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Pistol Grip Power Tool Handle and Trigger Size Effects on Grip Exertions and Operator Preference

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Finger and palmar forces were measured during actual pneumatic nutrunner operation using a strain gauge dynamometer. Eighteen student subjects were assigned to one of three categories based on hand length. Two triggers and four handle spans were presented randomly. Handle span affected maximal and submaximal grip force. As span increased from 4 cm to 7 cm, average peak finger force increased 24%, peak palmar force increased 22%, and average finger and palmar tool-holding forces increased 20%. When an extended trigger was used, average peak finger force decreased 9%, peak palmar force decreased 8%, finger tool-holding force decreased 65%, and palmar tool-holding force decreased 48%. Hand size affected grip strength (MVC), grip force, and exertion level (force/MVC). Holding exertion level was maximum for large-handed subjects using a 4-cm handle and for small-handed subjects using a 7-cm handle. Subjective handle span preference increased as hand size increased. A similar experiment was performed using 11 factory workers.

INTRODUCTION

Pneumatic hand-held power tools are widely used in industry. Power tools reduce manual force requirements, shorten the time to accomplish tasks, and improve the quality of work. The use of power tools, however, is not without stress. Rauko, Herranen, and Vuori (1988) interviewed 66 workers from two companies in Finland. Their investigation showed that one in five workers (20%) felt that the most stressful task in their work was connected directly to the use of pneumatic screwdrivers and nutrunners. There is also growing concern about designing and selecting power tools for preventing cumulative trauma disorders (CTDs).

Repetitive motion, forceful exertion, awkward posture, contact stress, cold temperature, and vibration are risk factors often associated with CTDs (Armstrong, Radwin, Hansen, and Kennedy, 1986). The use of pneumatic power tools may involve one or more of these risk factors. The best method currently available for preventing cumulative trauma disorders is to minimize risk factors associated with tasks, tools, and the workplace (Armstrong, 1986). Risk factors

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associated with trigger and handle design are the focus of the current study.

A CTD risk factor related to trigger design is stress concentrations at the volar side of the fingers. The CTD known as *trigger finger*, or *stenosing tenosynovitis crepitans* (Bonnici and Spencer, 1988; Nasca, 1980), is associated with repeatedly operating the trigger of a pistol grip power tool when this risk factor is present. Multifinger-operated triggers have been suggested as a way of redistributing finger force over two or more fingers when activating a power tool and thus reducing contact stress (Lindqvist, Ahlberg, and Skogsberg, 1986; Putz-Anderson, 1988). Use of these tool modifications, however, may affect how the tool is handled. It is not known whether tool operators distribute the required force among the fingers or whether the sum of the forces produced by each finger is greater than the force exerted using only one finger.

Multifinger-operated triggers also leave fewer fingers available for holding and supporting the tool. The remaining fingers are often the fourth and fifth digits, the ones that are the weakest and contribute the least force. Studies have shown that the index and middle fingers contribute more to the resultant grip force than do the ring or small finger, and that individual finger contribution is influenced by exertion level (Amis, 1987; Radwin, Oh, Jensen, and Webster, 1992). This study investigates the effect of multifinger triggers on finger exertions during tool operation.

Previous research in tool handle design has focused on finding the optimal handle dimensions. Recommendations for handle size were often based on the span that maximizes grip strength or minimizes fatigue. Hertzberg (1955), in an early air force study, reported that a handle span of 6.4 cm maximized power grip strength. Ayoub and Lo Presti (1971) found that a 3.8-cm diameter was optimum for a cylindrical handle. This was based on maximizing the ratio between strength and electromyographic activity, and on the number of work cycles before onset of fatigue. Greenberg and Chaffin (1975) recommended that a tool handle span be in the range of 6.4 cm and 8.9 cm in order to achieve high grip forces. Another study, by Petrofsky, Williams, Kamen, and Lind (1980), showed that the greatest grip strength occurred at a handle span between 5 and 6 cm.

Grip strength is also affected by hand size. Fitzhugh (1973) showed that the handle span resulting in maximum grip strength for a 95th-percentile male hand length is larger than the handle span for that of a 50th-percentile female. Therefore it is hypothesized that a person with a small hand may benefit from using a smaller handle, compared with a person with a large hand. This study tests that hypothesis.

