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Evaluation of the Contributions of Individual Finger Forces in Various Submaximal Grip Force Exertion Levels

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Objective: The aim of this study is to evaluate contributions of individual finger forces associated with various levels of submaximal voluntary contraction tasks.

Background: Although many researches for individual finger force have been conducted, most of the studies mainly focus on the maximal voluntary contraction. However, Information concerning individual finger forces during submaximal voluntary contraction is also very important for developing biomechanical models and for designing hand tools, work equipment, hand prostheses and robotic hands. Due to these reasons, studies on the contribution of individual finger force in submaximal grip force exertions should be fully considered.

Method: A total of 60 healthy adults without any musculoskeletal disorders in the upper arms participated in this study. The young group (mean: 23.7 yrs) consisted of 30 healthy adults (15 males and 15 females), and the elderly group (mean: 75.2 yrs) was also composed of 30 participants (15 males and 15 females). A multi-Finger Force Measurement (MFFM) System developed by Kim and Kong (2008) was applied in order to measure total grip strength and individual finger forces. The participants were asked to exert a grip force attempting to minimize the difference between the target force and their exerted force for eight different target forces (5, 15, 25, 35, 45, 55, 65, and 75% MVCs). These target forces based on the maximum voluntary contraction, which were obtained from each participant, were randomly assigned in this study.

Results: The contributions of middle and ring fingers to the total grip force represented an increasing trend as the target force level increased. On the other hand, the contributions of index and little fingers showed a decreasing trend as the target force level increased. In particular, Index finger exerted the largest contribution to the total grip force, followed by middle, ring and little fingers in the case of the smallest target force level (5% MVC), whereas middle finger showed the largest contribution, followed by ring, index and little fingers at the largest target force levels (65 and 75% MVCs).

Conclusion: Each individual finger showed a different contribution pattern to the grip force exertion. As the target force level increase from 5 to 75% MVC, the contributions of middle and ring fingers showed an increasing trend, whereas the contributions of index and little fingers represented a decreasing trend in this study.

Application: The results of this study can be useful information when designing robotic hands, hand tools and work equipment. Such information would be also useful when abnormal hand functions are evaluated.

Keywords: Grip force, Contribution, Individual finger force, Submaximal voluntary contraction

1. Introduction

Human's hand is not only a main source for exercise activity and the sense of touch, but one of the main means contacting the external physical environment together with eyes. Since most activities of daily living (ADLs), such as writing or having a meal, depend on the smooth function of hand, a hand can be a very important physical organ. Therefore, many studies on hands have been carried out. However, there are few studies on the function or contribution of individual fingers, due to limitations in the study environment or experimental equipment.

A study on each finger's contribution is important to establish hand's biomechanical models, and design and improve hand tools and manual activities (Radwin et al., 1992). Especially, the acquisition of each finger's contribution and biomechanical data in the ergonomics field is not only essential information in the design of hand tools or prosthetic hand (Crago et al., 1991), robotic arm (Mason and Salisbury, 1985), and working environment, but can be used as vital information in the judgment of hand function's abnormality (An et al., 1985).

Although many studies on fingers' contributions have been conducted, most studies are on the contributions upon maximal grip force exertion (Ohtsuki, 1981; Talsania and Kozin, 1998; Kong and Lowe, 2005; Kim and Kong, 2008; Kong et al., 2008; Lee et al., 2009; Kong et al., 2011). However, studies on each finger's contribution upon submaximal voluntary contraction lack a lot. As mentioned above, finger's contribution is an important research task in the case of maximal grip force exertion; however, submaximal voluntary contraction exertion more frequently occurs than maximal grip force in daily living. In addition, studies on submaximal voluntary contraction is really important, since most difficult tasks are carried out through precise coordination of submaximal voluntary contraction.

According to researches on the contribution of individual finger force) upon submaximal voluntary contraction (10, 20, 30% MVCs) of Radwin et al. (1992), middle finger's contribution increased from 25% to 38%, when force increased from 10% MVC to 30% MVC, whereas index finger's MVC decreased from 35% to 31%. However, the study of Radwin et al. (1992) observed only three levels of grip forces at slightly low levels of less than 30% MVC, and therefore there is a difficulty to compare with contributions upon exerting bigger forces.

In this study, eight levels of target forces (5, 15, 25, 35, 45, 55, 65, 75% MVCs) were chosen as independent variables to complement limitations of existing researches. This study measured contribution of individual finger forces in various submaximal voluntary contractions, and analyzed change aspects of contribution according to the force exerted. In order to analyze the contribution change difference between the young group and the elderly group, this study recruited 30 young people and 30 elderly people. This study conducted an experiment under the assumption that there would be a difference in the contribution of individual finger force) according to various levels of %MVCs.

