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Study on the grip spans of combination pliers in a maximum gripping task

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ABSTRACT

A newly developed system was applied in this study to evaluate the effects of the grip spans (45–80 mm) of combination pliers on the total grip strength, individual finger force, resultant force, and subjective discomfort. A total of twenty-six males participated and were asked to exert their maximum grip strength with two repetitions. The highest and the lowest total grip strength and resultant force (311.8 N and 737.9 N vs. 210.1 N and 501.7 N) were obtained at a 60 mm and 80 mm grip spans, respectively. In general, the participants considered the 50 and 60 mm grip spans as being the least discomfort, whereas the 80 mm grip span was considered as the most discomfort grip span in a maximum grasping task. The results can be utilized as basic data for the manufacturing and design industries of two-handle hand tools, such as pliers and wrenches.

Practitioners summary: Custom-made combination pliers were applied in this study to evaluate grip strength, resultant force, and subjective discomfort, relative to five grip spans. The authors expect that the results of the present study will provide valuable information for the designers and users of pliers.

1. Introduction

Despite the automation of production facilities and the development of efficient motor-driven tools, many jobs performed by workers required the use of hand tools (Cochran and Riley, 1986; Hakkanen et al., 1997; Lin et al., 2007). In most manufacturing or assembling processes, workers hold or manipulate various machine parts using hand tools (Mital and Kumar, 1998; Dianat et al., 2012). When workers use non-ergonomic hand tools, they tend to apply unnecessary force or adopt awkward postures for hands, wrists, and shoulders. In particular, if the upper extremities are repeatedly applied for the use of hand tools, an increase occurs in the risk of upper extremity musculoskeletal disorders (MSDs) such as tendinitis, stenosing tenosynovitis (trigger finger or trigger thumb), carpal tunnel syndrome, and shoulder tendinitis (Brickbeck and Beer, 1975; Masear et al., 1986; Silverstein et al., 1987; Kim, 2012; Fernandez and Marley, 2014). Thus, designing the appropriate hand tools suitable for users is very important to reduce the risk of work-related MSDs (WMSDs).

Tool users experience discomfort resulting in body stress, according to the studies conducted by Fellows and Freivalds (1991) and Aldien et al. (2005a,b). Along with repetition, awkward postures, vibrations, and forceful exertion were considered critical factors that caused MSDs resulting from the use of hand tools (Armstrong et al., 1990; Nazari et al., 2012; Dianat and Salimi, 2014). Furthermore, researchers have noted that most tasks that require the use of hand tools included one or more of these factors (Chang and Wang, 2000; Aldien et al., 2005a,b; Das, 2007).

To prevent hand-related MSDs resulting from the use of hand tools, researchers have attempted to design appropriate handles by considering such characteristics as size, shape, surface material, and texture (Cochran and Riley, 1982; Fraser, 1983; Fellows and Freivalds, 1991; Grant et al., 1992; Kong and Freivalds, 2003; Eksioglu, 2004; Kong and Lowe, 2005; Jung et al., 2007; Lowndes et al., 2012; McDowell et al., 2012; Dianat et al., 2016). Numerous studies have shown that the handle grip span is an important hand tool design factor to maximize grip strength, reduce stress on the digit flexor tendons, and avoid stress to the first metacarpal ulnar collateral and carpometacarpal ligaments (Chaffin and Anderson, 1984; Meagher, 1987; Grant et al., 1992; Blackwell et al., 1999).

Only a few studies have examined hand tools with angulated

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handles, such as various types of pliers and nippers associated with grip spans, although hand tools with one-handle grips such as drivers, hammers, and meat hooks have often been studied (Pheasant and Scriven, 1983; Grant et al., 1992; Talsania and Kozin, 1998; Kong and Freivalds, 2003; Eksioglu, 2004; Penzkofer et al., 2015). Of the results of hand tool studies related to angulated handles, Fransson and Winkle (1991) evaluated the traditional grip and reversed grip for slip joint pliers and suggested an optimum grip span (the highest resultant force) for males of 55–65 mm and for females of 50–60 mm. Greenberg and Chaffin (1977) recommended 64–89 mm as the optimum grip span for adult males, while Kong et al. (2014) suggested the most recommended grip spans were 45–50 mm, in terms of the strength of maximum exertion according to the A-handle force measurement (AFM) system. However, the AFM system relies on A-shape mock-ups, which were custom-made by a rapid prototype machine (3D printer). Hence, these handles were not associated with real hand tools. Thus, Kong et al. 2011 finding may not be suitable for its application to the design of real commercially available hand tools.