The underlying assumption in designing handles based on maximum grip strength is that the actual force exerted is independent of handle size. If the grip force used during tool operation is the same for all handle sizes, then the handle span associated with the greatest grip strength will result in the lowest exertion level. *Exertion level* in this paper is defined as the ratio of the actual grip force used to the maximum voluntary contraction (MVC) force-generating capacity (force/MVC). If grip force is affected by handle size, then the handle span associated with the greatest grip strength may not be the handle span resulting in the minimum exertion level. This study investigates the validity of that assumption.

The effects of hand size, handle span, and trigger type on grip exertions during actual tool operation were investigated in this study using an automatic shut-off pistol grip power tool. A tool handle instrumented with strain gauges was attached to a functioning power tool for measuring the forces exerted when operating the tool. The relationships among anthropometry, force, and subjective preferences were also considered.

METHODS

Experimental Apparatus

An apparatus was constructed for simulating a pneumatic pistol grip nutrunner in order to measure forces produced during tool operation. Two strain gauge dynamometers were installed in a handle for measuring forces at the finger and palmar sides. The dynamometer handle was attached perpendicularly to a modified in-line pneumatic nutrunner motor in the configuration of a pistol grip power tool and mounted on a rigid frame (see Figure 1). The motor was a 1000-rpm Ingersoll-Rand 6W-TM3 nutrunner. This motor contained an automatic air shut-off torque control mechanism and was operated at a 6.8-N · m torque setting. The two dynamometers were mounted in parallel on a track so the handle span could be continuously adjusted between 40 mm and 132 mm.

The aluminum dynamometers were constructed so their force sensitivity was independent of the point of application. They were able to add force linearly along the handle length by measuring the shearing stress in the cross section of a beam using strain gauges aligned 45 deg to the long axis (Pronk and Niesing, 1981). Details of the dynamometer construction are provided in Radwin, Masters, and Lupton (1991). These dynamometers were calibrated by suspending weights, ranging from 0.5 kg to 10 kg, perpendicular to the handle in the axis of sensitivity. Least squares linear regression indicated that the force sensitivity of the beams was 2 mV/N with a coefficient of determination $R^2 = 0.99$.

Two plastic caps were attached to the dynamometer beams in order to simulate the contours of a power tool handle. The finger side cap was 24 mm wide and the palmar side

