand-dominant males participated in this study.
[19]	The subjects were 26 male university students.
[20]	Twenty-four males were recruited via advertisements within the university community.
[21]	The research was conducted on a group of nine subjects.
[22]	Seven healthy volunteers participated as subjects in the experiments.

In this study, ten right-handed healthy male subjects (with no history of upper limb injuries or musculoskeletal disorders) participated in the experiments. The subjects had similar hand sizes, as the size of the cylindrical handle used in the experiment was not adjustable. Using subjects with a similar hand size reduced the error due to the diameter of the handle. The means and standard deviations (SDs) of the participants' age, height, weight, hand length, and hand width were 27.9 (4.3) years, 176.2 (4.6) cm, 74.7 (9.6) kg, 19.2 (0.7) cm, and 8.9 (0.4) cm, respectively.

2.2. Apparatus

The grip-force measurement system (Figure 1B) used by Luo et al. [13] was employed in this study. Four force sensors (Figure 1C) (HT-7303 M3-20, Hangyudongfang High-tech Development Co. Ltd., Beijing, China; diameter of 20 mm, ±0.5% full scale) were used, and the interface was at the distal phalanges. The length of the cylindrical handle was 100 mm. To ensure an adequate press force at the distal phalange of fingers [13], the diameter of the cylindrical handle was 42 mm. The finger pad (Figure 1D) had a width of 20 mm to eliminate the forces from other fingers. One-dimensional force data were obtained from four sensors, which were located at the distal phalanges of the fingers. Four sensors were placed in a row inside the handle and the bulge on each sensor touched the back of the corresponding finger pad. The sampling rate was 700 Hz, and the data were processed using MATLAB and SPSS.

2.3. Procedures

Before the experiments, all the participants provided informed consent, and the ethical committee of the university approved the study. A researcher first briefly introduced the device and experiment to the participants. After the introduction, the subjects were given several minutes to become familiar with the use of the device (gripping the handle to follow random target waves (TWs) provided by the researchers).

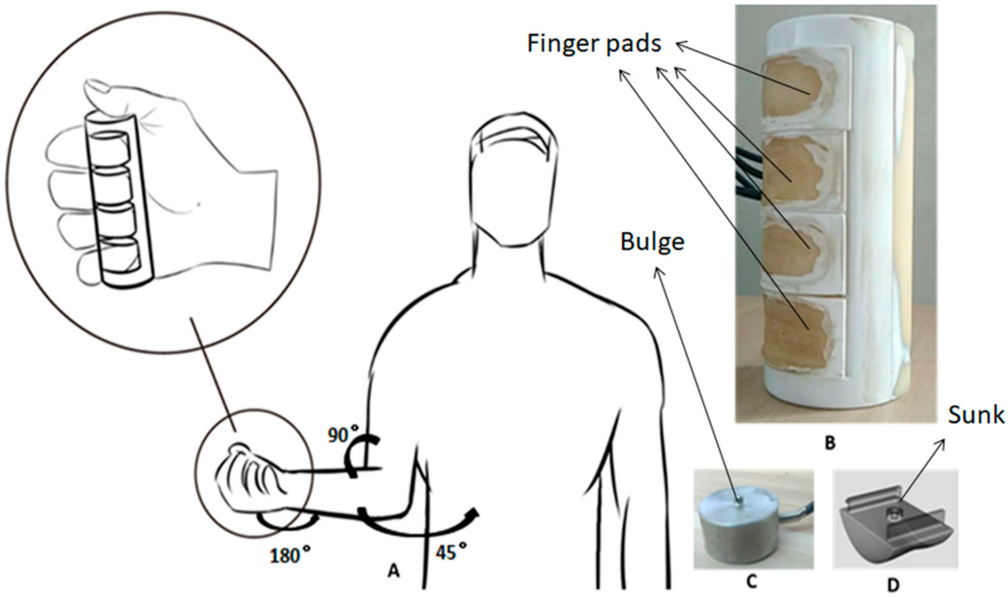


Figure 1. (**A**) shows the posture of the experiment (the enlarged image is top view). (**B**) is the handle used, four-finger pads placed in a row in the handle. (**C**) is the force sensor. (**D**) is the structure of the finger pad. The bulge of the sensor touch the sunk on the back of finger pad.

Figure 1A shows the experimental posture (guided by American Society of Hand Therapists [23]): each participant sat on an upright chair with both arms hanging at the sides of the upper trunk. The elbow of the right arm was bent at 90° with an abduction angle of 45°, while the wrist remained in the natural position (0°). The thumb was placed at the end of the cylindrical handle to ensure that only the other four fingers participated in the trials during all the tasks, including the maximal voluntary contraction (MVC) trials.

After the subject was ready (i.e., familiar with the use of the device and in the correct posture), they participated in four trials: two MVC trials (the two trials were identical) and two force following trials. The MVC trials were performed first. In each MVC trial, when the participants heard the start tone from the computer, they exerted their maximal force [4] until they heard the end tone (time duration is 5 s). A 3 min rest was provided between the two trials [20] to prevent muscle fatigue, and the second MVC trial was exactly the same as the first one [4,5,8,9,13,16,19]. It is notable that there are new standards in performing MVC tests [21] in which the EMG signal was used to determine the best movement for certain muscles in the MVC test. However, in this study, the posture was fixed, so the traditional MVC test was used in the experiment. The maximum force of the two trials was recorded as the MVC value for each participant. Visual feedback (real-time grip-force curve) was provided, and there was no verbal encouragement during the MVC trials.

After the MVC trials were done, subjects started the force-following trials. The sinusoidal function force following tasks comprised two parts: a low-load (LOW) part and a high-load (HIGH) part, which were conducted within a 20–40% MVC area and a 60–80% MVC area, respectively. The participants took the LOW part first and rested for at least 3 min between the two trials. During the experiment, the participants exerted a force to follow the TW with visual feedback (TW and real-time grip-force curve) as closely as possible.