In general, many types of pliers have been used mainly for cutting electrical wires, tying different parts together, holding materials during assembly, and fastening and unfastening components (Li, 2003) in many occupational areas such as construction (Anton et al., 2001; Li, 2002; Vi, 2006; Husain et al., 2013), electrical assembly (Groenesteijn et al., 2004), and telecommunications (Paivinen, 2006). Combination pliers have not yet been studied, to our knowledge, in spite of the wide use in many industry sites of combination (lineman's) pliers that have a snub nose, short-round handles, and a multi-function head.

Thus, the objectives of this study include: (1) to evaluate the effects of grip span on total grip strength, individual finger force, resultant force, and subjective discomfort rating; (2) to investigate the contribution of individual finger forces to the total grip strength associated with the grip span; and (3) to suggest guidelines, based on this study, for the grip spans of combination pliers to hand tool users or designers, or both.

2. Methods

2.1. Participants

A total of 26 males, with no history of upper extremity MSDs, volunteered for this study. At the beginning of the experiment, each participant was given an informed consent form and a brief description of the goals and procedures of the experiment. The means and standard deviations (SDs) of the participants' age, height, and weight were 25.8 ± 1.5 years, 173.8 ± 5.4 cm, and 74.0 ± 12.9 kg, respectively. The average hand length, hand width, and hand thickness were 18.5 ± 0.7 cm, 8.1 ± 0.3 cm, and 2.9 ± 0.2 cm, respectively. Further details about the characteristics of the participants are summarized in Table 1.

2.2. Measurement system

Combination pliers with an adjustable grip span were developed for this experiment. An adjustable mechanism was applied to the region between the hinge and the front part of the combination pliers handles so that the grip spans could be changed in a 45–80 mm range. Four load cells (Model 13 subminiature load cell, ranging from 0 to 50 lb., 3/8″ diameter; Honeywell) were also mounted in the handles of combination pliers and one load cell (Model 13 subminiature load cell) was inserted into the jaws of the pliers to measure individual finger force and resultant force, respectively, with a sampling rate of 10 Hz (Fig. 1, top). All five load cells were calibrated by known weights (1–5 kg) on a custom-made calibration fixture due to their large linearity of ±0.5% full scale. The output data (voltage) from the load cells were measured using a NI USB-6259 DAQ board and analyzed using a data acquisition program written in LabVIEW software (National Instrument; Austin, TX, USA). The correlation (R^2) between the output voltage data and applied known weights was more than 0.998 for all load cells. The display of the data acquisition program was composed of two large windows for the total grip strength and resultant force and there were four small windows for each finger force (Fig. 1, bottom).

The combination pliers were modified to change the grip span from 45 to 80 mm when there was no object between the jaws of the pliers. Five grip spans were chosen for this experiment (45 mm, 50 mm, 60 mm, 70 mm, and 80 mm), and the grip span was defined as the distance between the middle finger-side handle and the palm-side handle. More details about the specifications of the combination pliers are summarized in Table 2.

2.3. Experimental procedures

Before the experiments, the participants completed a questionnaire about upper extremity MSDs. The anthropometric data of each participant were assessed. Then, prior to the experiments, all participants were provided with a brief description of the experimental procedure and performed a practice test for familiarization with the grasping task.

For this study, the participants exerted their maximum grip force by gripping the handles of the pliers. All participants were instructed to apply exertion as fast as possible (about 1 s) to reach their maximum from an initial state of relaxation and then to maintain their maximum grip exertion for 4 s. After applying their maximum exertion, they were asked to relax. The average of maximum exertion force during the last 4 s was measured. The participants were given three minutes to rest between each trial in order to minimize muscle fatigue. The maximum grasping task was repeated twice for each grip span (45 mm, 50 mm, 60 mm, 70 mm, and 80 mm) hence, each participant performed ten exertions. The trials were selected in a random order. After performing a grasping

Table 1
Characteristics of participants.

