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To cite this article: Soo-Jin Lee , Yong-Ku Kong , Brian D. Lowe & Seongho Song (2009) Handle grip span for optimising finger-specific force capability as a function of hand size, Ergonomics, 52:5, 601-608, DOI: [10.1080/00140130802422481](https://doi.org/10.1080/00140130802422481)

To link to this article: <https://doi.org/10.1080/00140130802422481>



Published online: 28 May 2009.



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Handle grip span for optimising finger-specific force capability as a function of hand size

Soo-Jin Lee^a, Yong-Ku Kong^{b*}, Brian D. Lowe^c and Seongho Song^d

^aThe College of Medicine, Hanyang University, Seoul, Korea; ^bDepartment of Systems Management Engineering, Sungkyunkwan University, Suwon, Korea; ^cNational Institute for Occupational Safety and Health, Cincinnati, OH, USA; ^dDepartment of Mathematical Sciences, University of Cincinnati, OH, USA

Five grip spans (45 to 65 mm) were tested to evaluate the effects of handle grip span and user's hand size on maximum grip strength, individual finger force and subjective ratings of comfort using a computerised digital dynamometer with independent finger force sensors. Forty-six males participated and were assigned into three hand size groups (small, medium, large) according to their hands' length. In general, results showed the 55- and 50-mm grip spans were rated as the most comfortable sizes and showed the largest grip strength (433.6 N and 430.8 N, respectively), whereas the 65-mm grip span handle was rated as the least comfortable size and the least grip strength. With regard to the interaction effect of grip span and hand size, small and medium-hand participants rated the best preference for the 50- to 55-mm grip spans and the least for the 65-mm grip span, whereas large-hand participants rated the 55- to 60-mm grip spans as the most preferred and the 45-mm grip span as the least preferred. Normalised grip span (NGS) ratios (29% and 27%) are the ratios of user's hand length to handle grip span. The NGS ratios were obtained and applied for suggesting handle grip spans in order to maximise subjective comfort as well as gripping force according to the users' hand sizes. In the analysis of individual finger force, the middle finger force showed the highest contribution (37.5%) to the total finger force, followed by the ring (28.7%), index (20.2%) and little (13.6%) finger. In addition, each finger was observed to have a different optimal grip span for exerting the maximum force, resulting in a bow-contoured shaped handle (the grip span of the handle at the centre is larger than the handle at the end) for two-handle hand tools. Thus, the grip spans for two-handle hand tools may be designed according to the users' hand/finger anthropometrics to maximise subjective ratings and performance based on this study. Results obtained in this study will provide guidelines for hand tool designers and manufacturers for designing grip spans of two-handle tools, which can maximise handle comfort and performance.

Keywords: optimal grip span; two-handle tool designs; hand size; performance

1. Introduction

Grip span of two-handle tools is an important factor to maximise grip performance and minimise stress on the digit flexor tendons and first metacarpal ulnar collateral and carpometacarpal ligaments (Meagher 1987). Grip span can also influence force exertion in manual work during hand tool uses (Khalil 1973, Grant *et al.* 1992, Blackwell *et al.* 1999). The grip span of two-handle tools, among other design parameters, has also been hypothesised as a critical factor not only contributing to the work-related musculoskeletal disorders risk factors but also to the performance of the workers (Pheasant and Scriven 1983, Fransson and Winkel 1991, Blackwell *et al.* 1999).

A number of investigators have attempted to obtain the optimal grip span of two-handle tools for maximum grip strength resulting in various recommendations, from 45 mm to 66.3 mm (Petrofsky *et al.* 1980, Pheasant and Scriven 1983, Härkönen *et al.*

1993, Oh and Radwin 1993, Talsania and Kozin 1998). Petrofsky *et al.* (1980) tested 14 males and eight females with six grip spans (32 to 80 mm) and reported that the maximum grip strength occurred at a span between 50 and 60 mm in both female and male subjects. Pheasant and Scriven (1983) recruited 40 subjects (20 males and 22 females) and found that a handle separation of 45 to 55 mm was optimal for both males and females. According to Härkönen *et al.*'s (1993) experiment with ranges from 35 to 86 mm, male and female subjects provided the highest grip strength when they used a 60.3-mm grip span. Oh and Radwin (1993) and Talsania and Kozin (1998) also reported that the maximum grip strength grip spans were 50 to 60 mm and 56 mm, respectively.

