International Journal of Occupational Safety and Ergonomics (*JOSE*) 2005, Vol. 11, No. 3, 303–313

Evaluation of Hook Handles in a Pulling Task

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To evaluate the effect of handle design characteristics on subjective ratings and pulling forces, meat-hook handles with various handle shapes, sizes, and hook positions were tested in a pulling task. Finger and phalange force data measured by force sensitive resistors and subjective ratings of discomfort were also evaluated. Generally subjects preferred 37-mm double frustum, 30-mm oval handles followed by 30-mm double frustum handles, 37-mm oval, and 45-mm double frustum handles. In the analyses of total pulling force, 37- and 45-mm double frustum handles showed less required pulling force than the others. The averages of finger force contributions to the total pulling force were 27.2, 28.1, 23.9, and 20.8% in order from index to little fingers. The average of phalange force contributions were 28.8, 33.6, and 37.6% for the distal, middle, and proximal phalanges, respectively. The findings illustrate that the pulling finger forces and subjective discomfort ratings were related to the handle shape as well as handle size.

handle evaluation   finger/phalange force contributions   hook pulling task

1. INTRODUCTION

Many industries still require workers to use hand tools in spite of increasing mechanization and automation. Human hands are used to support the hand tools during use. Some forces on the wrist, palm, finger, tendons, and tendon sheaths are inevitable when using any types of hand tools. Thus, it is likely that use of these tools would increase the risk of developing work-related musculoskeletal disorders [1].

A meat-hook is a basic hand tool used in the meat packing industry. Repetitive and high pulling exertions are required when workers perform their tasks of cutting and transferring meat. These exertions can cause injuries in the soft tissues of the upper extremities. Scientific studies have shown that proper design of hand tools may play an important role in the reduction or prevention of work-related disorders of the hand and forearm [1, 2, 3, 4, 5].

1.1. Literature Review

Much research has been conducted on tool design characteristics, focusing on handle size, shape, surface type and texture. Among these design characteristics, handle size and shape are important factors to optimize force exertion in manual work, reduce stress on the digit flexor tendons, and avoid stress to the first metacarpal ulnar collateral and carpometacarpal ligaments [6, 7].

Although several research studies have applied subjective ratings to evaluate various handles and body postures [8, 9, 10], relatively few studies have focused on the relationship between handle size and user's hand size, and the effect of the relationship

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on task performance and subjective ratings of handle comfort. Recently, some researchers have emphasized that the relationship between handle size and anthropometric dimensions of the user's hand should be an important factor for handle design. It has been suggested that handles should be designed to vary in size to achieve maximum performance and handle comfort [3, 7, 11, 12]. Cochran and Riley [13] found that there were significant effects of handle shape and interactions between shape and size on force generating capabilities. They also presented maximum handle sizes of 28.6–35.0 mm and 35.0–41.0 mm for females and males, respectively. Grant et al. [13] evaluated the effects of handle size on manual effort during a simulated industrial task and recommended handle sizes for reducing effort and potential hand injury. Yakou et al. [12] also reported that the optimal grasping diameter depended strongly on the hand length but weakly on the hand width in a holding task. The optimum grasping diameters for males were suggested 30–40 mm, about 10% larger than those for females.

The distribution of the forces on the fingers is another important factor in the design of handles [14]. Individual finger and phalange force distributions have been studied with cylindrical handles in a gripping task [15, 16, 17, 18, 19]. Based on their reports, the average contributions of finger forces to the total grip force, from index to little fingers, were 23–31, 29–33, 22–30, and 14–22%, respectively. They also found that the average contributions of distal, proximal, and middle phalanges to the total grip force were 44–50, 32–34, and 18–22%, respectively. The distal phalanges always exerted more force than the other two phalanges in the gripping task. Meanwhile, Kong and Freivalds [20] studied the finger and phalange force distribution with 7 meat-hook handles in a maximum pulling task. They reported that the force of the middle finger was strongest followed by the ring, index, and little finger. They also presented that the proximal phalanges exerted the greatest force, followed by the middle and the distal phalanges in their maximum pulling task. That is, average phalange force contributions to the total pulling finger force were 20.9, 33.7, and 45.4% for the distal, middle, and proximal phalanges, respectively. In their study, the optimality of double frustum handles was supported by empirical physiological measurements and theoretical biomechanical calculations.

1.2. Objectives

The objectives of this study were to (a) evaluate the effects of handle type, hook position, and users' hand size on subjective ratings of discomfort and mean of individual phalange forces in a pulling task; (b) evaluate force distributions of fingers and phalanges in a pulling task; and (c) recommend the handle types based on subjective discomfort ratings and mean of individual phalange force in a pulling task.