	Mean ± SD	Range		Mean ± SD	Range
Age (yr)	25.8 ± 1.5	23.0–30.0	Wrist circumference (cm)	16.0 ± 0.7	14.8–17.9
Weight (kg)	74.0 ± 12.9	56.7–113.2	Hand length (cm)	18.5 ± 0.7	17.4–19.8
Height (cm)	173.8 ± 5.4	156.4–184.5	Hand width (cm)	8.1 ± 0.3	7.6–8.6
Sitting height (cm)	79.3 ± 8.6	41.4–87.2	Hand thickness (cm)	2.9 ± 0.2	2.6–3.2
Arm length (cm)	54.1 ± 4.5	35.0–59.4	Palm length (cm)	10.7 ± 0.5	10.0–12.0
Upper arm length (cm)	34.8 ± 5.3	30.1–59.8	Index finger length (cm)	7.1 ± 0.4	6.4–8.0
Lower arm length (cm)	26.4 ± 1.6	23.1–30.3	Middle finger length (cm)	7.8 ± 0.4	7.2–8.5
Upper arm circumference (cm)	31.2 ± 3.4	25.2–38.4	Ring finger length (cm)	7.3 ± 0.4	6.7–8.1
Lower arm circumference (cm)	25.5 ± 1.6	22.8–29.3	Little finger length (cm)	6.0 ± 0.3	5.5–6.7