Some researchers agreed with the findings of some studies for the average grip force difference between males and females (56% to 70% female grip strength to that of males; Pheasant and Scriven 1983, Härkönen

*Corresponding author. Email: ykong@skku.edu

et al. 1993, Talsania and Kozin 1998) and that between the dominant and non-dominant hand (80% to 89% non-dominant hand strength to the dominant hand; Ohtsuki 1981, Talsania and Kozin 1998). These researchers also showed a similar trend of decreasing grip strength above and below the optimal grip span, although there were various optimal grip spans.

However, there is a discrepancy between the results of these studies for the effects of users' hand size on optimal grip spans. Pheasant and Scriven (1983) and Härkönen *et al.* (1993) reported that the hand size did not affect the grip strength significantly, whereas Oh and Radwin (1993) and Eksioğlu (2004) reported that the optimal grip span depends on the user's hand size. In the study of Oh and Radwin (1993), subjects were arbitrarily divided into three hand-length groups (this was not the same criteria as used in the present study) and found that grip strength significantly increased as hand length increased for the university student subjects. Additionally, the researchers reported that the maximum grip strength occurred at a grip span of 50 mm for small- and medium-size hands and at a grip span of 60 mm for large-size hand subjects.

For the studies of individual finger forces, Talsania and Kozin (1998) reported that individual finger force contributions to total grip force were approximately 25%, 35%, 26% and 15% for the index, middle, ring and little finger, respectively. Kattel *et al.* (1996) and Farris *et al.* (1997) found that the effects of wrist postures on the individual finger forces were statistically significant and reported that the contribution of the middle finger to the total force was 33.9% to 39.5%, 25.5% to 31.5% for the index finger, 19.5% to 28.2% for the ring finger and 8.7% to 14.9% for the little finger. Although these researchers applied a similar methodology and measurement device (NK Digits Grip Device) as the current study, Talsania and Kozin (1998) tested only three grip spans (56 mm, 70 mm and 84 mm) and Kattel *et al.* (1996) and Farris *et al.* (1997) used only one fixed grip span (81.5 mm for males and 51 mm for females) for all subjects. In addition, subjects' hand sizes were not considered in their studies.

As mentioned above, the findings of the studies for optimal grip spans that can provide maximum grip strength were diverse and the results of the effects of user's hand size on optimal grip spans and grip strength were contributable in two-handle tools. Thus, the primary objective of the present study was to investigate the relationship between users' hand size and handle grip span in terms of maximising grip force capability. The secondary objective was to investigate the finger-specific force contribution to maximum grip force at the ideal handle span using a specialised hand grip dynamometer with individual force sensors.

2. Methods

2.1. Subjects

Altogether, 46 male subjects between 20 and 39 years of age (mean 25.9 ± 4.9 years) were recruited through advertising from the University of Cincinnati. Each participant was paid at a rate of \$15.00 per hour for participation. Participants were all healthy volunteers and free of known musculoskeletal injuries. At the beginning of the experiment, informed consent was obtained and anthropometric measurements including hand thickness, hand width, hand length and wrist circumference were measured. Hand length was defined by the distance from the crease of the wrist to the tip of the middle finger with the hand held straight and stiff. Details are described in Table 1. Based on the hand length, each participant was assigned into one of the following three hand size groups: (1) small hand, up to 186.0 mm; (2) medium hand, 186.1 to 196.3 mm; (3) large hand, over 196.3 mm.

2.2. Instrumentation

The NK DIGITS-grip measurement system (NK Biotechnical Corp., Minneapolis, MN, USA), which contains four sensors, was used to accurately measure the force contributions of each individual finger as well as the total grip force. Custom made slip-on adapters were used to test five grip spans from 45 mm to 65 mm, in 5-mm increments, (Figure 1). The data acquisition program (HAS2003) provided by NK Biotechnical Corp. was used to record the strength data of each individual finger force (index, middle, ring and little finger) and total grip force (sum of four finger forces) and displayed in both numerical and graphical formats.

2.3. Experimental design

To evaluate the effects of grip span and user's hand size on the subjective preference and grip finger forces, five grip spans (45, 50, 55, 60 and 65 mm) and three levels of hand size (small, medium and large) were

Table 1. Characteristics of the subjects.