2. Methods

2.1 Participants

A total of 60 healthy adults without any musculoskeletal disorders in the upper arms participated in this study. To examine the differences between age groups, this study classified the participants into the young group and the elderly group. The elderly and young groups composed of 30 people, respectively (15 males and 15 females, each). The anthropometric dimensions including height, weight and arm length were measured before the experiment, and the basic information of participants were recorded. This study used the measurement method recommended by the Size Korea. The detailed anthropometric data of the participants are shown in Table 1.

Table 1. Anthropometric data of participants

	Elderly group		Young group	
	mean	S.D	mean	S.D.
Age [yr.]	75.2	6.1	23.7	2.1
Weight [kg]	58.5	8.9	65.4	13.5
Height [cm]	156.2	7.8	170.3	8.9
Arm length [cm]	51.4	5.0	55.5	3.3
Upper-arm length [cm]	32.5	2.3	34.8	1.9
Lower-arm length [cm]	25.2	1.5	26.0	3.6
Upper-arm circumference [cm]	28.9	3.1	29.8	4.2
Elbow circumference [cm]	27.3	2.3	26.9	2.8
Wrist circumference [cm]	16.3	1.1	15.4	0.9
Hand length [cm]	17.3	0.9	17.5	1.0
Hand width [cm]	8.0	0.6	7.7	0.6
Hand thickness [cm]	2.9	0.3	2.7	0.3

2.2 Measurement system

To measure total grip force and individual finger force, this study used the MFFM (Multi-Finger Force Measurement) System (Kim and Kong, 2008). The MFFM system is composed of four sub-miniature load cells (Honeywell Model 13) to measure individual finger forces (Figure 1). For precise measurement, each load cell was calibrated using 1~5kg weight, and a high linear relationship between load and output signal was revealed ($R^2 > 0.99$).

The data measured through the MFFM System were converted into digital values using the NI DAQ-USB 6008 (National Instrument Ltd.), and the converted values were sent to the computer. To analyze individual finger force and total grip force, this study used an analysis module written in LabVIEW Program (National Instrument, Austin, Texas).

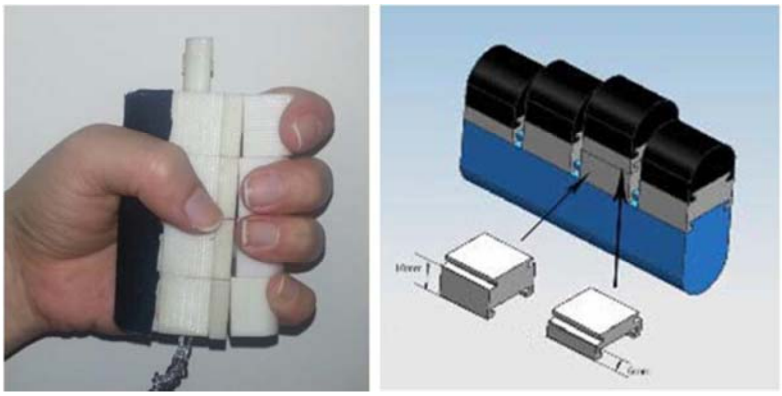

Figure 1. MFFM (Multi-Finger Force Measurement) System

2.3 Experimental design

To identify the trend of contribution according to target force, this study carried out a tracking task maintaining a certain target force for ten seconds (Figure 2). Target force levels were selected on the basis of each participant's maximal grip force. This study selected fingers (index, middle, ring and little fingers), target forces (5, 15, 25, 35, 45, 55, 65, 75% MVCs), age (the elderly and the young) and gender (male and female) as independent variables. Each finger's individual contribution (%) was selected as the dependent variable. The contribution of individual finger force was calculated as shown in equation 1.