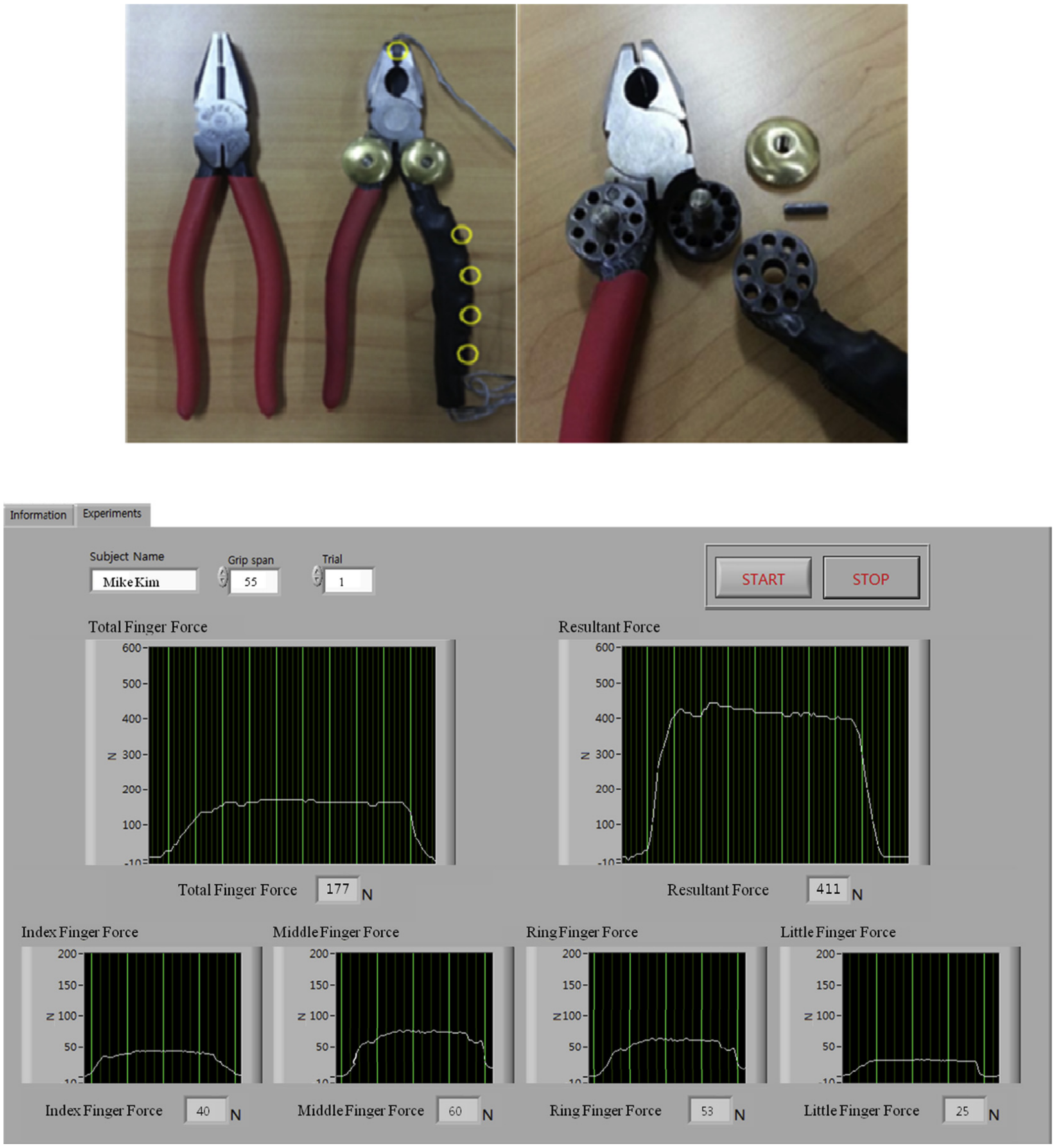

Fig. 1. Custom-made combination pliers and location of inserted load cells (top); Display of data acquisition program written in LabVIEW (bottom).

Table 2
Specifications of combination pliers.

Grip span (mm)	45	50	60	70	80
Index	40.7	45.8	51.5	57.7	62.0
Middle	45.0	50.0	60.0	70.0	80.0
Ring	40.0	49.8	62.6	72.3	86.5
Little	30.8	44.0	60.2	72.1	90.4

task, each participant was asked to provide a subjective discomfort rating for each grip span using the Borg CR10 scale.

The electrical signal outputs from four load cells (Model 13 subminiature load cell; Honeywell) were converted into digital signals and then sent to a computer using a National Instrument USB-6008 DAQ board. The individual finger force, total grip strength, and resultant force were collected and analyzed using LabVIEW software. The total grip strength was obtained by adding up the four individual finger forces.

2.4. Data analysis

In this study, a repeated-measures analysis of variance was applied (SPSS v. 18.0; significance level of 0.05) to evaluate the effects of the five levels of grip spans (45 mm, 50 mm, 60 mm, 70 mm, and 80 mm) on the four measured responses (total grip strength, individual finger force, resultant force, and subjective discomfort ratings). The Tukey's test was also used as a post-hoc analysis at the same confidence level ($p < 0.05$). The subject was considered as a random effect, whereas the grip span was considered as a fixed effect. All 10 trials (five levels of grip spans with two repetitions each) were completely randomized.

3. Results

3.1. Resultant force between the jaws

The results of the ANOVA indicated that the grip span was a significant factor on the resultant force exerted between the jaws ($p < 0.01$). Fig. 2 shows the results of the resultant forces associated

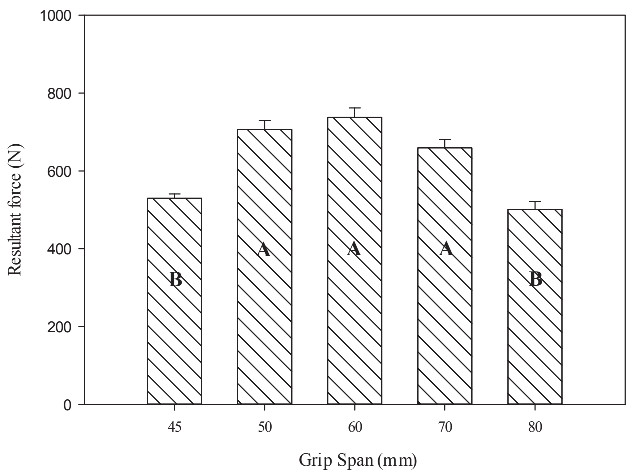

Fig. 2. Resultant force over the five grip spans. [Note: Superscript letters indicate Tukey's multiple test results, i.e., same letters are not significantly different.].