2.4. Data Processing and Statistics

The duration of the *TW* used in the experiment was 25 s. Consider the LOW part as an example. As shown in Figure 2, the functional expression of the *TW* is as follows:

$$TW(t)\begin{cases} 30\%MVC, & (5\text{ s} \le t \le 10\text{ s}) \\ 10\%MVC\cdot\sin\left(\frac{\pi}{5}(t-10)\right)+30\%MVC, & (10\, s \le t \le 20\, s) \\ 30\%MVC, & (20\text{ s} \le t \le 30\text{ s}) \\ 10\%MVC\cdot\sin\left(\frac{2\pi}{5}(t-25)\right)+30\%MVC, & (25\, s \le t \le 30\, s) \end{cases} \tag{1}$$

where t represents time.

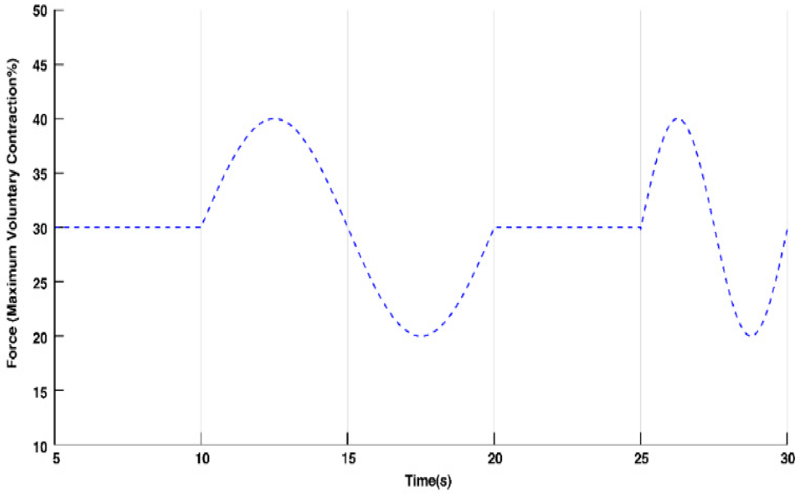


Figure 2. Target wave of 20–40% maximal voluntary contraction trial.

The TW was normalized using the MVC value of each participant. There was a 5 s preparation period at the beginning to allow the participants to exert force to reach the TW; thus, the data recording started at 5 s.

Four independent sensors were placed at the distal phalanges of each participant's four fingers to determine the vertical forces of individual fingers. At each time point, the real-time forces corresponding to the individual finger forces were normalized to a percentage of the MVC according to the MVC data for subject i and were recorded as the index-finger force (IFF_i), middle-finger force (MFF_i), ring-finger force (RFF_i), and little-finger force (LFF_i); then, a moving average with an interval of 15 samples was taken. The equation used to normalize finger force into the percentage of MVC is shown in Equation (2), taking the index finger as an example. In Equation (2) $IFFraw_i$ is the value of index finger force of subject i, MVC_i is the largest MVC value of the subject i in two MVC trials.

$$IFF_i = \frac{IFFraw_i}{MVC_i} \times 100\% \tag{2}$$

At each point in time, the grip force (GF_i) of subject i was the sum of IFF_i, MFF_i, RFF_i, and LFF_i, as shown in Equation (3). IFC_i, MFC_i, RFC_i, and LFC_i represented the FCs of the four individual fingers of subject i. The following error (FE) of subject i was recorded as FE_i. To determine the common mechanism and avoid any unique mechanism in specific subjects, the grip force, finger force, FC, and FE used for mechanism analysis were the average values for all the subjects. The expressions of mentioned parameters are listed below.

$$GF_i = IFF_i + MFF_i + RFF_i + LFF_i, \tag{3}$$

$$GF = \sum\nolimits_1^N GF_i/N, \tag{4}$$

$$IFF = \sum\nolimits_1^N IFF_i/N, \tag{5}$$

$$IFC_i = \frac{IFF_i}{GF_i} \times 100\%, \tag{6}$$

$$IFC = \sum_1^N IFC_i/N, \tag{7}$$

$$FE_i = |GF_i - TW|, \tag{8}$$

$$FE = \sum_1^N FE_i/N, \tag{9}$$

Here, N represents the number of subjects. The equations are identical for the middle, ring, little, and index fingers.

When the fingers were grouped into pairs, the linearity of the time-FC curve of one pair had to be identical to that of the other pair (because the sum of the FCs was 100% at any time point). Hence, only one pair of each grouping pattern is presented in the results.

The indicators used for finger grouping in previous studies include the variance of the finger force, the finger FCs at specific time points, and the moment produced by the finger forces [11,14,17,18]. However, in the present study, the time-FC curves of individual fingers and finger pairs were the key indicators.

A former study [13] indicated that the changing trend of GF (increase, hold, or decrease) affects the distribution mechanism of finger force. Therefore, the force-following trials were normalized by time and then classified into three phases (hold, increase, and decrease) according to the changing trend of the TW. In each phase, the variation data of the FC for different force following trials were fitted linearly using the least square method and compared with the results of the linear force following the experiment of [13]. The goodness of fit (R^2, $0 \leq R^2 \leq 1$) was used to assess the linearity of the data (a value closer to 1 indicated better linearity), and the residual sum of squares (RSS) reflected the stability of the data (a smaller RSS indicated better stability). R^2 and RSS were calculated by Equations (10) and (11).

$$R^2 = 1 - \left(\sum_t (\hat{y}_t - y_t)^2 / \sum_t (\overline{y} - y_t)^2\right) \tag{10}$$

$$RSS = \sum_t (\hat{y}_t - y_t)^2 \tag{11}$$

where t is the time point in each changing phase of TW, $\hat{y}_t$ is the value of regression line at t, y_t is the value of FC curve at t, and $\overline{y}$ is the mean value of FC in this specific trial.