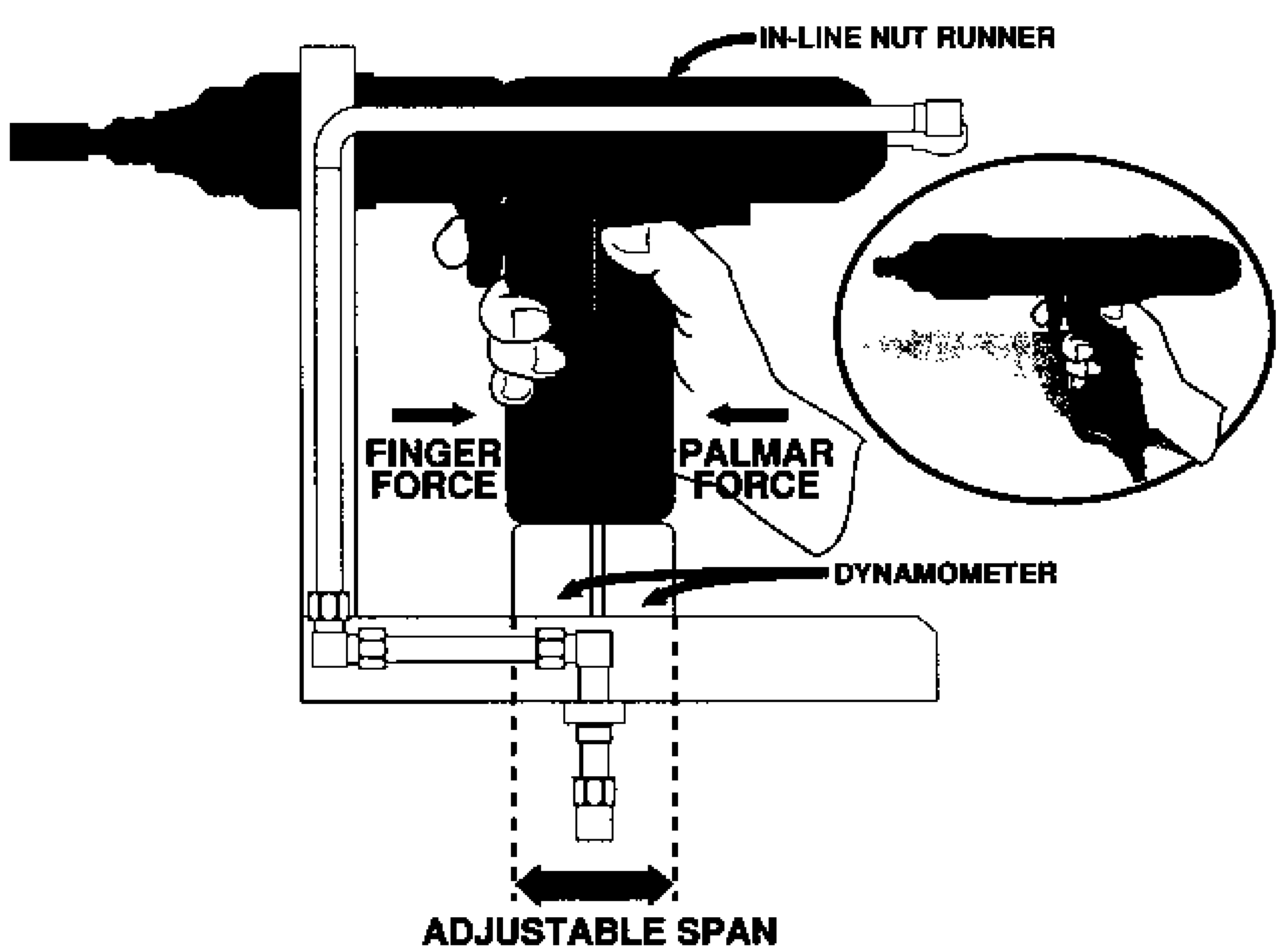

Figure 1. *Experimental apparatus used for simulating a pistol grip power tool. The device has an adjustable handle span and strain gauge dynamometers inside the handle. The inset shows how the apparatus simulates the shape of a pistol grip power tool.*

cap was 32 mm wide. Both caps were 129 mm long, and the contact surface was curved, having a radius of curvature of 159 mm. The circumference of the handle for a span of 4 cm was 12 cm, measured between two points tangent to the cap contact surfaces. The handle circumference increased an additional 2 cm as the handle span was increased by 1 cm. The tool trigger was mounted on the finger side cap of the handle, similar to a conventional hand tool (see Figure 1).

Two different trigger types were used. One was a conventional power tool trigger, activated using only the index finger. The second was longer than the conventional trigger and activated using both the index and middle fingers. These two triggers are depicted on power tools in Figure 2. The conventional trigger was 21 mm long and the extended trigger was 48 mm long. A leaf spring for controlling tension and a contact switch were installed inside the triggers. When the trigger was squeezed, the switch tripped a relay and a solenoid valve for supplying air to the power tool motor. Activation force, measured using a Chattilon force gauge, was approximately the same for both triggers. The conventional trigger required 8 N, and the extended trigger required 11 N for activation.

Ten bolts were contained in threaded holes in a vertical 13-mm-thick steel panel. The bolts were 7.3-cm long, 1.6-cm diameter, number 18 screws with a 1.4-cm hex head. Belleville washers were used for controlling the torque rate. The washers' outside diameter was 4.0 cm, the inside diameter was 2.0 cm, and the thickness was 0.2 cm. The holes in the panel were located in two rows of five across. The vertical location of the screw panel was controlled using an adjustable platform that allowed all subjects to hold the tool at elbow height using a neutral wrist posture.