Variable (n = 46)	Mean (SD)	Min–Max
Age (years)	25.9 (4.9)	20–39
Height (mm)	176.0 (6.6)	163–195
Weight (kg)	73.9 (10.7)	54.5–103.5
Hand thickness (mm)	30.4 (2.4)	23.9–34.5
Hand width (mm)	83.0 (4.8)	72.1–97.3
Hand length (mm)	187.1 (8.7)	173.5–208.0
Wrist circumference (mm)	171.4 (9.9)	144.0–192.0

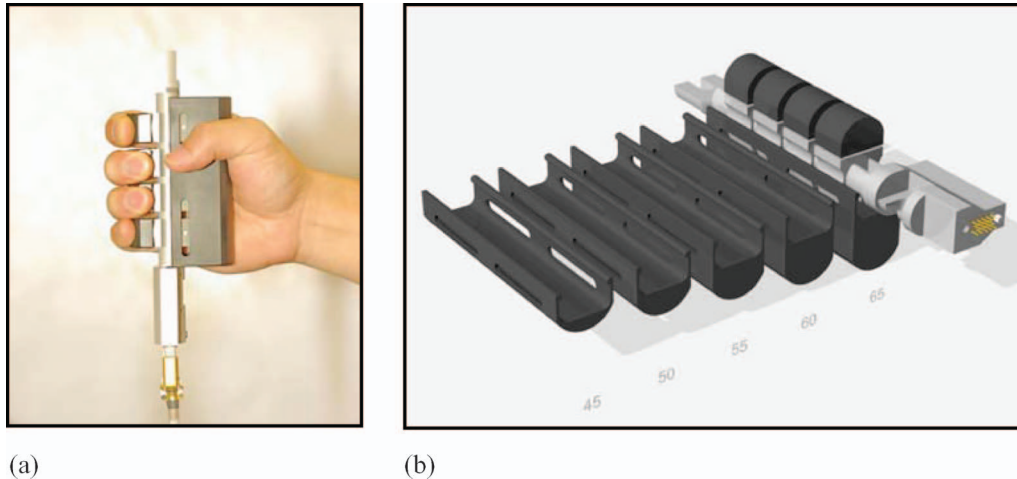


Figure 1. Grip force measurement system (a) and custom made five slip-on adapters (b).

evaluated. Based on the hand size criteria, 25 recruited subjects fell into the small hand-size group, 12 subjects fell into the medium hand-size group and nine subjects fell into the large hand-size group. Subjects were nested under the hand-size group. The subject was considered as a random effect variable and all others were considered as fixed effect variables. This was an unbalanced design and all grip spans were assigned in a random order for each subject.

2.4. Experimental procedures

Subjects were provided with a brief description of the purpose and procedures of the experiment. Each subject was seated upright in a chair with the forearms bent at 90° to the upper arm and wrist and forearms in a neutral position. Subjects were instructed to exert as fast as possible (about 1 s) to reach their maximum from an initial state of relaxation and then to maintain their maximum isometric grip exertion for 3 s. The average of maximum isometric grip force during the last 3 seconds was measured. A chair with an armrest was used to support the subject's forearm while testing. The hand of the subject and the NK DIGITS-grip dynamometer held in the grip were unsupported as they extended beyond the end of the armrest. Visual feedback regarding performance was not allowed. Five different grip spans were tested, 45, 50, 55, 60 and 65 mm, by replacing slip-on adapters. Three trials for each grip span were performed with 2 min resting time between trials. All subjects were asked to provide a subjective ranking of overall hand comfort associated with each grip span. Subjective rankings were obtained from the ranking of the five span settings.

2.5. Experimental model

In this experiment, subject factors are similar but not identical for the different hand-size groups. In this case, the nested-factorial design is an appropriate statistical analysis model with the subjects nested under the hand-size group. Subjects are selected randomly from each level of hand size. The factor of hand sizes and grip span are fixed and the subjects factor is random. The statistical model for the nested-factorial design is as follows:

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{k(j)} + (\alpha\beta)_{ij} + \varepsilon_{(ijk)l}$$

where α_i is the effect of the grip span, β_j is the effect of the hand size, $\gamma_{k(j)}$ is the effect of the subject within the level of hand size and $(\alpha\beta)_{ij}$ is the interaction effect of grip span and hand size. For hypotheses testing, the errors $(\varepsilon_{(ijk)l})$ are assumed to be normally and independently distributed with mean zero and variance (σ^2) and the random effect $(\gamma_{k(j)})$ normally and independently distributed with mean zero and variance (σ_r^2) . Independence between $\varepsilon_{(ijk)l}$ and $\gamma_{k(j)}$ is also assumed. The significance level of all the tests is $\alpha = 0.05$.