2. METHOD

2.1. Subjects

Thirty subjects (15 female and 15 male) between 18 and 45 years, with an average of 28.4 years, were voluntarily recruited from the student population at the Pennsylvania State University, USA. All subjects were screened for any hand and wrist injuries or any hand surgery, which may have limited their physical activities. The subjects were provided with a brief description of the purposes and procedures of the experiment. The hand length was measured from the crease of the wrist to the tip of the middle finger with the hand held straight and stiff and classified into one of three groups (small, middle, or large) for each gender [21], as follows:

1. Small hand size group: up to 30th percentile (under 186 mm and under 169.8 mm, for male and female, respectively);
2. Middle hand size group: 30th–70th percentile (186–196.3 mm and 169.8–180.3 mm for male and female, respectively);
3. Large hand size group: over 70th percentile (over 196.3 mm and over 180.3 mm for male and female, respectively).

Table 1 represents the summary of participants' characteristics.

TABLE 1. Characteristics of Subjects

Subject	Gender	Age	Height (cm)	Weight (kg)	Hand Length (mm)	Percentile Stature	Percentile Hand Length	Hand Size Group
1	Male	31	170	70	182	21.8	18.4	Small
2	Male	26	165	64	186	7.00	30.9	Small
3	Male	35	174	74	184	42.0	24.2	Small
4	Male	29	171	55	180	26.4	13.3	Small
5	Male	32	169	72	183	18.0	21.2	Small
6	Male	27	179	67	193	68.8	57.9	Middle
7	Male	33	175	70	196	47.2	69.1	Middle
8	Male	32	173	65	194	36.3	61.8	Middle
9	Male	29	186	83	190	93.1	46.0	Middle
10	Male	26	173	60	188	36.3	38.2	Middle
11	Male	33	183	80	202	85.5	86.4	Large
12	Male	32	183	72	203	85.5	86.7	Large
13	Male	31	183	86	197	85.5	72.6	Large
14	Male	21	180	69	203	73.6	88.5	Large
15	Male	30	180	75	204	73.6	90.3	Large
16	Female	19	168	90	167	80.5	21.2	Small
17	Female	30	150	41	158	3.00	4.50	Small
18	Female	18	163	70	165	53.2	15.9	Small
19	Female	28	157	52	163	19.5	11.5	Small
20	Female	29	150	47	160	3.00	6.70	Small
21	Female	19	166	66	175	70.9	50.0	Middle
22	Female	27	171	60	180	90.8	69.2	Middle
23	Female	19	166	55	177	70.9	57.9	Middle
24	Female	30	167	50	177	75.8	57.9	Middle
25	Female	32	160	48	174	34.8	46.0	Middle
26	Female	30	168	63	181	80.5	72.6	Large
27	Female	35	168	68	181	80.5	72.6	Large
28	Female	28	165	54	181	65.2	72.6	Large
29	Female	20	170	62	183	87.9	78.8	Large
30	Female	32	172	66	183	68.4	78.8	Large
	Average	28.4	170.2	65.1	183			
	SD	5.77	8.96	11.70	12.67			

2.2. Equipment

A portable hand/handle force sensor glove was developed by overlaying force sensitive resistors (FSRs; Part #400, Interlink Electronics, USA) on a thin and soft golf glove. Twelve FSRs were placed on the pulpy parts of each phalange to analyze the finger forces on distal, middle, and proximal segments. The active area of the FSR sensor was 5.0 mm in diameter and 0.3 mm in thickness. The output signals from the FSR were sent to a custom-made voltage division circuit box (Figure 2b).

Calibrations for all sensors were conducted before the experiment. Output voltages from sensors were screened on the oscilloscope and sampled after these voltages remained at a steady level. After the sensor outputs for the first known mass were sampled at a frequency of 40 Hz by a 12-bit A/D converter for a period of 5 s, the output of the next known mass was recorded. This procedure was repeated until all eight masses (0.59, 1.16, 3.16, 5.16, 7.16, 8.3, 9.5, 10.6 kg) were tested. The eight calibration points obtained from each sensor were fitted to a logarithm equation for each day of testing per sensor. The sensors showed consistent responses from trial to trial and day to day.