3. Results

3.1. Changing Trend of Individual FC in Sinusoidal Function Tasks

Figure 3 shows the curves of the TW, FE, and individual-finger FCs in sinusoidal function force following tasks. The individual FCs exhibited similar trends in the 20–40% MVC (LOW) and 60–80% MVC (HIGH) trials. At all times, the middle finger exhibited the largest FC, and the little finger exhibited the smallest FC. The FC of the ring finger was larger than that of the index finger at most times (with the exception of 5.77–5.88 s in the 20–40% MVC trial). The mirrored change phenomenon was not as significant as that in the linear tasks, except in cases where the slope of the TW was relatively stable (e.g., at 5–10 s (TW slope 0), approximately 15 s (TW slope was close to -4π% MVC), approximately 26.25 s (TW slope was close to 0), and approximately 27.5 s (TW slope was close to -8π% MVC) in the under LOW trial. Although the FE was significantly smaller under the LOW condition than under the HIGH condition, it changed with the TW only under the LOW condition.

3.2. Time-FC Curves of Grouped Fingers

3.2.1. Difference of FC between Pairs

The fingers were grouped into index–ring and middle-little finger pairs, index-middle and ring-little pairs, and index-little and middle-ring pairs. The real-time FC of each pair was calculated, as shown in Figure 4. Regarding the index-middle and ring-little and index-little and middle-ring groupings, the finger pairs that contained the middle finger always had larger FCs than the other pairs. This difference between the pairs was smaller under the HIGH condition than under the LOW condition. It decreased over time under the HIGH condition but not under the LOW condition. For the index-ring and middle-little groupings, the FCs under the LOW and HIGH conditions exhibited different qualities. The index-ring pair had a larger FC than the middle-little pair under the LOW condition (except at approximately 15–22 s in the linear task); however, the middle-little pair had a larger FC under the HIGH condition.

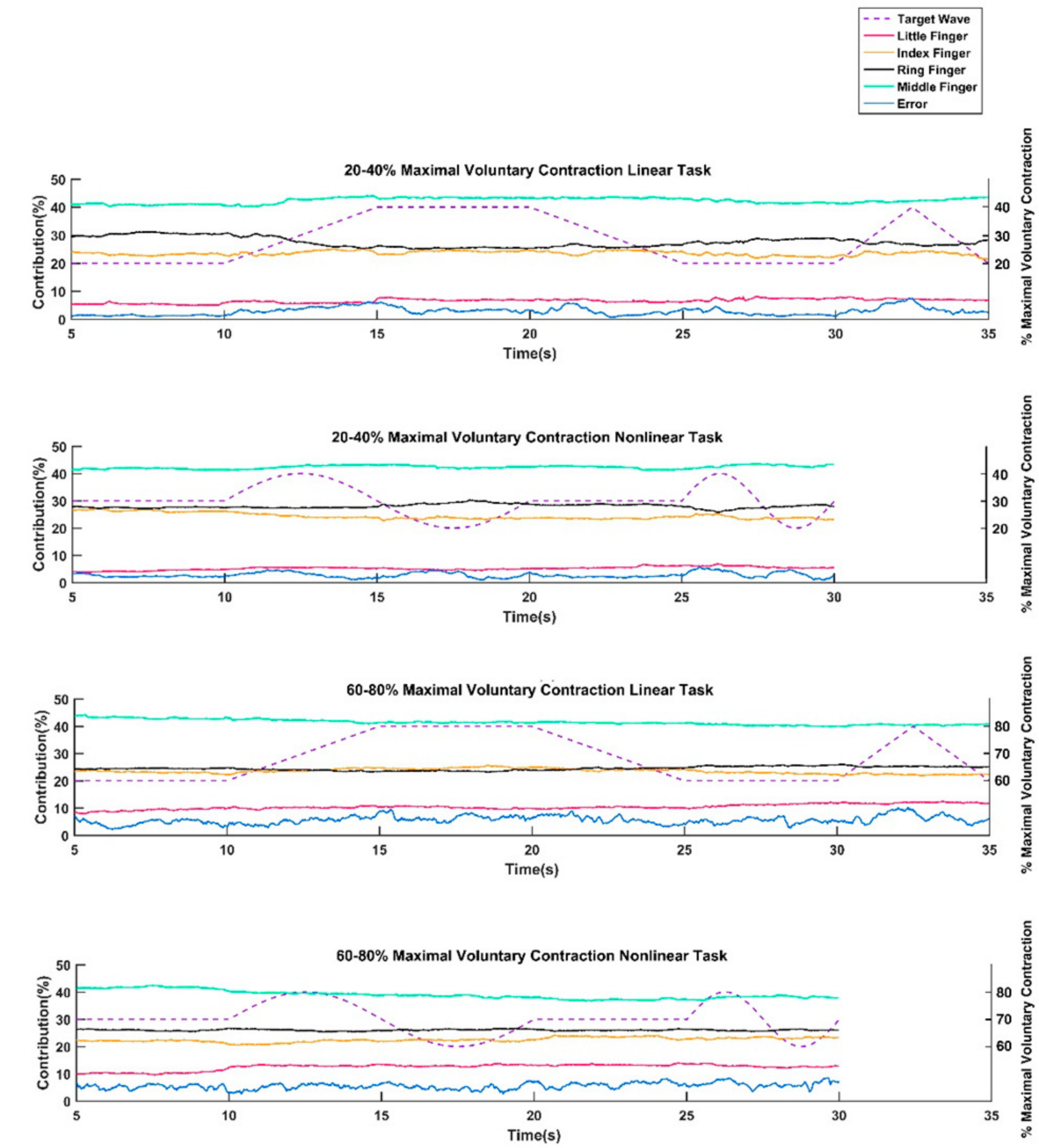


Figure 3. Curves of target force (TW), individual force contribution (FC), and following error (FE) in different force following tasks. Values of force contribution and following error refer to the left vertical axis, and values of target wave refer to the right vertical axis.

3.2.2. Linearity of Time-FC Curves

The mean and SD value of the R^2 and RSS for each finger and pair in different phases of TW and different load levels were calculated, and the results are shown in Figure 5. Fisher's p-value was used to describe the significance of the difference between R^2 of the different finger or finger pairs.