3. Results

3.1. Subjective comfort ranking

Statistical analysis with the nested-factorial design showed that the effects of grip span ($p < 0.001$) and the interaction of hand size and grip span ($p = 0.0134$) on the subjective comfort ranking (1 = most, 5 = least) were statistically significant at the significant level $\alpha = 0.05$. Figure 2 shows the results of the evaluation of subjective comfort in the maximum

gripping task with various grip spans from 45 mm to 65 mm. Tukey’s multiple comparison test showed that, overall, participants rated the 55- and 50-mm grip spans more highly for comfort, whereas the 45- and 65-mm grip spans were rated as less comfortable than the other grip spans.

In the interaction effect between hand size and grip span, small and medium hand-sized groups rated 55- and 50-mm grip spans as comfortable handles and 65-mm grip span as the least comfortable handle, whereas the large hand-sized group reported that the 55- and 60-mm grip spans were more comfortable than others, and the 45-mm grip span was the least comfortable grip span.

3.2. Total grip force

Statistical analysis of total grip force showed that the main effect of grip span ($p < 0.0001$) and the interaction effect of grip span and hand size ($p = 0.003$) were statistically significant for the total grip force. In all three hand-size groups, participants produced a

high grip force at 55- and 50-mm grip spans (433.6 N and 430.8 N, respectively), followed by 45-mm and 60-mm. A 65-mm grip span showed the least grip force (378 N) over the other grip spans. Table 2 shows a summary of total grip force for hand size and grip span.

In the analysis of the interaction effect of grip span and hand size, the highest total grip forces were obtained for the small hand group at the 45-mm grip span, followed by 50 and 55 mm, for the medium hand group at the 55-mm grip span followed by 50 and 45 mm and for the large hand group at the 55-mm grip span followed by 60 mm. As mentioned before, the 65-mm grip span had the least total grip force of all three hand-size groups.

In general, the average total grip force of the large hand group (470.3 N) was 11.0% and 19.2% higher than the medium hand group (423.6 N) and small hand group (394.5 N), respectively. The average total grip force of the medium hand group was 7.4% higher than the small hand group.

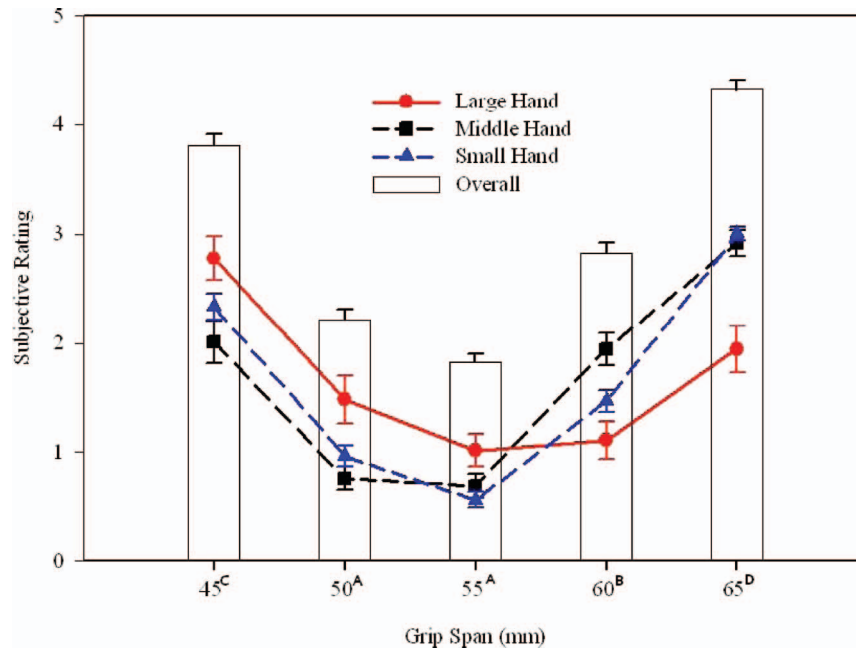


Figure 2. Subjective rankings for grip span: 1 = most comfortable; 5 = least comfortable.