The measured data were analyzed using SPSS 18.0 (Lead Technologies, Inc., Chicago, USA). To identify the effects of age, gender and finger on the dependent variable, the analysis of variance (ANOVA) was carried out at the significance level of α=0.05. As for post hoc test, Tukey's Studentized Rage (HSD) was conducted on the significant effects.

$$\text{Contribution (\%)} = \frac{\text{individual finger force}}{\text{total grip force}} \times 100 \quad \cdots\cdots\cdots\cdots \quad \langle\text{equation 1}\rangle$$

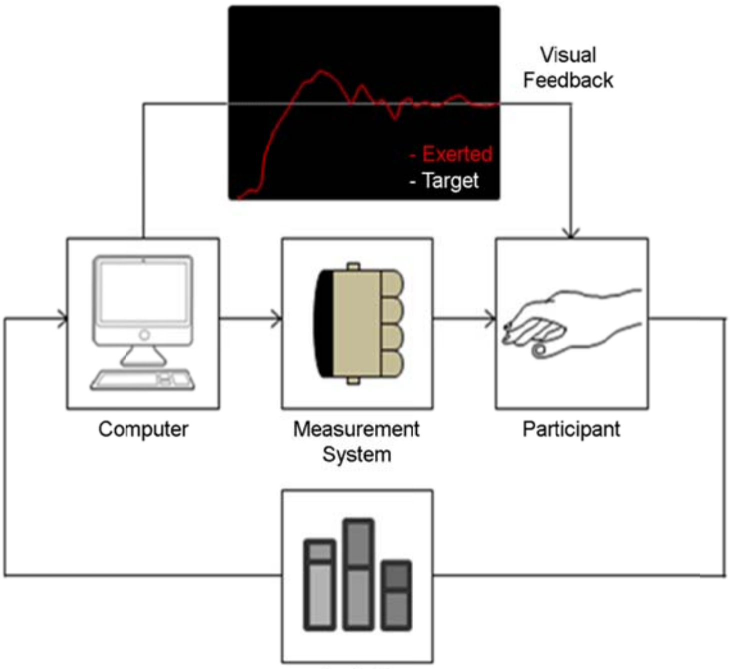

Figure 2. Structure of a tracking task system

2.4 Experimental procedures

Before the experiment, the participants were instructed to fill up the questionnaire answer sheet on musculoskeletal disorders on upper extremities and other diseases, and also anthropometric data and basic information of participants were also measured before the experiment. For target force level selection of each participant, this study measured maximal grip force for five seconds twice, and used the mean value of the measured data. Practice was sufficiently conducted for familiarization with the gripping method, experimental posture and experimental method. Concerning experimental posture, according to the suggestion of the American Society of Hand Therapists (ASHT), the participants were instructed to let down shoulders naturally, flex elbow 90 degrees, and maintain forearm and wrist in the neutral position in the sitting posture in the chair (Fess and Moran, 1981). Each participant performed 14 exertions (7 target force levels × 2 trials) for this study. To exclude learning effects, the measurement was conducted in the random order. A 3-minute break between trials was provided to minimize participant's muscle fatigue (Trossman and Li, 1989).

3. Results

3.1 Contributions of individual finger forces

The contribution of individual finger force showed statistically significant differences ($p < 0.001$) (Table 2), whereas middle finger's contribution was the highest at 36.4%[A], irrelevant of gender or age, followed by index finger (29.0%)[B]. The little finger's contribution (10.2%)[D] was statistically lower significantly than ring finger's contribution (25.2%)[C] (Figure 3). The interaction effect between the finger and gender for the individual finger force contribution was statistically significant ($p < 0.001$). Although the contributions showed the same order (middle-index-ring-little) in both genders, significant differences were shown in index finger and little finger. The contribution of females' index finger (31.6%) was relatively higher than that of males (26.4%). Although the contribution difference

Table 2. ANOVA on finger contribution

Source	Degree of freedom	Sum of squares	Mean square	*F*	Significance probability
Gender	1	18.0	18.0	.16	.688
Finger	3	1378601.3	459533.8	4115.63	.000
Age	1	154.2	154.2	1.38	.240
Target	7	975.3	139.3	1.25	.272
Gender * Finger	3	36880.6	12293.5	110.10	.000
Gender * Age	1	.9	.9	.01	.930
Gender * Target	7	205.4	29.3	.26	.968
Finger * Age	3	7884.8	2628.3	23.54	.000
Finger * Target	21	98111.7	4672.0	41.84	.000
Age * Target	7	99.5	14.2	.13	.996
Gender * Finger * Age	3	4058.7	1352.9	12.12	.000
Gender * Finger * Target	21	5436.9	258.9	2.32	.001
Gender * Age * Target	7	58.1	8.3	.07	.999
Finger * Age * Target	21	11296.7	537.9	4.82	.000
Gender * Finger * Age * Target	21	1745.7	83.1	.75	.790
Error	15031	1678297.3	111.7		
Total	15159	12925780.0			

of females' index and middle fingers was only 3.8%p, the difference of males was remarkable at 10.8%p (Table 3 & Figure 3).