During the hold phase, the little finger time-FC curve exhibited the highest linearity among the individual fingers (R^2 $p < 0.05$). The index-ring time-FC curve had the highest linearity under the HIGH condition but did not have significantly (R^2 $p = 0.872$) higher linearity than the index-middle time-FC curve under the LOW condition. However, the RSS of the index-ring time-FC curve was significantly smaller ($p < 0.05$) than that of the index-middle time-FC curve. The linearity of the little-finger FC curve and index-ring FC curve exhibited no significant difference in either the LOW (R^2 $p = 0.612$) or HIGH condition (R^2 $p = 0.708$).

During the increase phase, the curves of all the pairs and the individual index and middle fingers exhibited better linearity (larger R^2 values) under the LOW condition than under the HIGH condition ($p < 0.05$). Although the ring-finger FC curve exhibited the same trend, the difference between the LOW and HIGH conditions was not significant (R^2 $p = 0.628$). The little-finger FC curve did not exhibit high linearity in the increase phase under either condition (mean $R^2 < 0.3$). The index-ring FC curve had higher linearity than the curves for the other two pairs under the LOW condition (R^2 $p < 0.05$) but not under the HIGH condition (R^2 p between index-ring and index-middle = 0.457; R^2 p between index-ring and index-little = 0.773).

During the decrease phase, the little-finger FC curve exhibited its highest linearity under the LOW condition ($p < 0.05$) among all phases and loads, but its linearity was lower under the HIGH condition (R^2 significantly smaller than that for the hold phase, $p < 0.05$). The R^2 of the ring-finger FC curve was significantly larger than that for the hold phase ($p < 0.05$) but did not exhibit a significant difference from that of the increase phase (low $p = 0.851$ and high $p = 0.763$). The middle-finger FC curve exhibited no significant difference between the HIGH and LOW conditions (R^2 $p = 0.496$). Among the curves for the three pairs, the index-ring FC curve had the highest linearity under the LOW condition (R^2 $p < 0.05$), but no significant differences were observed under the HIGH condition (R^2 p between index-ring and index-middle = 0.827; R^2 p between index-ring and index-little = 0.689). Additionally, the linearity of the index-little FC curve was significantly reduced under the HIGH condition compared to the LOW condition (R^2 $p < 0.05$). However, the index-middle FC curve did not exhibit a significant difference between the two conditions (R^2 $p = 0.722$).

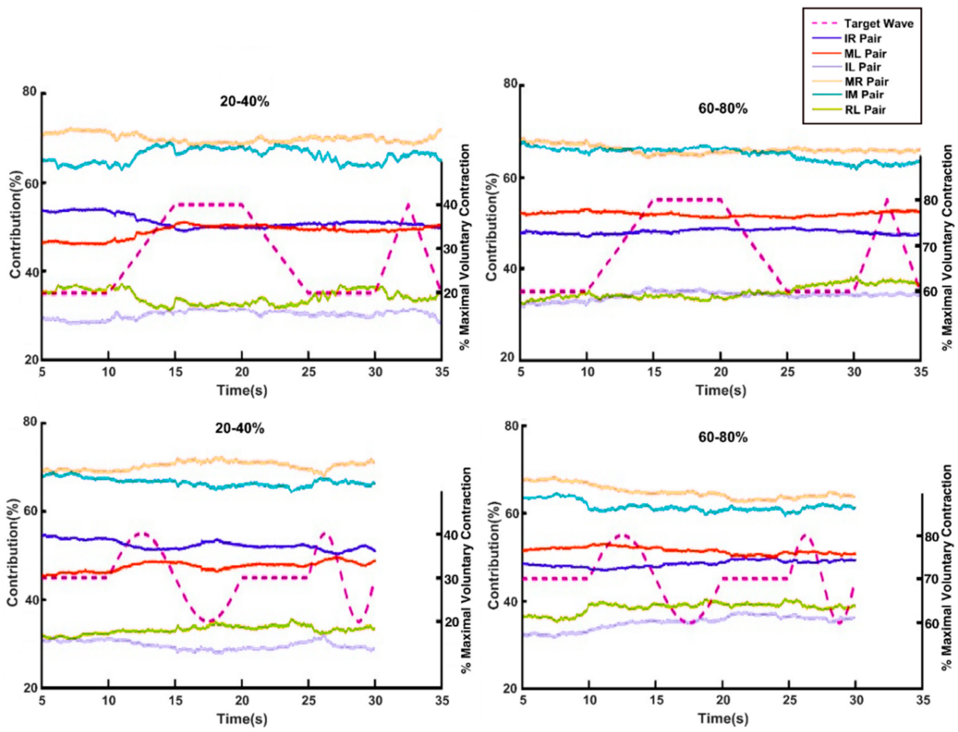


Figure 4. Force-contribution curves of grouped fingers. Values of force contribution refer to the left vertical axis and values of target wave refer to the right vertical axis.

The index-ring FC curve had a small RSS throughout all the phases and under both the load conditions (largest RSS of 160.6 occurred during the decrease phase under the LOW condition).