Ten meat hooks with various sizes, shapes (double frustum and oval), and hook positions (center and off-center) were tested in this study. The cross-sectional shape of a double frustum handle was circular and the circumference of the handle gradually decreased from the center to both ends

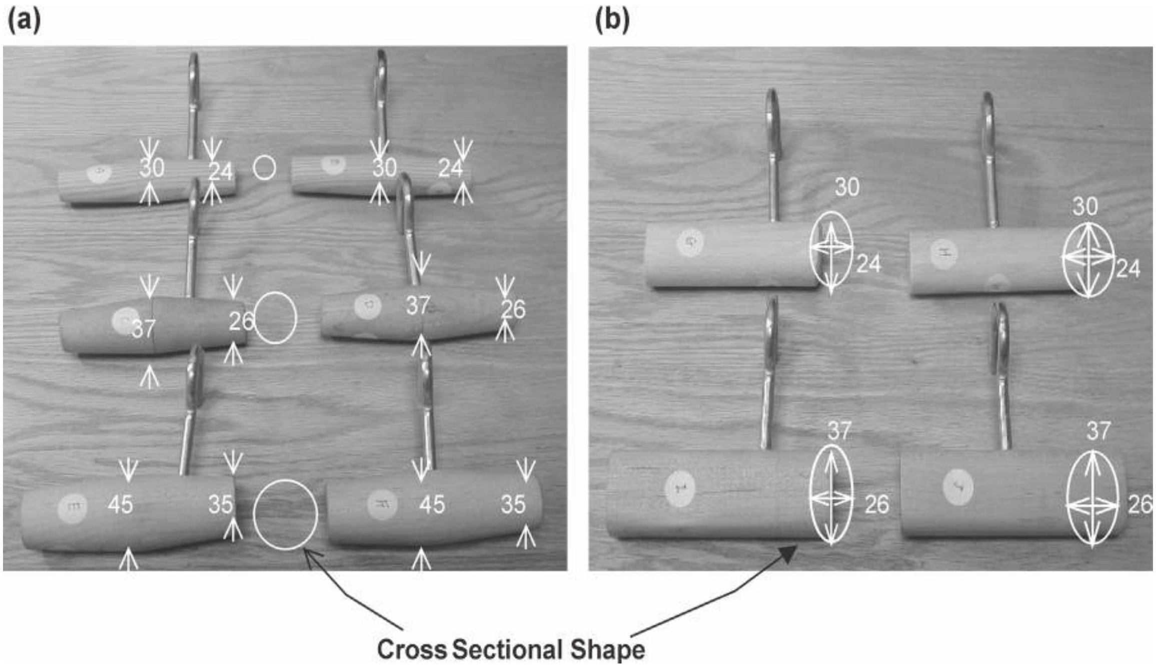

Figure 1. Handle types: (a) double frustum handles; (b) oval handles. *Notes*. (a) Double frustum handles (small, medium and large) have a cylindrical cross-sectional shape. The diameters of the center are 30, 37, and 45 mm, while the diameters of both ends are 24, 26, and 35 mm, respectively. Each double frustum handle has a hook inserted at the center or off-center at the smaller end. (b) The oval handles (medium and large) have an oval cross-sectional shape. The short spans are 24 and 26 mm, while the long spans are 30 and 37 mm, respectively. Each oval handle has a hook inserted at the center or off-center.

(Figure 1a). The double frustum handles included three sizes; the diameters at the center were 30, 37, and 45 mm, whereas the diameters at the both ends were 24, 26, and 35 mm, respectively. The cross-sectional shape of an oval handle was elliptical and the size was the same throughout its whole length (Figure 1b). The oval handles included two sizes; the long spans were 30 and 37 mm, while the short spans were 24 and 26 mm, respectively. It is noted that 30-DF, 37-DF, and 45-DF represented three sizes of the double frustum handles and 30-Oval and 37-Oval represented two sizes of the oval handles, respectively.

Each handle had a hook inserted at the center or off-center. Note that for off-center handles, the hook projected between the index and middle finger, while for the center handles, the hook projected between the middle and ring finger. The length of all handles was 140 mm.

2.3. Experimental Design

To evaluate the effects of various variables on the two responses (subjective discomfort rating and pulling force), a crossed-nested mixed effects analysis of variance (ANOVA) was employed. In the pulling force response, finger and phalange forces were also considered. Hand size was nested within gender, denoted by handsize(in gender), and subject was nested under the combination of gender and hand size, denoted by subject(in gender × handsize). There were three levels of hand size groups for each gender. In each combination of gender and hand size, 5 subjects were evenly assigned based on their hand size. Since each subject was involved in only one level of gender and hand size combination, the nested design was applied. Subject effect was considered as random and the others were considered as fixed effects. A total of treatment combinations were performed in random order.