Table 3. Contributions of individual finger force by gender

	Index	Middle	Ring	Little
Female	31.6%	35.4%	24.7%	8.4%
Male	26.4%	37.2%	25.0%	11.4%

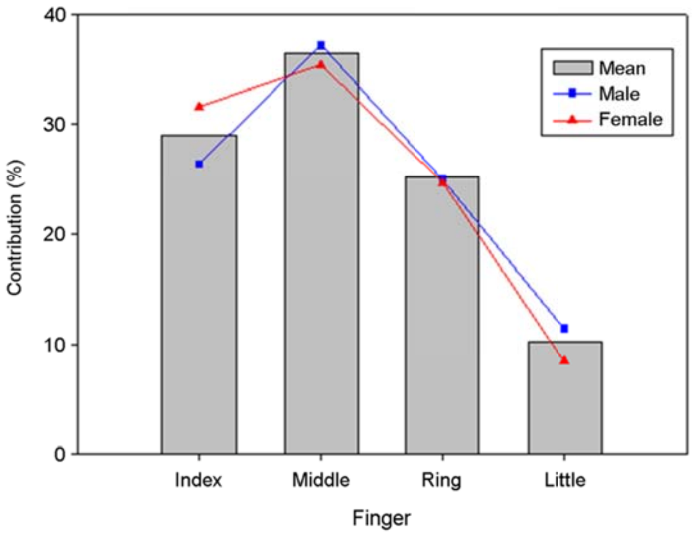

Figure 3. Contributions of individual finger force to the total grip force

3.2 Trends of individual finger force at various target force levels

The interaction effect between the finger and target force level for the individual finger contribution was statistically significant ($p < 0.001$). According to the analysis result, the largest contribution was found at the index finger, followed by middle, ring and little fingers at the smallest target force level (5% MVC). In the 15~55% MVCs, the contribution was shown in the following order: middle-index-ring-little finger. In the large target force levels (65 and 75% MVCs), the contribution was shown in the order of middle-ring-index-little finger. Therefore, as the target force level increased, the contributions of middle and ring fingers increased, whereas index finger's contribution decreased (Figure 4).

The interaction effect between the finger and target force level for the individual finger contribution was statistically different according to the age ($p < 0.001$). In the case of the elderly people, the contribution of ring finger was higher than that of index finger at 55% MVC of the target force level and higher (Figure 5, left). In the case of the young group, index finger's contribution was bigger than ring finger's contribution at all target force levels (Figure 5, right).