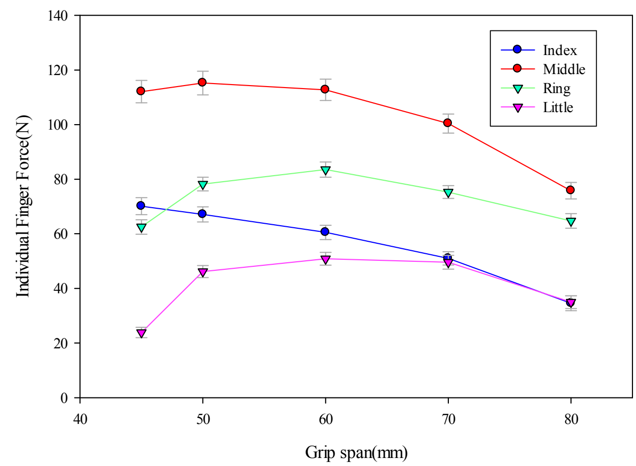

Fig. 3. Individual finger force over the five grip spans.

with the grip spans in the maximum gripping task. Tukey's multiple comparison showed that participants exerted significantly higher forces at 50–70 mm grip spans than at other sizes.

The highest resultant forces of 737.9 N, 706.7 N, and 659.4 N were obtained from 60 mm, 50 mm, and 70 mm grip spans, respectively. The lowest resultant forces of 529.9 N and 501.7 N were obtained from 45 mm and 80 mm grip spans, respectively.

3.2. Total grip strength and individual finger force

A statistical analysis of the total grip strength showed that the main effect of the grip span was statistically significant for the total grip strength ($p < 0.01$). In general, the total grip strength showed a similar trend as the resultant force (Section 3.1) for the five grip spans in this study. The participants exerted the highest total grip strength at 60 mm and 50 mm grip spans (311.8 N and 310.1 N, respectively), followed by 70 mm (277.2 N) and 45 mm (273.1 N) grip spans. The largest grip span (80 mm) showed the lowest total grip strength (210.1 N), compared with the other grip spans.

The statistical analysis of the individual finger force showed that the main effect of the grip span was statistically significant in this study ($p < 0.01$). Table 3 summarizes the total grip strength (sum of individual finger forces) and individual finger force, as well as the contribution to the total grip strength with respect to the grip span.

The strongest finger force (103.2 N) and the highest contribution (37.2%) to the total grip strength were obtained from the middle finger, followed by the ring (72.8 N and 26.7%) and index (56.4 N and 20.2%) fingers, respectively (see Table 3). The weakest finger force (40.9 N) and the lowest contribution (14.9%) to the total grip strength were obtained from the little finger, as hypothesized.

The interaction effect between the individual finger force and the grip span was also statistically significant ($p < 0.01$). The observed patterns of the individual finger forces of the grip span are shown in Fig. 3. In general, the index and middle fingers showed a decreasing trend when the grip span increased, i.e. the lowest finger forces in both fingers were obtained at an 80 mm grip span (the largest grip span). Conversely, the ring and little finger forces increased with an increased grip span of up to 60 mm, and then decreased at larger grip spans.

In summary, the greatest finger force of the index and middle fingers (70.1 N and 115.2 N) was obtained at the 45 mm and 50 mm grip spans, respectively, whereas the largest finger force of the ring and little fingers (83.5 N and 50.8 N) was obtained at a 60 mm grip span. The least finger force for all fingers (34.6 N, 75.8 N, 64.7 N, and 35.0 N) was observed at the 80 mm grip span.

3.3. Subjective discomfort rating

The ANOVA showed that the grip span in relation to the subjective discomfort was statistically significant ($p < 0.01$). Fig. 4 shows the results of subjective discomfort in the maximum gripping task with combination pliers. Tukey's multiple test showed that the participants significantly rated the 50 mm and 60 mm grip spans as the most comfortable handle size (2.7 ± 0.2 and 3.3 ± 0.3, respectively), followed by 45 mm (3.9 ± 0.4), and 70 mm (4.8 ± 0.3) grip spans. The largest grip span handle (80 mm) was rated as the most uncomfortable handle (8.2 ± 0.2) in this study.