Maximum pulling force was measured for each subject using a load cell. For testing purposes, an exertion equivalent to 50% of the maximum pulling force was applied through a pulley system with several weights. The task was a horizontal pulling task, which is similar to an operator pulling meat horizontally (Figure 2a). The direction of

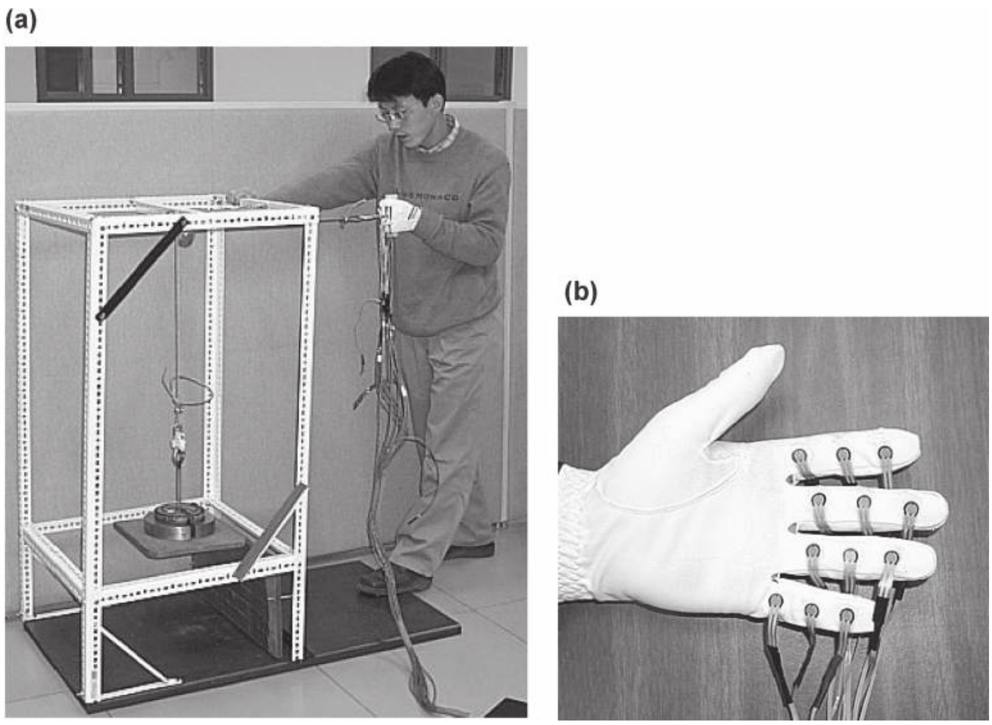

Figure 2. Experimental equipment: (a) pulling device, (b) FSR glove. *Notes.* FSR–force sensitive resistor.

the task was held constant for each condition and each subject. Three different sizes of force sensor gloves were used and subjects selected one of these three sized gloves according to their hand size. The subjects were requested to pull the weight for 3 s with two trials for each hook and were allowed 3 min resting time between each trial. Subjective ratings were asked for discomfort of hand tool use with modified 7-point scales [12]. All of 20 trials (10 handles × 2 trials) were completely randomized.

All possible effects of main factors on the following dependent variables were evaluated.

1. Subjective Discomfort Rating: the subjects were asked to provide subjective rating of handle discomfort. (*very comfortable*—1; *moderately comfortable*—2; *somewhat comfortable*—3; *cannot determine*—4; *somewhat uncomfortable*—5; *moderately uncomfortable*—6; and *very uncomfortable*—7).
2. Individual Phalange Force: individual phalange segment forces were measured by all 12 FSR sensors for all treatment combinations.

3. RESULTS

3.1. Subjective Rating

Statistical analysis on subjective ratings resulted in significant effects for handle types and the interactions of gender × handletype and handsize × handletype(in gender) at .05 level of significance. Here, handsize × handletype(in gender) denotes the interaction effect between hand size and handle type nested in gender. Tukey's pairwise mean comparison (Table 2) shows that the mean discomfort ratings of 37-Oval and 45-DF were significantly higher than of the other handles. Overall the subjects provided less discomfort for the 37-DF, 30-Oval, and 30-DF handles.

TABLE 2. Tukey Multiple Comparison for Mean Subjective Discomfort Rating

Factor		*M*	Tukey test	
Handle Type	37-DF	2.84	A	
	30-Oval	2.85	A	
	30-DF	3.19	A	B
	45-DF	3.84		B
	37-Oval	4.28		B

Notes. 30-DF, 37-DF, 45-DF—30-, 37-, 45-mm diameters of center for double frustum handles, respectively; 30-Oval, 37-Oval—30-, 37-mm diameters of long span for oval handles, respectively.