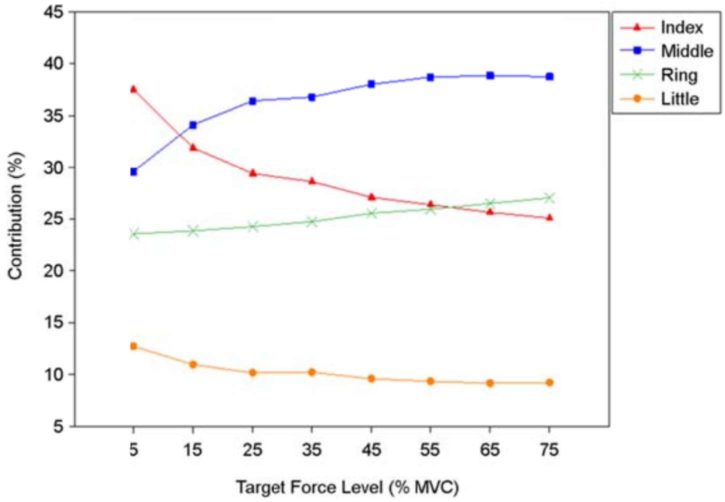

Figure 4. Trends of individual finger force contributions by target force levels

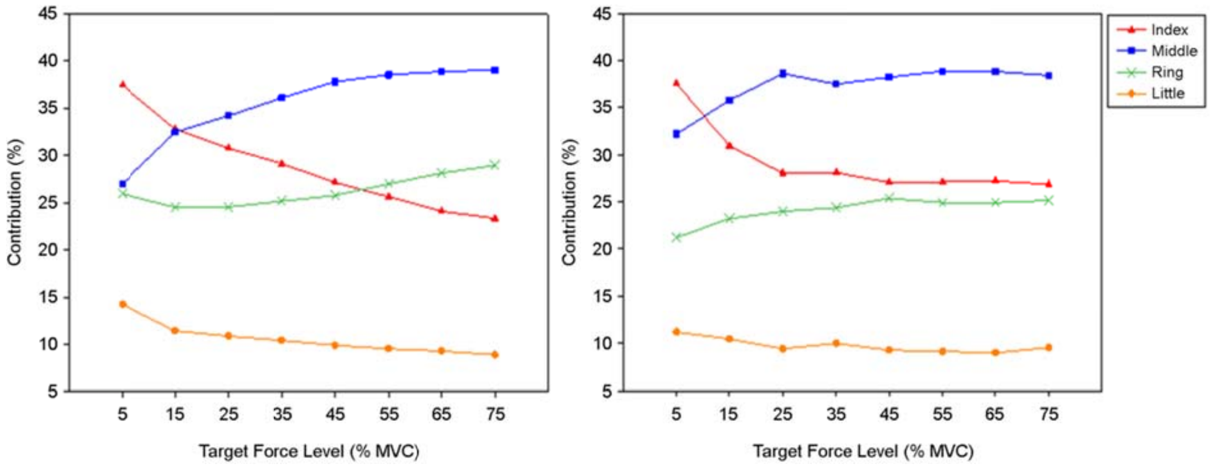

Figure 5. Interaction effects of individual finger and target force level (left: the elderly; right: the young)

4. Discussion

In this study, tracking task was conducted at the eight target force levels (5, 15, 25, 35, 45, 55, 65, 75% MVCs) to identify the change of finger's contribution according to the target level. As a result, middle finger's contribution was the largest at 36.4%, and the little finger's contribution was the smallest at 10.2%. The index finger and ring finger showed 29.9% and 25.2% of contribution, respectively.

The interaction effect of gender and fingers for the contribution was statistically significant. Males and females showed the same contribution trend in the order of middle-index-ring-little finger. However, females showed relatively higher contribution of index finger than males. Upon looking at the difference in the contributions of index and middle fingers, there was 3.8%p difference in females, but it was 10.8%p in males, which was about 2.8 times bigger than females. This means that females' use of index and middle fingers is relatively even, whereas males' middle finger use ratio is much higher. Therefore, it is desirable to fully consider the use of middle finger when designing hand tools for males.

The contributions of index and little fingers showed a decreasing trend as the target force level increased. On the other hand, the contributions of middle and ring fingers represented a decreasing trend as the target force level increased. For summarization, the contributions were shown in the order of index, middle, ring and little fingers at the smallest target force level (5% MVC). However, the contributions were shown in the order of middle, index, ring and little fingers at the medium level MVCs from 15% to 55% MVCs with the increase of middle finger's contribution.

Namely, the roles of index finger and middle finger were replaced at the target force level of 15% MVC, which was similar to the result of a study by Radwin et al. (1992) on the contributions in the case of exerting submaximal voluntary contraction (10, 20 and 30% MVCs).

According to Radwin et al. (1992), the contribution of index finger was larger than that of middle finger at the smallest MVC (10% MVC) and this result is similar to the result of the current study which shows the order of index-middle-ring and little finger at the smallest target force level (5% MVC). Radwin et al. (1992) also reported that the contributions were shown in the order of middle, index, ring and little fingers with middle finger's contribution being larger than index finger's contribution at the 20% and 30% MVCs, which showed the similar contribution result shown at the 15~55% MVCs in this study. In the relatively higher target force levels (65 and 75% MVCs), ring finger's contribution was higher than index finger's contribution, and showed in the contribution order of middle, ring, index and little fingers, which can be a similar trend with the existing studies on hand's contribution in the case of maximal grip force exertion (Kim and Kong, 2008; Kong and Lowe, 2005; Kong et al., 2008; Kong et al., 2011; Lee et al., 2009; Ohtsuki, 1981; Talsania and Kozin, 1998). According to the result of this study, middle and ring fingers play an important role in the case of exerting large grip force, and index finger is analogized to be mainly involved in a precise control of grip force.

The interaction effects of fingers and target force level showed different trends according to age. In the elderly group, ring finger's contribution was higher than index finger at the higher target force level of 55% MVC. However, in the young group, index finger's contribution was higher than ring finger at all target force levels. While the change of contribution was not huge according to target force level in the young group, the elderly group's contribution aspects were different according to target force level, and especially, ring finger was hugely involved upon exerting large grip force.

If finger's contribution is considered according to target force level, the design of hand tools for efficient use of index finger is predicted suitable upon exerting precise and small level of force. The design of hand tools mainly considering the use of middle and ring fingers upon exerting relatively large force of 65% MVC and higher should be conducted. The results of this study are expected to be helpful to the prevention of occupational musculoskeletal disorders and worksite's efficiency enhancement through hand tools reflecting the results in the design of ergonomic hand tools.

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