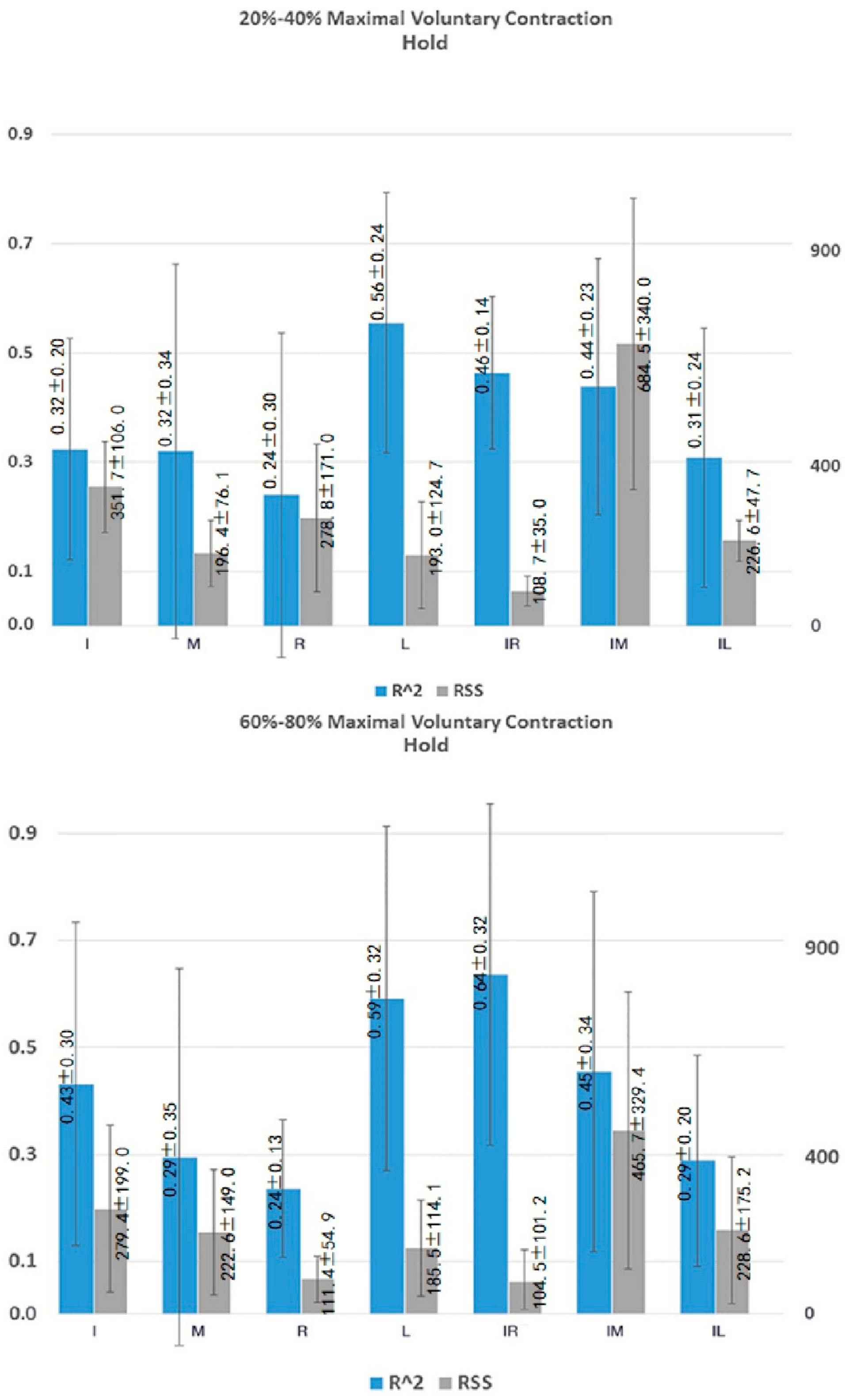
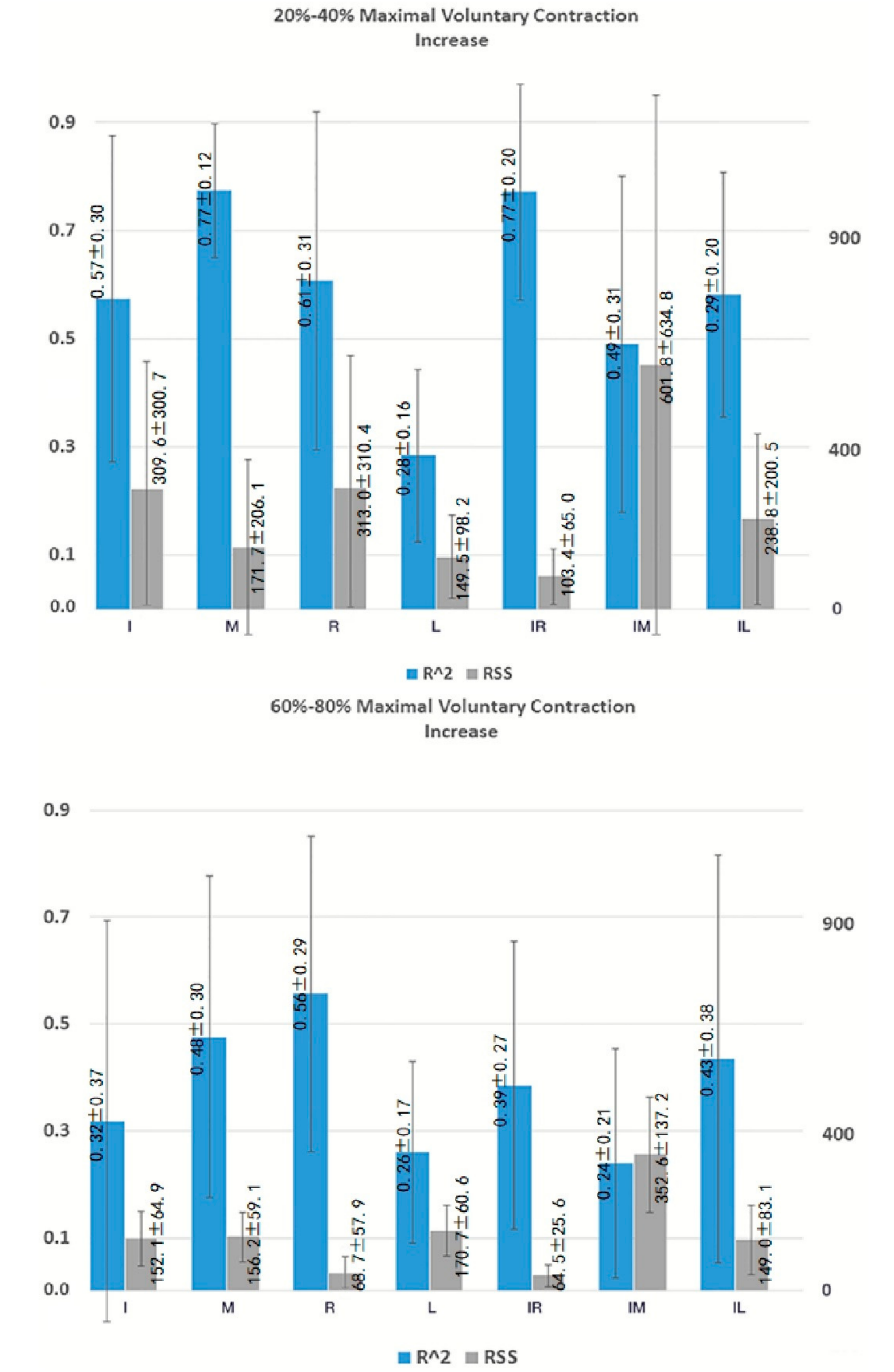