Table 2. Total grip force for hand size and grip span.

	45 mm	50 mm	55 mm	60 mm	65 mm
Overall	427.9 N ^{AB}	430.8 N ^A	433.6 N ^A	414.6 N ^B	378.0 N ^C
Small hand	411.2 N ^A	410.9 N ^A	404.8 N ^A	391.2 N ^B	354.6 N ^C
Medium hand	438.9 N ^A	442.4 N ^A	447.1 N ^A	411.7 N ^B	378.1 N ^C
Large hand	459.3 N ^{CD}	470.5 N ^{BC}	495.6 N ^A	483.3 N ^{AB}	443.0 N ^D

Note: Superscript letters indicate Tukey multiple test results, i.e. same letters are not significantly different.

3.3. Subjective comfort ranking and total grip force vs. normalised grip span

Normalised grip span (NGS), the ratio of grip span to user's hand length, was applied to determine the optimum grip span for maximising subjective comfort and total grip force based on the user's hand size in this study. NGS was defined by the following equation:

$$NGS_{ij} = \frac{GS_j}{HL_i} * 100 \quad (1)$$

where, i = subject, j = handle, NGS_{ij} = NGS of subject i for handle j , GS_j = grip span (mm) of handle j , HL_i = hand length (mm) of subject i .

The following regression models (Equations (2) and (3)), representing the relationship between subjective comfort ranking and NGS, and total grip force ranking and NGS were used to derive the optimal NGS that maximises subjective comfort and total grip force. Total grip forces for handle sizes for each participant were converted into rankings to normalise the grip force for each participant.

$$\text{Subjective comfort ranking} = 0.0523 * (NGS)^{2-} \\ 3.0354 * (NGS) + 46.22, R^2 = 0.37 \quad (2)$$

$$\text{Total grip force ranking} = 0.0262 * (NGS)^{2-} \\ 1.4143 * (NGS) + 21.482, R^2 = 0.24 \quad (3)$$

The optimal NGS at 29% and 27% were obtained based on the first derivative of Equations (2) and (3) ($NGS\% = 3.0354/(2*0.0523)$; $NGS\% = 1.4143/(2*0.0262)$). The optimal NGS were used to derive the recommended grip spans associated with the user's hand length (recommended grip span = user's hand length*NGS), as shown in Table 3.

3.4. Individual finger force

Table 4 summarises individual and total finger forces with the contribution of finger force to the total finger force as a function of grip spans. As expected, the finger contributing the most to the total force was the middle finger (average force 156 N, contribution 37.5%), followed by the ring (119.6 N, 28.7%) and index (84.1 N, 20.2%) fingers. The average force and contribution of the little finger were 56.9 N and 13.6%, respectively. The individual finger forces were related to grip span. Based on the Tukey test, the middle finger force was the largest at 55 mm and decreased when grip span decreased or increased, whereas the little finger force showed a significantly decreasing trend as the grip span

Table 3. Recommended grip spans for hand sizes based on maximising handle comfort and grip force using normalised grip span (NGS) ratios.

Hand size	Hand length (mm)	Grip span (29% NGS)* (mm)	Grip span (27% NGS)† (mm)	Grip span (overall) (mm)
Small hand	175.0–186.0	51–54	47–50	47–54
Medium hand	186.0–196.3	54–57	50–53	50–57
Large hand	196.3–205.0	57–60	53–55	53–60

*29% NGS corresponds to subjective comfort.

†27% NGS corresponds to grip force.

increased (largest at 45 mm and least at 65 mm). In both index and ring finger forces, the least finger forces were also obtained at a 65-mm grip span.

The analysis of the interaction effects of hand size and grip span for each finger is shown in Table 5. Results indicated the interaction effects were significant on the middle and ring fingers ($p = 0.0049$ and $p = 0.0061$, respectively). With regard to the middle finger, small- and medium-hand participants exerted their maximum finger force at 50- and 55-mm, whereas large-hand participants produced their maximum finger force at 55 and 60 mm. For the ring finger, the small-hand group exerted a maximum force at 45 and 50 mm, and the medium-hand group showed a maximum force from 45 to 55 mm, whereas the large-hand participants showed their maximum force at 55- and 60-mm grip spans.