According to the interaction between gender and handle type showed in Figure 3, both genders provided high discomfort for the 37-Oval and 45-DF handles. Females rated less discomfort for the 30-DF, 37-DF, and 30-Oval handles, whereas males, who generally have larger hand sizes than females, provided high discomfort for the 30-DF handles, which were too small to pull/hold the handles.

Figure 4 shows the interaction plot between handle type and hand size for each gender separately. From the figure, the interaction effects were not evident in all combinations, except for the small-handed females. They showed significantly less discomfort level for the 30-DF handles than for any other handles. Again, overall the mean discomfort ratings for the 45-DF and 37-Oval handles were higher than for the other handles for all combinations of gender and hand size.

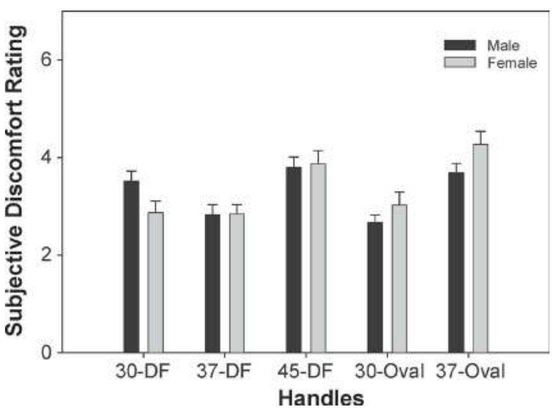

Figure 3. The interaction effects (gender × handletype) for subjective discomfort ratings. *Notes*. 30-DF, 37-DF, 45-DF—30-, 37-, 45-mm diameters of center for double frustum handles, respectively; 30-Oval, 37-Oval—30-, 37-mm diameters of long span for oval handles, respectively.

3.2. Individual Phalange Force

Statistical data analysis showed gender, handle type, finger, and phalange and interactions between gender and finger, gender and phalange, phalange and handle type, finger and hook position, phalange and hook position, phalange and finger, finger and hand size(in gender), phalange and hand size(in gender) were significant at the $\alpha = .05$ level (Table 3).

A comparison of handle types for the mean phalange forces (in Table 4) indicates that the oval and 30-DF handles required more phalange forces to maintain the given load than the 37-DF and 45-DF handles. The finger effect was also significant. When Tukey's test was used to compare the mean phalange force of fingers, the middle finger (31.6 N, 28.1% of total force) had the largest mean phalange forces followed by the index (30.7 N, 27.2% of total force), ring (27.0 N, 23.9% of total force) and little fingers (23.4 N, 20.8% of total force). The force of the index was larger than that of the ring finger. As expected, the mean phalange force of the little finger was the lowest. Each phalange also showed a significantly

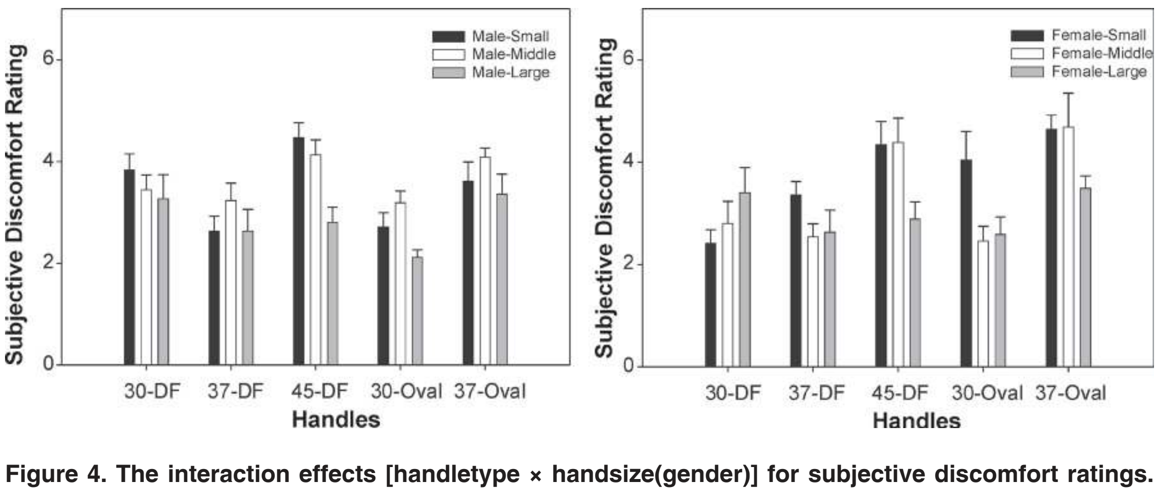

Figure 4. The interaction effects [handletype × handsize(gender)] for subjective discomfort ratings. *Notes*. 30-DF, 37-DF, 45-DF—30-, 37-, 45-mm diameters of center for double frustum handles, respectively; 30-Oval, 37-Oval—30-, 37-mm diameters of long span for oval handles, respectively.