An overhead spring balancer was used for counterbalancing the weight of the simulated tool. The tool weighed 2.65 kg without the

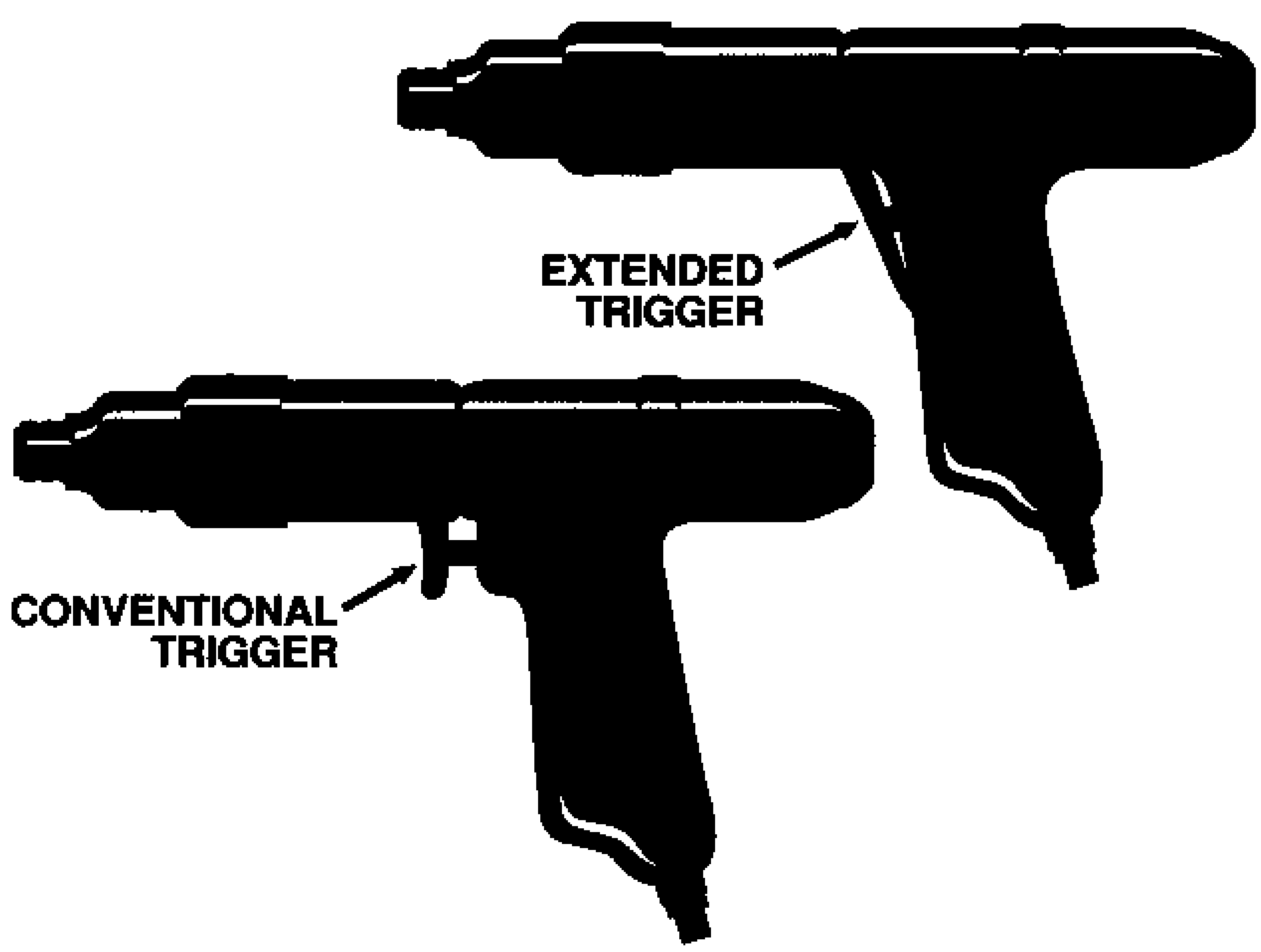

Figure 2. *A conventional trigger and an extended-length trigger on pistol grip power tools.*

balancer and was 0.25 kg with the balancer installed. Because the counterbalance force was proportional to displacement, the distance between the spring balancer and the screw panel was kept constant so the counterforce was the same for each subject.

The outputs of the two dynamometers were sampled using a GW Instruments MacADIOS II 12-bit analog-to-digital converter. Activation of the trigger was also monitored by recording the relay voltage. Sample rate was 30 Hz for a sampling period of 50 s. Data acquisition was controlled using an Apple Macintosh II microcomputer and National LabView software.

Subjects

Two groups of subjects were studied. The first included inexperienced tool operators from the University of Wisconsin-Madison campus. The second group included experienced tool operators recruited from two local automobile assembly plants.