Two-handle hand tools could be designed with different grip spans for each finger. For instance, the grip spans for the index, middle and ring fingers could be greater than that of the little finger, while the grip spans of the middle finger could be slightly greater than that of the index or ring finger associated with users' hand size. Table 6 shows the recommended grip spans for each finger based on the users' hand sizes.

4. Discussion

The evaluation of subjective ranking for handle comfort indicated that, overall, participants preferred the 50- to 55-mm grip span over the smallest (45 mm) or the largest grip span (65 mm). Total grip force showed the highest grip force in the 50- to 55-mm grip spans. The largest grip spans showed the least subjective comfort as well as the least grip force exertion. In this study, subjective ratings did appear to be influenced by the performance of total grip force.

An interaction effect was observed between hand size and grip span in both subjective ratings and total grip force analyses. The small- and medium-hand users

reported that 50 and 55 mm were comfortable sizes and the largest grip span (65 mm) was the least comfortable size. They also exerted the highest grip force at the 45 to 55 mm grip span and the lowest grip force at 65 mm, which was the least comfortable grip span. The large-hand group reported slightly larger grip spans (55 to 60 mm) as comfortable handle sizes and the smallest grip span (45mm) as the least comfortable size. They also exerted the highest grip force at 55 to 60 mm, which were rated as the more comfortable sizes. Thus, the small- and medium-hand groups generally preferred middle sizes or small grip spans, whereas the large-hand group preferred middle or large grip spans. Thus, this study shows that the maximum total grip force follows the same trend with the subjective ratings of hand comfort. This result is in agreement with a previous study (Eksioglu 2004).

Total grip force varies according to grip spans and hand size in this study. This can be explained by the force-length relationship in the finger flexor muscles of

the forearm such as flexor digitorum profundus and flexor digitorum superficialis. According to the sliding filament model of muscle contraction, muscles consist of overlapping arrays of actin and myosin filaments that can slide past each other. When a muscle contracts, the active sliding force between the filaments can be developed by cross-bridges on these two protein filaments (Huxley 1973). Maximum muscle force generation is possible in the resting length of the muscle with a maximal number of cross-bridges and the maximum muscle force is reduced above and below this length of muscle with non-maximal cross-bridge conditions. Changes of the grip strength in two-handle tools for various grip spans were also reported in Fransson and Winkel (1991). They reported that not all fingers can grip properly around the handle of the tool, resulting in a loss of grip strength for wide-hand grip spans.

NGS is defined simply as the relationship between handle grip span and a user's hand length. In this study, optimal ratios of 29% and 27% of NGS were obtained by the regression equation (Equations (2) and (3)) and applied to recommend the most comfortable handle grip spans and highest performance handle grip span associated with users' hand length, as shown in Table 3. Although there are some differences in recommended grip sizes due to ratios (i.e. recommended grip spans of maximum performance were slightly smaller than that of maximum subjective ratings), an advantage of applying NGS is assigning different handle grip spans to users who have different hand lengths rather than assigning only one size of grip span to everyone. The current findings were slightly different from the previous researchers' findings for maximum grip strength test using various grip spans (Petrofsky *et al.* 1980: 50–60 mm, Pheasant and Scriven 1983: 45–55 mm, Härkönen *et al.* 1993: 60.3 mm, Oh and Radwin 1993: 50–60 mm, Talsania and Kozin 1998: 56 mm). In Table 3, the

Table 4. Total individual finger forces and contributions.

Grip span	Total force	Mean forces of individual fingers and percentage contributions			
		Index	Middle	Ring	Little
45 mm	427.9 N	84.8 N ^A (19.83%)	154.3 N ^B (36.06%)	124.4 N ^A (29.08%)	64.3 N ^A (15.04%)
50 mm	430.8 N	86.9 N ^A (20.18%)	160.7 N ^{AB} (37.29%)	123.3 N ^A (28.63%)	59.9 N ^B (13.90%)
55 mm	433.6 N	87.8 N ^A (20.26%)	163.8 N ^A (37.77%)	123.8 N ^A (28.54%)	58.2 N ^B (13.43%)
60 mm	414.5 N	83.4 N ^A (20.11%)	156.6 N ^B (37.77%)	120.7 N ^A (29.11%)	54.0 N ^C (13.02%)
65 mm	378.0 N	77.5 N ^B (20.51%)	146.7 N ^C (38.79%)	106.0 N ^B (28.03%)	47.9 N ^D (12.67%)
Mean	417.0 N	84.1 N (20.18%)	156.4 N (37.54%)	119.6 N (28.68%)	56.9 N (13.61%)

Note: Superscript letters indicate Tukey multiple test results, i.e. same letters are not significantly different).