TABLE 3. Pulling Finger Force ANOVA Summary

Source	*DF*	*SS*	*MS*	*F*	*P*-value
** Gender	1	273.91	273.91	26.67	<.0001
HandSize(in Gender)	4	59.68	14.92	1.45	.248
Error(Subject(in Gender x HandSize))	24	246.51	10.271		
** Subject(in Gender*HandSize)	24	246.51	10.271	26.71	<.0001
** HandleType	4	35.24	8.81	22.91	<.0001
HookPos	1	0.25	0.25	0.66	.417
** Finger	3	393.22	131.07	340.90	<.0001
** Phalange	2	348.07	174.03	452.63	<.0001
HandleType x Gender	4	0.63	0.16	0.41	.801
HookPos x Gender	1	1.16	1.16	3.01	.083
** Finger × Gender	3	9.29	3.10	8.05	<.0001
** Phalange × Gender	2	62.95	31.47	81.86	<.0001
HandleType x HandSize(in Gender)	16	7.28	0.45	1.18	.273
HookPos x HandSize(in Gender)	4	0.96	0.24	0.62	.647
** Finger × HandSize(in Gender)	12	15.99	1.33	3.47	<.0001
** Phalange × HandSize(in Gender)	8	70.69	8.84	22.98	<.0001
HookPos x HandleType	4	0.91	0.23	0.59	.671
Finger x HandleType	12	6.65	0.55	1.44	.139
** Phalange × HandleType	8	46.17	5.77	15.01	<.0001
** Finger × HookPos	3	81.53	27.18	70.68	<.0001
* Phalange × HookPos	2	2.88	1.44	3.74	.024
** Phalange × Finger	6	164.39	27.40	71.26	<.0001
Error	3475	1336.12	0.38		

Notes. *significant at .05 level; **significant at .01 level.

TABLE 4. Tukey Multiple Comparison of the Mean Phalange Force

Factor			*M* (*N*)	Tukey test			
Gender		Male	30.87	A			
		Female	25.48		B		
Handle Type		37-Oval	29.20	A			
		30-Oval	28.91	A			
		30-DF	28.42	A			
		37-DF	27.44		B		
		45-DF	26.56			C	
Hand Size							
	Female	Small	23.83		B		
		Middle	27.76		B		
		Large	24.74		B		
	Male	Small	31.67	A			
		Middle	30.62	A			
		Large	30.25	A			
Hook position		Center	28.06	A			
		Off-center	28.23	A			
Finger		Index	30.67		B		
		Middle	31.56	A			
		Ring	26.95			C	
		Little	23.42				D
Phalange		Distal	24.30			C	
		Middle	28.32		B		
		Proximal	31.75	A			

Notes. 30-DF, 37-DF, 45-DF—30-, 37-, 45-mm diameters of center for double frustum handles, respectively; 30-Oval, 37-Oval—30-, 37-mm diameters of long span for oval handles, respectively.