Subjects were arbitrarily divided into three categories according to their hand length. Hand length up to 17 cm was classified as small, between 17 cm and 19 cm as medium, and greater than 19 cm as large. A hand length of 17 cm corresponded to a 21st-percentile female or a 0.3-percentile male. A hand length of 19 cm corresponded to an 88th-percentile female or a 35th-percentile male (Greiner, 1991).

University students. Students were recruited by posting advertisements on bulletin boards in university buildings or by invitation of the experimenter. Participants had no history of hand injuries or neuromuscular disorder symptoms. They were paid for their participation on an hourly basis.

Participating in this experiment were 18 students: 7 males and 11 females. After the first 15 subjects were randomly recruited, 4 were classified as having small hands, 5 as medium, and 6 as large. Based on their hand length, two additional small-handed subjects and one medium-handed subject were recruited to have the same number of subjects in each size category. The average hand length was 17.1 cm (SD = 1.0 cm) for the females and 19.9 cm (SD = 0.8 cm) for the males. All 18 subjects described themselves as right-handed and reported no prior experience using pneumatic power tools. A summary of student subject anthropometric characteristics is included in Table 1.

Factory workers. Eleven factory workers were recruited from two automobile assembly plants in the midwestern United States. Subjects were selected based on their experience using pistol grip pneumatic power hand tools. Of the 11 subjects, 8 were currently using similar pistol grip pneumatic power hand tools with shut-off torque between 4.5 N · m and 6.8 N · m in their jobs. The remaining three subjects reported that they had previous experience in using pistol grip pneumatic power hand tools in their jobs for at least one year.

Eight subjects were male and three were female. Average hand length was 19.0 cm (SD = 1.2 cm) for the females and 19.5 cm (SD = 1.1 cm) for the males. Ten subjects described themselves as right-handed and one subject as left-handed. Five subjects were classified with medium hands and six with large hands. A summary of the factory worker anthropometric characteristics is listed in Table 2.

Experimental Procedures

Prior to the experiment, a power grip strength test for the dominant hand was administered to subjects while they stood in the same posture used for operating the power tool. Grip strength was measured using a strain gauge dynamometer of similar dimensions as those of the power tool simulator handle. Grip force was recorded for 3 s, and MVC level was calculated by averaging

TABLE 1

Summary of University Student Characteristics

Hand Size Category	Age (years)	Hand Length (cm)	Hand Length Percentile[a]	Gender	Hand Width (cm)	Palm Length (cm)	Mean Grip Strength (N)[b]
Small	22	15.7	1.1	F	7.5	9.5	236 ± 47
	21	16.2	4.4	F	7.6	9.3	152 ± 13
	20	16.4	7.3	F	7.4	9.5	220 ± 22
	20	16.6	10.7	F	7.6	9.6	179 ± 20
	20	16.7	13.0	F	7.4	9.4	122 ± 28
	29	16.7	13.0	F	7.4	9.8	181 ± 15
Medium	24	17.1	24.7	F	8.3	10.0	346 ± 43
	26	17.4	39.2	F	8.0	10.9	195 ± 21
	20	18.1	61.4	F	8.2	10.7	181 ± 17
	20	18.3	70.7	F	8.3	10.0	115 ± 24
	31	18.8	27.5	M	8.7	10.9	362 ± 97
	24	18.9	86.5	F	8.1	10.5	273 ± 46
Large	25	19.2	43.3	M	8.6	10.9	286 ± 29
	29	19.8	66.8	M	8.7	11.1	308 ± 26
	23	20.0	73.4	M	9.9	11.2	525 ± 137
	26	20.1	76.4	M	8.4	11.5	433 ± 58
	34	20.8	90.8	M	9.0	12.2	399 ± 85
	22	20.9	91.9	M	9.5	11.9	492 ± 86
Mean	24	18.5			8.3	10.5	279
SD	4	1.7			0.7	0.9	133

[a] Male and female hand length percentiles are calculated separately based on Greiner (1991) data.
[b] Average grip strength at spans of 4 cm, 5 cm, 6 cm, and 7 cm ± one standard deviation.

for 1.5 s after maximum voluntary contraction was fully developed. Five different handle spans, ranging from 4 cm to 8 cm, in 1-cm increments, were presented randomly. A 4-min rest period was given between trials. Because some of the small-handed subjects were unable to hold the tool handle at the 8-cm handle span, that condition was eliminated from the experiment.