Figure 5. *Cont.*



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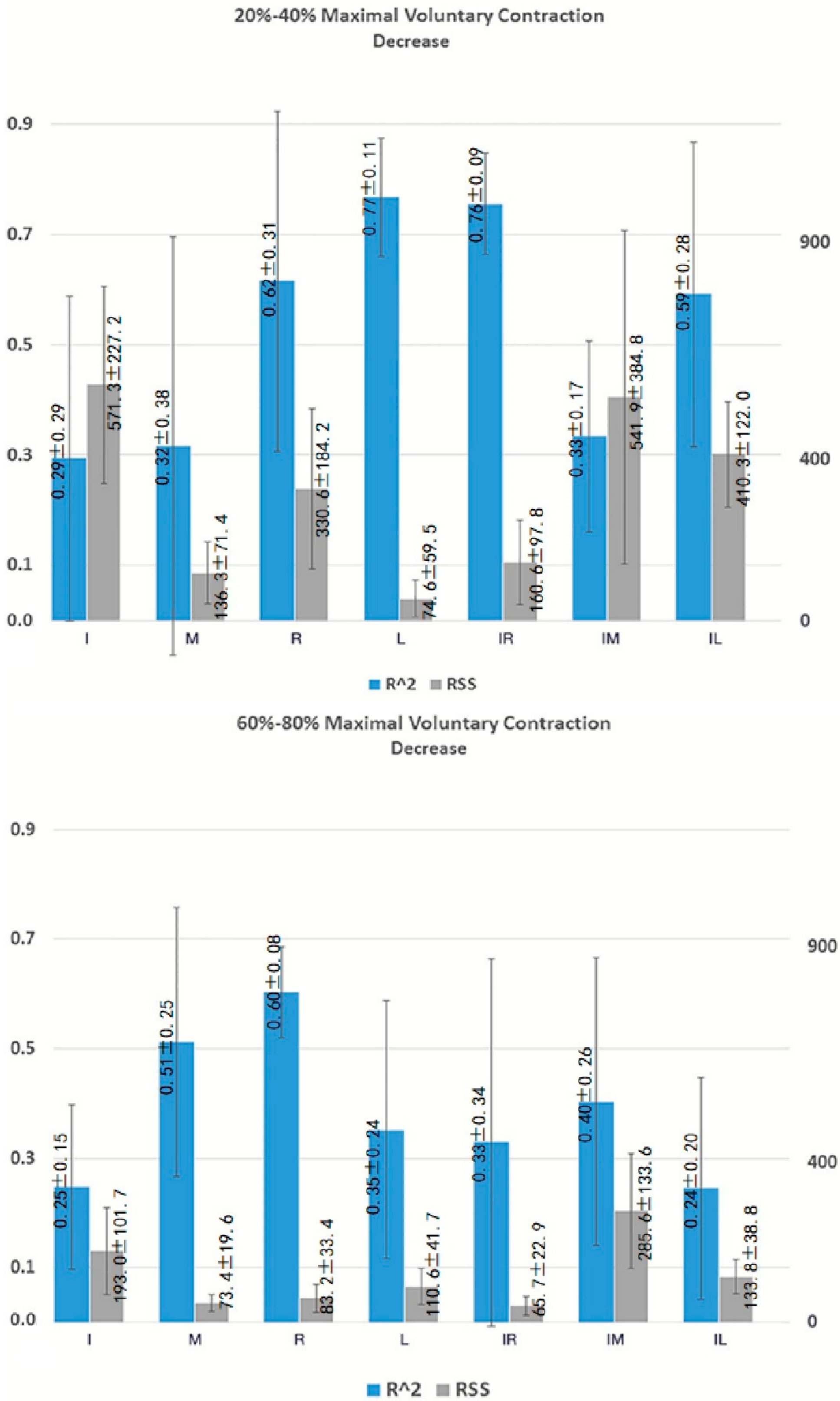

Figure 5. R^2 and residual sum of squares (RSS) of individual fingers and paired fingers, R^2 refers to the left vertical axis; the residual sum of squares refers to the right vertical axis.

4. Discussion

In previous studies on four-finger force following [13], a linear TW was used to conduct the force-following experiments. The slopes of the TW curves were always constant (absolute value of slope is 0 in the hold phase, 4% MVC/s in slow-changing phases, and 8% MVC/s in fast-changing phases). The study revealed that in the linear force-following task, (1) a change in the ring-finger FC always occurred with an opposite change in the FE; (2) the middle- and little-finger FCs did not exhibit a clear trend when the TW changed under the HIGH condition, but the middle-finger FC decreased slowly over time, and the little-finger FC increased over time; and (3) the ring- and little-finger FCs exhibited mirrored changes throughout the trials. In this study, the TW was a sinusoidal function with a varying slope (absolute value of the slope varied from 0 to 8π% MVC/s). The first two results were observed in the sinusoidal function force-following tasks (Figure 3).