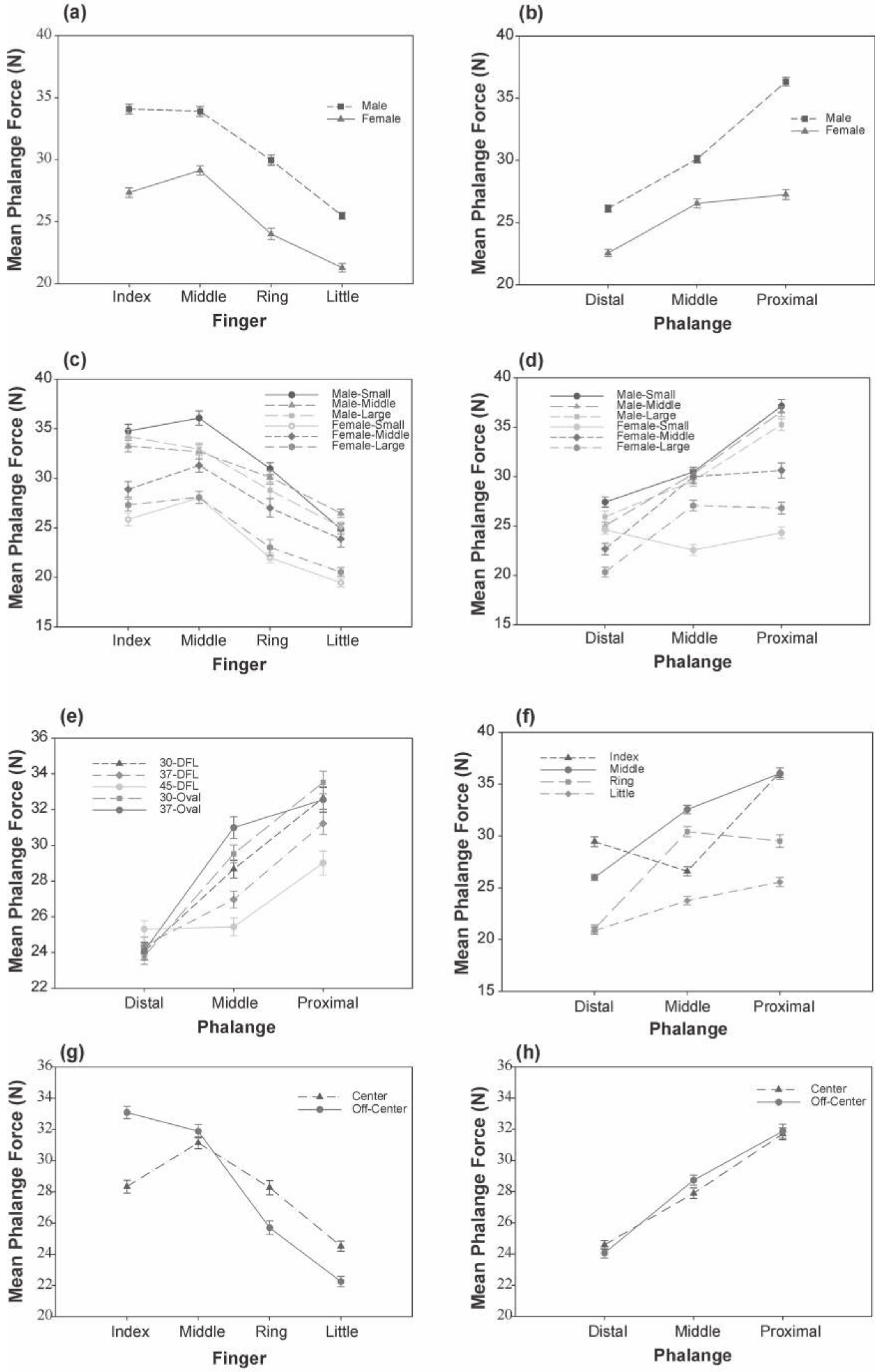

Figure 5. The interaction effect plots for pulling finger force: (a) interaction effect of finger and gender; (b) interaction effect of phalange and gender; (c) interaction effect of finger and hand size (gender); (d) interaction effect of phalange and hand size (gender); (e) interaction effect of phalange and handle type; (f) interaction effect of phalange and finger; (g) interaction effect of finger and hook position; (h) interaction effect of phalange and hook position.

different force distribution. The mean comparison tests demonstrated that, on average, the proximal phalange (31.8 N, 37.6% of total force) exerted more force than the middle (28.3 N, 33.6% of total force) and distal phalange (24.3 N, 28.8% of total force).

According to the interaction plot between gender and fingers (Figure 5a), males showed high index finger force, which was very close to middle finger force, whereas females showed that middle fingers was the strongest followed by index, ring and little fingers. This also can be shown with the interaction plots (Figure 5c) for finger and hand size(in gender). In these plots, large- and middle-handed males showed slightly stronger finger force in index than middle fingers. The interaction effect between the finger and hook position is shown in Figure 5g. As expected, center hook position handles indicated index (28.3 N, 25.2%), middle (31.1 N, 27.8%) and ring (28.2 N, 25.2%) fingers evenly shared the pulling forces, although the middle finger contribution was still the highest. The contributions of index and ring fingers were very close to each other. In the case of off-center hook handles, however, high forces of index (33.1 N, 29.3%) and middle (31.9 N, 28.3%) fingers were obtained. The contributions of these two fingers were almost 60% of the total finger force. For off-center handles, the contributions of ring (25.7 N, 22.7%) and little (22.2 N, 19.7%) fingers were much lower than those of center handles.