Fifteen minutes were provided for training and practice operating the power tool. During training subjects had an opportunity to use the tool simulator with the conventional trigger and with the extended trigger for a handle span of 5.5 cm. Subjects were given more time if they requested it. Numbers were assigned to each bolt, and subjects followed the same sequence. Because tool torque was controlled by an air shut-off mechanism, subjects were instructed to release the trigger after the tool stopped automatically.

All combinations of two types of triggers and four handle spans were presented randomly. Subjects were required to tighten 10 bolts in succession in a 50-s period for each trial. Three replications were performed for each experimental condition. A 1-min rest was given after finishing each trial. Every subject operated the power tool for all experimental conditions.

A representative force record during tool operation is plotted against time in Figure 3. The peak force at the finger and palmar sides of the tool handle was determined for each of the 10 bolts in a single trial, then averaged. *Peak force* was defined as the maximum force achieved each time the tool was activated. The average tool-holding force used between

TABLE 2

Summary of Factory Worker Characteristics

Hand Size Category	Age (years)	Hand Length (cm)	Hand Length Percentile[a]	Gender	Hand Width (cm)	Palm Length (cm)	Mean Grip Strength (N)[b]	Experience Using Pistol Grip Power Tools (years)
Medium	46	18.1	63.6	F	8.7	10.7	221 ± 41	4
	41	18.3	12.7	M	9.2	11.2	411 ± 36	3
	52	18.4	15.0	M	8.9	10.3	313 ± 58	10
	46	18.5	76.9	F	7.8	10.2	259 ± 17	3
	51	19.0	35.0	M	9.7	10.7	315 ± 46	24
Large	51	19.1	39.2	M	9.6	10.5	328 ± 71	25
	48	19.5	55.4	M	10.1	11.3	277 ± 24	23
	49	20.0	73.4	M	9.2	11.6	391 ± 120	2
	60	20.3	99.2	F	8.7	11.2	289 ± 52	16
	43	20.8	90.8	M	10.3	11.6	384 ± 83	3
	39	21.2	95.2	M	10.3	11.8	413 ± 151	1
Mean	48	19.4			9.3	11.0	327	10
SD	6	1.1			0.8	0.6	90	10

[a] Male and female hand length percentiles are calculated separately based on Greiner (1991) data.
[b] Average grip strength at spans of 4 cm, 5 cm, 6 cm and 7 cm ± one standard deviation.

screws was also computed from the finger and palmar sides of the handle. *Holding force* was defined as the force used for holding the tool when the trigger was off. Because a certain amount of force was required to activate the trigger, a small lag occurred between holding the handle and initiating trigger activation, and between trigger deactivation and holding the handle. Both of these lags were accounted for by eliminating 0.1 s before and after trigger activation. Exertion levels were reported in terms of percentage of maximum voluntary contraction (%MVC), calculated by taking the ratio of the peak force to grip strength for a given handle span.

Analysis of variance (ANOVA) was used for testing statistically significant effects for the full factorial experimental design. Subject was a random effect variable nested within hand length. Trigger type, handle span, and hand length were fixed-effect variables. Because there were no small-handed subjects in the worker group, the data were pooled and the hand length variable was eliminated for that study. Only the third replication for each experimental condition was used in the data analysis in order to eliminate learning effects.

After completing all handle and trigger combinations, subjects were asked which handle span they preferred for each trigger type and which trigger type they preferred overall. They were given another opportunity