Table 5. Interaction effects of hand size and grip span for each finger.

Finger	Hand Size	45 mm	50 mm	55 mm	60 mm	65 mm
Index	Small hand	80.9 N ^A	80.5 N ^A	81.2 N ^A	77.2 N ^{AB}	73.1 N ^B
	Medium hand	88.2 N ^A	91.4 N ^A	91.9 N ^A	86.2 N ^A	77.2 N ^B
	Large hand	91.1 N ^B	98.9 N ^A	100.8 N ^A	96.6 N ^{AB}	90.3 N ^B
Middle*	Small hand	152.9 N ^{AB}	158.5 N ^A	157.6 N ^A	151.7 N ^B	140.6 N ^B
	Medium hand	154.3 N ^B	161.9 N ^{AB}	165.2 N ^A	155.3 N ^B	143.0 N ^C
	Large hand	157.9 N ^C	164.7 N ^B	179.1 N ^A	171.6 N ^{AB}	168.3 N ^B
Ring*	Small hand	119.3 N ^A	118.1 N ^{AB}	115.2 N ^{AB}	114.0 N ^B	98.5 N ^C
	Medium hand	127.2 N ^A	124.4 N ^A	125.4 N ^A	115.5 N ^B	106.2 N ^C
	Large hand	135.1 N ^B	136.5 N ^B	145.3 N ^A	145.9 N ^A	126.4 N ^C
Little	Small hand	58.0 N ^A	53.8 N ^B	50.8 N ^{BC}	48.2 N ^C	42.5 N ^D
	Medium hand	69.3 N ^A	64.6 N ^B	64.7 N ^B	54.6 N ^C	51.6 N ^C
	Large hand	75.3 N ^A	70.4 N ^{AB}	70.5 N ^{AB}	69.1 N ^B	58.0 N ^C

*Statistically significant.

Table 6. Recommended grip spans for each finger according to the hand-size group.

Finger	Small Hand	Medium Hand	Large Hand
Index	45–50 mm	50–55 mm	50–55 mm
Middle	50–55 mm	50–55 mm	55–60 mm
Ring	45–50 mm	45–55 mm	55–60 mm
Little	45 mm	45 mm	45 mm

recommended handle grip spans for the grip force were 47 to 50 mm, 50 to 53 mm and 53 to 55 mm for the small, medium and large hand-size groups, respectively. The results of NGS will provide guidelines for designing two-handle hand tools to provide maximum handle comfort and task performance for various hand sizes in a maximum gripping task.

Individual finger force and the contribution to the total grip force in a maximal hand dynamometer grip exertion were investigated in this study. The traditional hand grip dynamometer exertion involves finger contact that is distributed mostly on the middle phalangeal segments. This is a different pattern of hand contact force from the grip of handles that are more cylindrical in shape, in which the distal phalanges create a larger percentage of the contact force. However, in terms of the finger-specific contribution of each finger to total hand force, the findings of the present study are in agreement with those of previous studies (Hazelton *et al.* 1975, Ohtsuki 1981, Amis 1987, Kattel *et al.* 1996, Farris *et al.* 1997, Talsania and Kozin 1998, Kong and Lowe 2005a). The contribution by the middle finger to total grip force was the largest (37.5% in this study, ranging from 33 to 39.2% in previous studies) and the contribution by the little finger to the total grip force was the least (13.6% in this study, ranging from 11.7 to 18% in previous studies). The results of contributions of the index (20.2%) and ring (28.7%) fingers were similar to the results reported in other grip force studies. The relationship between grip span and individual finger force showed that the middle finger force was decreased when grip span decreased or increased from the 55-mm grip span, whereas the little finger force was apparently decreased when grip span increased from 45 mm to 65 mm. All four fingers exerted the least finger force at the largest grip span (65 mm).