The effects of the phalange force distribution are of interest. The average pattern of force contribution, which is in the order of proximal-middle-distal, is evident for males, while the pattern is not distinctive for females (Figure 5b). Figure 5d plots the interaction effects between phalange and hand size for each gender group. It is interesting to note that the interaction is highly significant for females, while the interaction effect is not evident for males. Small-handed females are distinguished from middle- and large-handed females in terms of phalange force distribution, which is distributed evenly. The interaction between the handle type and the phalange is plotted in Figure 5e. Generally the force distributions of phalanges show similar pattern to handle types, which are the proximal phalange exerted the greatest force followed by the middle and distal phalanges. Especially the 37-Oval handle showed the highest contributions of middle phalange (31.0 N, 35.3%) to total pulling force among the five handle types. This can be explained by a flat shape of this handle.

It is noteworthy that the phalange force distributions significantly interacted with fingers (Figure 5f). Especially the index finger showed higher distal phalange contribution (29.4 N, 32%) than the other fingers. For the ring finger, the highest contribution was given by middle phalange rather than proximal phalange, though the difference was not significant. The phalange force distribution was close even in the little finger. The interaction between the phalange and hook position was minor (Figure 5h).

All significant interaction plots are shown in Figures 5a–5j.

4. DISCUSSION

The proportional force distributions of each finger and phalange to the total pulling force were studied. The results indicated that 53 and 58% of the total pulling force was exerted by the index and middle fingers for center and off-center hook handles, respectively. The high contributions of the index and middle fingers can be explained by the muscle capability of fingers and the hook position effect. Ketchum et al. [22] reported that the difference of the muscle capability between the middle and index finger was only 2.4%, whereas the difference between the middle and ring finger was 14%. Thus, according to this study, the muscle capability of the index finger was about 11% stronger than that of the ring finger. The off-center hook handles required high forces on the index and middle fingers due to the hook position between the index and middle fingers. Although the center hook handles could lead to high forces on the middle and ring fingers because of the hook position between the middle and ring fingers, the index finger still took an important role in the pulling task.

The finding showed that proximal phalange showed the largest exertion, followed by the middle and distal phalanges. A similar finding was also reported by Kong and Freivalds [20]. They reported high localized pressure on the proximal phalange area or A1 pulley area, which is the palmar surface of the metacarpophalangeal joint of each finger in the maximum pulling task from the evaluation of meat-hook handles. According to studies on the relationship between externally applied finger forces and internal finger tendon forces, internal tendon forces can be 1.5 to 4.2 times (2.77–3.47 for the profundus and 1.51–4.23 for the superficialis) greater than external finger forces in a power grip function [23, 24]. It means that the tendons of high pressure areas are more vulnerable to injuries than those of low pressure areas. Karwowski and Salvendy [25] reported that the localized compression in the A1 pulley area is one of main factors of trigger finger injuries. Therefore, high pressure concentrations on the proximal area may explain the high frequencies of trigger finger injuries in the hook pulling tasks compared to static holding or grasping tasks.

An analysis of subjective comfort showed that the participants suffered less discomfort from the 37-DF handles, followed by the 30-oval handles or 30-DF handles. It is assumed that people prefer more contact area between handle surface and the hand in hook pulling tasks as compared to gripping tasks. In a gripping study, 30-DF handles provided the best subjective rating among handles [26]. Participants, however, did not prefer too large contact area, i.e., they rated highest discomfort level for both 45-DF handles and 37-oval handles. Some participants complained about discomfort to the middle and proximal phalanges while they used 37-oval handles. This is due to the relatively sharp edges of those flat handles, which dug into the palmar side of middle phalange for each user's hand. It may turn to high discomfort levels for the 37-oval handles. Especially small-handed participants were significantly more sensitive to the size of the handle for subjective ratings. It is noted that the subject's upper extremity was placed in a posture (Figure 2a) such that the upper arm was hanging comfortably down with the forearm bent at approximately a 90^{o} angle. This corresponds to a comfortable working posture, which minimizes any negative effects or discomforts from the upper extremity while developing a maximum pulling force.

According to this study, handle sizes and handle shapes may lead to considerable differences in both subjective ratings and pulling forces. In general, small-handed subjects experienced high discomfort from large handles, whereas large-handed subjects rated high discomfort levels for small-sized handles, which were too small to hold firmly. If the handle is too small, the small muscles of the fingers are susceptible to undue stress, whereas if the handle is too large, the pullies and sheaths of the fingers can become swelled and inflamed. This might be a cause of a trigger finger or tenosynovitis [3].

Therefore, finding the proper handle size and shape according to the users' hand size is very important in obtaining efficient muscle contraction, performance, and the best subjective ratings.

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