The third result was about the mirror change. In this research, the linearity of the index-ring FC curve is used to evaluate the level of mirror change. The index-ring FC curve had higher linearity than the index-middle and index-little FC curves in all three phases under the LOW condition and in the hold phase under the HIGH condition. Higher linearity (more significant mirror change) indicates that the index and ring fingers have a stronger complementary relationship than other fingers, in agreement with the work of [12], who proved that the index and ring fingers had the weakest synchrony in a multi-finger task using EMG (electromyography) analysis. Under the HIGH condition, the R^2 values of the index-ring and index-little FC curves were significantly smaller than those under the LOW condition in both the increase and decrease phases. The index-middle FC curve exhibited the same phenomenon in the increase phase, but the R^2 was small under both conditions in the decrease phase. If high linearity represents an appropriate adjustment in the finger force, this low linearity for all the finger pairs reflects control disorders in the changing phases under the HIGH condition. This can be explained by the force capacity of related muscles: the flexor muscles of the fingers can support a more stable and accurate force-distribution mechanism under the LOW condition than under the HIGH condition. However, a higher load makes the muscles unable to perform the adjustment, retaining only the force output. This explains the higher linearity in the hold phase than changing phases under the HIGH condition. In all the trials, the R^2 of the index-middle FC curve never reached 0.5 (maximum of 0.49 in the increase phase under the LOW condition), and RSS of the index-middle FC curve was the largest among all three grouping patterns, indicating that the index-middle and ring-little grouping pattern cannot reflect the compensation mechanism of the fingers.

Comparing the FCs of the finger pairs in the three different grouping patterns revealed a unique quality of the index-ring and middle-little patterns. Although the difference between the index-ring and middle-little FCs never exceeded 10% (the largest difference was 9.8% at 5 s, sinusoidal function under the LOW condition), their magnitudes exhibited a significant difference between the LOW and HIGH conditions. The index-ring FC always exceeded the middle-little FC when the TW was <40% MVC (except at approximately 15–22 s in the linear task); in contrast, the middle-little FC was larger when the TW was >60% MVC. This change in FCs under different loads has not been previously reported, and this was different from the study of Kong et al. [5] in which the middle-little FC always exceeded index-ring FC at the static grip load. This difference may be caused by the shape of the handle and the location of the thumb. For the other two grouping patterns, the FCs of finger pairs that included the middle finger (index-middle pair and middle-ring pair) exceeded those of the other pairs. The FC difference between the finger pairs decreased as the gripping load increased. This indicates that the middle finger is capable of exerting greater force under the LOW condition, but the ability decreased as the GF increased, and the little finger compensated for the lost force of the middle finger. Kong et al. [5] obtained similar results. In their study, the force contribution of the middle finger keeps decreasing before the grip force reaches 30–40% MVC. These findings indicate that the coordination mechanisms of fingers depends on the gripping load. Muscle fatigue reduces the differences in the FC between the finger pairs over time; hence, the muscles cannot maintain the functions of individual fingers.

As the FE under the LOW condition was always smaller than that under the HIGH condition, it can be concluded that the following accuracy is higher under low-load gripping tasks. However, a smaller FE was not observed at the lowest TW points but at approximately 16, 22.5, and 28–30 s in the linear following tasks and 14, 18, 27, and 29.5 s in the sine-function following tasks under the LOW condition (Figure 3). The FC curves of individual fingers and the other two grouping patterns did not exhibit special changing trends at these time points, but the FC curve of the index-ring finger pair exhibited unique qualities again. At the aforementioned time points of a smaller FE, the difference between the FCs of the index-ring finger pair and the middle-little finger pair reached its minimum values among the trials (except at approximately 18 s in the sine-function following tasks, which cannot be explained). The phenomenon indicates that when the FC of the index-ring finger pair exceeded that of the middle-little finger pair, the gripping load was relatively low, and a smaller difference between the FCs of the index-ring finger pair and the middle-little finger pair indicated a smaller FE.

Previous studies revealed that owing to the enslaving effect, the little finger does not participate in the GF adjustment; thus, the little-finger FC remains stable when the GF is in the hold phase [13,22]. This stability may explain the relatively high linearity of the little-finger FC curve in the hold phase. However, the excellent linear trend of the time-little-finger FC curve in the decrease phase under the LOW condition was unexpected. A possible explanation is that during the decrease phase under the LOW condition, the other three individual fingers reorganized the adjustment mechanism, but the little finger did not participate and remained in the steady state of the previous condition. Under the HIGH condition, the three-finger reorganization was insufficient to achieve the GF target; thus, the little finger participated in the adjustment, reducing the linearity.

Comparing the index-ring pair with the individual fingers (except the little finger) in the hold phase revealed that the linearity of the index-ring FC curve was significantly higher than those for the index, middle, and ring fingers. Additionally, in the changing phases under the LOW condition, the index-ring FC curve exhibited linearity as good as the highest linearity of any individual finger (the middle finger in the increase phase and the ring finger in the decrease phase). The index-ring FC curve always had a smaller RSS under all the loads and phases, indicating that the time-FC curve of the index-ring finger pair had high linearity in multi-finger tasks during the changing phase under the LOW condition and during the hold phase. Consequently, the linearity of the index-ring FC curve was higher than those for the other pairs and the individual fingers.

In studies on the total moment of the hand [11,16,24], the longitudinal functional axis of the hand was taken as the neutral line, and useful conclusions were drawn. Additionally, in some studies [16,18], fingers were grouped into pairs for analyzing the total moment. The fingers were grouped into peripheral and central (index-little and middle-ring) pairs, but these two pairs shared the same neutral line. According to the results of our study, the index-ring and middle-little grouping pattern yields a better coordination mechanism. The index-ring and middle-little grouping can be considered as two pairs of fingers, and their neutral lines exist between the index-ring and middle-little fingers, respectively. Therefore, a two-axis system can be applied in analyzing the total moment. The eventual neutral line lies between the two axes, and the moment on the two axes varies almost linearly. This may make it easier to analyze the moment.

The diameter of cylindrical handle used in this study was unadjustable. Although the hand length of the subjects was similar to reduce the impact of the handle diameter, this could still lead to some error in grip force exerted. Moreover, subjects were limited to male adults because other groups (for example, women, children) did not fit the handle well.