Figure 3 compares the findings of the present study, in which the NK Digits-grip system was used to characterise the finger-specific contribution to the maximum hand grip force, with the findings of two previous studies in which thin profile force sensors were attached over the phalangeal segments and metacarpals of the hand to similarly quantify grip force distribution over the fingers. The studies using

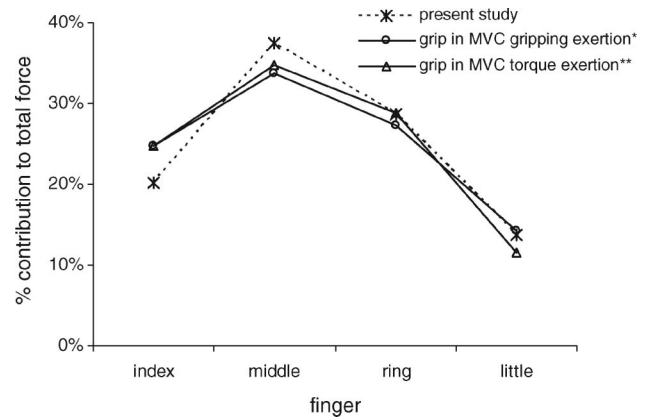


Figure 3. Comparison of the mean finger force distribution observed in the present study (measured with NK Digits-grip) with those reported in recent studies using thin profile force sensors to measure the finger-specific contribution to the total grip force in both maximum gripping and maximum torque exertion. *From Kong and Lowe (2005a); **from Kong and Lowe (2005b). MVC = maximum voluntary contraction.

thin profile force-sensing resistors (Kong and Lowe 2005a,b), for maximum grip force and maximum torque tasks, exhibit patterns with finger-specific contributions to the total grip force similar to that measured in the present study.

The analysis of the interactions of users' hand sizes and grip spans for each finger showed that the middle and ring fingers had the optimal finger spans and can provide the maximum finger force associated with users' hand size. In the small- and medium-hand users, the optimal finger spans for the middle and ring fingers were 50 to 55 mm and 45 to 50 mm, respectively. In the large-hand users, the optimal finger spans for the middle and ring fingers were the 55- to 60-mm grip spans. For users of all hand sizes, the optimal finger spans for the little finger to provide maximal finger force may not exceed a 45-mm grip span. Based on these results, different finger spans for each finger and each hand size are observed. Therefore, a bow-contoured handle profile, which has a different span for each finger, appears to be a better design than the straight handle 'A-shaped' design, which has the widest span at the end closest to the gripping point of the little finger.

The R-squares of Equations (2) and (3) for explaining the dependent measures with the hand length factor only were relatively low. In future studies, the other hand anthropometric data including hand thickness, hand width, wrist circumference and even other body anthropometric data such as forearm dimensions, height or weight should be included in the study of grip force strength as well as subjective preference for grip spans.

5. Conclusion

This study investigated the effects of handle grip span and user's hand size on maximum grip strength, individual finger force and the subjective ratings of comfort using a digital dynamometer. The findings of the current experiment led to the following conclusions:

- (1) Subjective ratings for handle comfort: Participants generally preferred grip spans of 50 to 55 mm. Grip spans of 45 and 65 mm were rated the lowest according to subjective preferences in the maximum grip strength test. The small- and medium-hand users rated 50 and 55 mm as the most comfortable sizes and 65 mm grip span as the least comfortable size, whereas the large-hand group rated 55 to 60 mm as the most comfortable handle sizes and the 45 mm grip span as the least comfortable size.
- (2) Total grip force: The largest grip strength occurred at a grip span between 50 to 55 mm and the lowest strength occurred at a grip span of 65 mm in all three hand size groups. The small-hand group exerted the highest grip strength using a 45-mm grip span, whereas the medium- and large-hand groups exerted the highest grip strength using a 55-mm grip span.
- (3) NGS was applied to recommend the most comfortable and highest performance handle grip span associated with users' hand lengths in this study.
- (4) Individual finger force: The average contribution of each finger to the total grip force was investigated in this study, 20%, 37.5%, 28.7% and 13.6% for the index, middle, ring and little fingers, respectively. The relationship between grip span and individual finger force showed that the middle finger force was decreased when the grip span decreased or increased from the 55-mm grip span, whereas the little finger force was apparently decreased when the grip span increased from 45 mm to 65 mm. All four fingers exerted the least finger force at the largest grip span (65 mm).

Acknowledgements

This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (R01-2007-000-10915-0). The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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