4. Discussion

The individual finger force and the contribution to the total grip strength in the maximum gripping tasks were evaluated in this study. The average finger force and the contribution of the middle

Table 3
Individual finger force (N) and contribution (%) relative to grip span.

Grip span (mm)	Total grip strength (N)	Index finger force (N) and contribution (%)	Middle finger force (N) and contribution (%)	Ring finger force (N) and contribution (%)	Little finger force (N) and contribution (%)
45	273.1 ± 65.0^{C}	70.1 ± 21.7 (26.1%)	112.1 ± 29.5 (41.7%)	62.5 ± 19.2 (23.3%)	23.9 ± 13.7 (8.9%)
50	310.1 ± 71.7^{AB}	67.1 ± 19.6 (21.9%)	115.2 ± 31.1 (37.6%)	78.2 ± 18.0 (25.5%)	46.2 ± 16.0 (15.1%)
60	311.8 ± 67.2^{A}	60.2 ± 19.2 (19.6%)	112.7 ± 28.1 (36.7%)	83.5 ± 20.2 (27.2%)	50.8 ± 16.1 (16.5%)
70	277.2 ± 56.2^{BC}	51.0 ± 17.7 (18.5%)	100.4 ± 25 (36.4%)	75.3 ± 16.8 (27.3%)	49.6 ± 18.1 (18.0%)
80	210.1 ± 58.4^{D}	34.6 ± 19.7 (16.5%)	75.8 ± 21.9 (30.1%)	64.7 ± 19.4 (30.8%)	35.0 ± 16.8 (16.7%)
Mean	276.5 ± 73.4	56.4 ± 23.3 (20.2%)^{C}	103.2 ± 30.8 (37.2%)^{A}	72.8 ± 20.3 26.7%)^{B}	40.9 ± 19.1 14.9%)^{D}

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

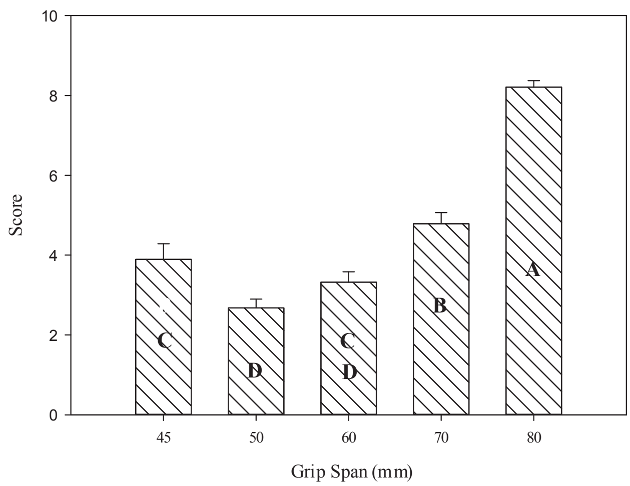

Fig. 4. Subjective discomfort ratings of the five grip spans. [Note: Superscript letters indicate Tukey's multiple test results, i.e., same letters are not significantly different.].

finger to the total grip strength was the highest (103.2 N; 37.2%, ranging from 30.1% to 41.7%), followed by the ring finger (72.8 N; 26.7%, ranging from 23.3% to 30.8%), the index finger (56.4 N; 20.2%, ranging from 16.5% to 26.1%), and the little finger (40.9 N; 14.9%, ranging from 8.9% to 18.0%), in that order. The highest and lowest contributions of the middle and little fingers to the total grip strength in the maximum gripping tasks concurred with the results from previous gripping studies for similar types of handles (Fransson and Winkle, 1991; Kong et al., 2009, 2014). According to those studies, the ranges of average contributions were 31.4%–33.6% for the middle finger, 26.0%–28.1% for the ring finger, 21.2%–25.4% for the index finger, and 16.9%–18.1% for the little finger.