5. Conclusions

According to the mirrored change phenomenon, the FC of the index-ring finger pair was selected as a parameter to assess the gripping status and finger function in multi-finger tasks. A slope-varying TW (sinusoidal function) was used to verify the qualities of time-FC curves of grouped and individual fingers. The following two conclusions are drawn. (1) When FC of the index-ring finger pair is greater than that of the middle-little finger pair, the gripping load is relatively low, and a smaller difference between the FCs of the index-ring finger pair and the middle-little finger pair indicates a smaller FE. (2) The FC of the index-ring finger pair is a better (higher linearity) parameter to assess gripping status. Thus, for the first time, we estimated the gripping status by analyzing the finger FC. The FC of the index-ring finger pair is a useful parameter for assessing the gripping status and finger function.

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References

1. Choi, J.H.; Chung, Y.G.; Oh, S. Motion control of joystick interfaced electric wheelchair for improvement of safety and riding comfort. *Mechatronics* **2019**, *59*, 104–114. [CrossRef]
2. Bae, J.; Kim, K.; Hong, D. Automatic Identification of Excavator Activities Using Joystick Signals. *Int. J. Precis. Eng. Manuf.* **2019**, *20*, 2101–2107. [CrossRef]
3. Kattel, B.; Sivasubramanian, K.; Fernandez, J.; Mcmulkin, M. Evaluation of the force exerted by individual fingers during a multidigital gripping task. In *Advances in Industrial Engineering Applications and Practice I*; International Journal of Industrial Engineering: Melbourne, VIC, Australia, 1996; pp. 267–272.
4. Vigouroux, L.; Rossi, J.; Foissac, M.; Grelot, L.; Berton, E. Finger force sharing during an adapted power grip task. *Neurosci. Lett.* **2011**, *504*, 290–294. [CrossRef]
5. Kong, Y.; Lee, K.; Kim, D.; Jung, M. Individual finger contribution in submaximal voluntary contraction of gripping. *Ergonomics* **2011**, *54*, 1072–1080. [CrossRef] [PubMed]
6. Rossi, J.; Berton, E.; Grelot, L.; Barla, C.; Vigouroux, L. Characterisation of forces exerted by the entire hand during the power grip: Effect of the handle diameter. *Ergonomics* **2012**, *55*, 682–692. [CrossRef]
7. Zatsiorsky, V.; Li, Z.M.; Latash, M. Coordinated force production in multi-finger tasks finger interaction and neural network modeling. *Biol. Cybern.* **1998**, *79*, 139–150. [CrossRef]
8. Li, S. Perception of individual finger forces during multi-finger force production tasks. *Neurosci. Lett.* **2006**, *409*, 239–243. [CrossRef]
9. Martin, J.; Zatsiorsky, V.; Latash, M. Multi-finger interaction during involuntary and voluntary single finger force changes. *Exp. Brain Res.* **2011**, *208*, 423–435. [CrossRef]
10. Latash, M.; Scholz, J.; Danion, F.; Schoner, G. Structure of motor variability in marginally redundant multifinger force production tasks. *Exp. Brain. Res.* **2001**, *141*, 153–165. [CrossRef]
11. Scholz, P.J.; Frederic, D.; Mark, L.L.; Gregor, S. Understanding finger coordination through analysis of the structure of force variability. *Biol. Cybern.* **2002**, *86*, 29–39. [CrossRef]
12. Winges, S.; Santello, M. Common input to motor units of digit flexors during multi-digit grasping. *J. Neurophysiol.* **2004**, *92*, 3210–3220. [CrossRef]
13. Luo, S.; Shu, G.; Gong, Y. Real time relationship between individual finger force and grip exertion on distal phalanges in linear force following tasks. *Appl. Ergon.* **2018**, *69*, 25–31. [CrossRef]
14. Zatsiorsky, V.; Gao, F.; Latash, M. Finger force vectors in multi-finger prehension. *J. Biomech.* **2003**, *36*, 1745–1749. [CrossRef]
15. Kuo, L.C.; Chen, S.W.; Lin, C.J.; Lin, W.J.; Lin, S.C.; Su, F.C. The force synergy of human digits in static and dynamic cylindrical grasps. *PLoS ONE* **2013**, *8*, e60509. [CrossRef] [PubMed]
16. Li, Z.M.; Latash, M.; Newell, K.M. Motor redundancy during maximal voluntary contraction in four finger tasks. *Exp. Brain Res.* **1998**, *122*, 71–78. [CrossRef] [PubMed]
17. Santello, M.; Soechting, J.F. Force synergies for multifingered grasping. *Exp. Brain Res.* **2000**, *133*, 457–467. [CrossRef]

18. Zatsiorsky, V.M.; Gregory, R.W.; Latash, M.L. Force and torque production in static multifinger prehension: Biomechanics and control. I. Biomechanics. *Biol. Cybern.* **2002**, *87*, 50–57. [CrossRef]
19. Dragan, M.; Aleksandar, N.; Sladjan, M.; Slobodan, J. Muscle strength testing: Evaluation of tests of explosive force production. *Eur. J. Appl. Physiol.* **2004**, *91*, 147–154.
20. Lim, C.M.; Kong, Y.K. Effects of the resting time associated with the number of trials on the total and individual finger forces in a maximum grasping task. *Appl. Ergon.* **2014**, *45*, 443–449. [CrossRef]
21. Kukla, M.; Wieczorek, B.; Wargula, L. Development of methods for performing the maximum voluntary contraction (MVC) test. *MATEC Web Conf.* **2018**, *157*, 05015. [CrossRef]
22. Shapkova, E.Y.; Shapkova, A.L.; Goodman, S.R.; Zatsiorsky, V.M.; Latash, M.L. Do synergies decrease force variability? A study of single-finger and multi-finger force production. *Exp. Brain Res.* **2008**, *188*, 411–425. [CrossRef] [PubMed]
23. Fess, E. *Clinical Assessment Recommendations*, 2nd ed.; American Society of Hand Therapists: Chicago, IL, USA, 1992; pp. 41–45.
24. Danion, F.; Schoner, G.; Latash, M.L.; Li, S.; Scholz, J.P.; Zatsiorsky, V.M. A mode hypothesis for finger interaction during multi-finger force-production tasks. *Biol. Cybern.* **2003**, *88*, 91–98. [CrossRef] [PubMed]