It is worth noting that the contribution levels of the index and ring fingers showed different tendencies associated with the grip spans (see Fig. 3 and Table 3). The index finger showed a higher finger force and contribution than the ring finger when the grip span was 45 mm, whereas the ring finger showed a higher finger force and contribution than the index finger when the grip span was 50 mm or larger; the differences increased as the grip span increased. The higher force of the index finger when the grip span was 45 mm can be explained by the fact that combination pliers basically have angulated shape handles. When the grip span was small, the opening between the two handles was relatively narrow, resulting in a structure closer to parallel shape (or one-handle) handles (differences in grip spans among the fingers are small). Thus, this study indicated that the level of contribution of the index finger to the total grip strength was significantly higher than that of the ring finger, which is similar to the results of previous studies on parallel shaped handle or one-handle tools (Amis, 1987; Radwin and Oh, 1992; Radhakrishnan and Nagaravindra, 1993; Kattel et al., 1996; Farris et al., 1997; Talsania and Kozin, 1998; Kong and Lowe, 2005). When the grip span was larger than 50 mm, the contribution of the ring finger to the total grip strength tended to be greater than that of the index finger, which was consistent with previous results (Fransson and Winkle, 1991; Kong et al., 2009, 2014).

The index finger exerted the highest strength with the smallest grip span of 45 mm and tended to show a gradually decreasing finger force as the grip span increased; whereas the middle, ring, and little fingers showed a tendency for the highest force level at a particular grip span (50 mm or 60 mm) and decreasing levels of contribution as the grip span changed (see Fig. 3).

Fig. 3 also shows that handles might be designed to be associated with the fingers to maximize force capability for each finger. According to this study, the index finger force and the middle finger force provided maximum force capabilities with the 45 and 50 mm grip span, respectively, whereas the ring and little finger force produced maximum force with the 60 mm grip span. This indicates that the handle shape of pliers should be considered in addition to grip span in handle design.

The highest grip strengths of 310.1–311.8 N were found at the 50–60 mm grip spans and 273 N was obtained at the smallest grip span of 45 mm, according to the results of analysis of the total grip strength. The lowest grip strength of 210.1 N was obtained at the largest grip span of 80 mm. Therefore, the highest total grip strength at 50–60 mm decreased by approximately 33.7% with a change in grip span. Similar tendencies were observed in the analysis of resultant force. The greatest resultant force of 737.9 N was obtained at a 60 mm grip span and showed a decreasing tendency as the grip span changed, and decreased by approximately 32.0%–501.7 N at the largest grip span of 80 mm. Similar findings for the measurement of resultant forces were reported in the study by Fransson and Winkle (1991) on slip joint pliers, although the resultant forces in the present study (501.7–737.9 N) were slightly lower than those of their findings (i.e. approximately 500.0–800.0 N for 45–80 mm; the actual data values are indeterminate as the values are only represented by a graph).

The subjective discomfort at the different grip spans was also analyzed. According to the results (Fig. 4), the subjective discomfort of grip span showed an inverse relationship with the total grip strength (Table 3) and resultant force (Fig. 2). In a study of torque tasks conducted by Magill and Konz (1986), the researchers stated that, with regard to the correlation between torque and subjective comfort, the subjective comfort was dominated by the impressions of task performance. Furthermore, in the present study, the participants indicated less discomfort at the 50 mm and 60 mm grip spans than at any other grip spans. This tendency is similar to the results of a study on one-handle type tools (Lee et al., 2009), and a study on an angulated handle (Kong et al., 2014). In those studies, the subjects also expressed the least discomfort at a certain grip span that resulted in the best task performance.

In summary, the 50–60 mm grip spans are recommended as the most desirable grip spans for combination pliers, based on the analyses of total grip strength, resultant force, and subjective discomfort in this study.

5. Conclusion

To investigate the effect of the various grip spans on the individual finger force, total grip strength, and resultant force in the use of combination pliers, an actual set of pliers was modified to have adjustable grip spans and a data measurement system and program were developed for this study. The individual subjective discomfort ratings were also rated for all the grip spans.

The results indicated that the 50–60 mm grip spans which are shown in Table 2 should be the recommended grip span in the maximum gripping task for the combination pliers, based on the analyses of resultant force, total grip strength, individual finger force, and subjective discomfort opinions. However, this study is limited in that it was conducted only with regard to the maximum gripping task, instead of considering diverse tasks. Furthermore, the experiment was conducted with only males. Thus, to produce guidelines that are more accurate, more research is necessary with larger ranges of working conditions to include task, age, and gender.

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