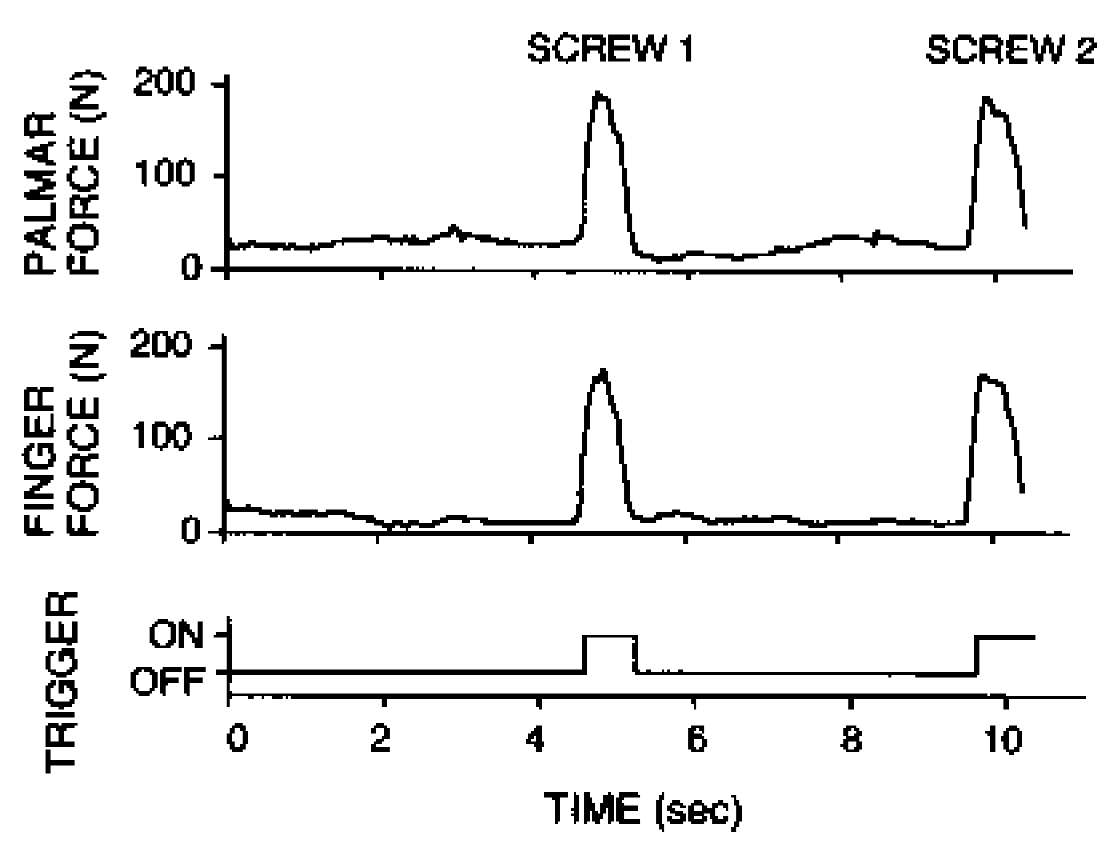

Figure 3. *Representative finger force and palmar force measured while handling a tool and during tool operation.*

to operate the tool and readjust the handle span until they were satisfied with their selection. The preferred span was then measured using a Fowler Ultra-cal II digital caliper.

RESULTS AND DISCUSSION

Grip Strength

Individual subject grip strength is given for each subject group in Tables 1 and 2. Grip strength, averaged over the four handle spans, was 200 N (*SD* = 70 N) for the female students and 404 N (*SD* = 111 N) for the male students. Average grip strength was 256 N (*SD* = 46 N) for the female factory workers and 354 N (*SD* = 89 N) for the male factory workers.

Average grip strength is plotted against handle span in Figure 4. Handle span had a significant effect on grip strength for student subjects (see Table 3) and worker subjects (see Table 4). Grip strength increased significantly as span increased from 4 cm to 5 cm for students (see Table 5) and factory workers (see Table 6).

The shape of the strength curve plotted against handle span was the familiar inverted U, similar to the results reported in numerous other grip strength studies (see Figure 4). The span resulting in maximum grip strength also agreed with the findings from previous strength investigations (Hertzberg, 1955; Petrofsky et al., 1980). Among student subjects, 17 of 18, and 10 of the 11 worker subjects, recorded their maximum grip strength for a span of 5 cm to 6 cm in this experiment (see Figure 4).

Although the handle span resulting in maximum grip strength and the grip strength function agreed with previous findings, the grip strength magnitude for both student and worker subjects was less than what has been previously reported. Schmidt and Toews (1970) collected grip strength data from 1128 male and 80 female Kaiser Steel Corporation employee applicants using a Jamar dynamometer. For a handle span of 3.8 cm, they reported an average of 499 N for the dominant male hand and 308 N for the dominant female hand. Swanson, Matev, and De Groot (1970) measured the grip strength of 50

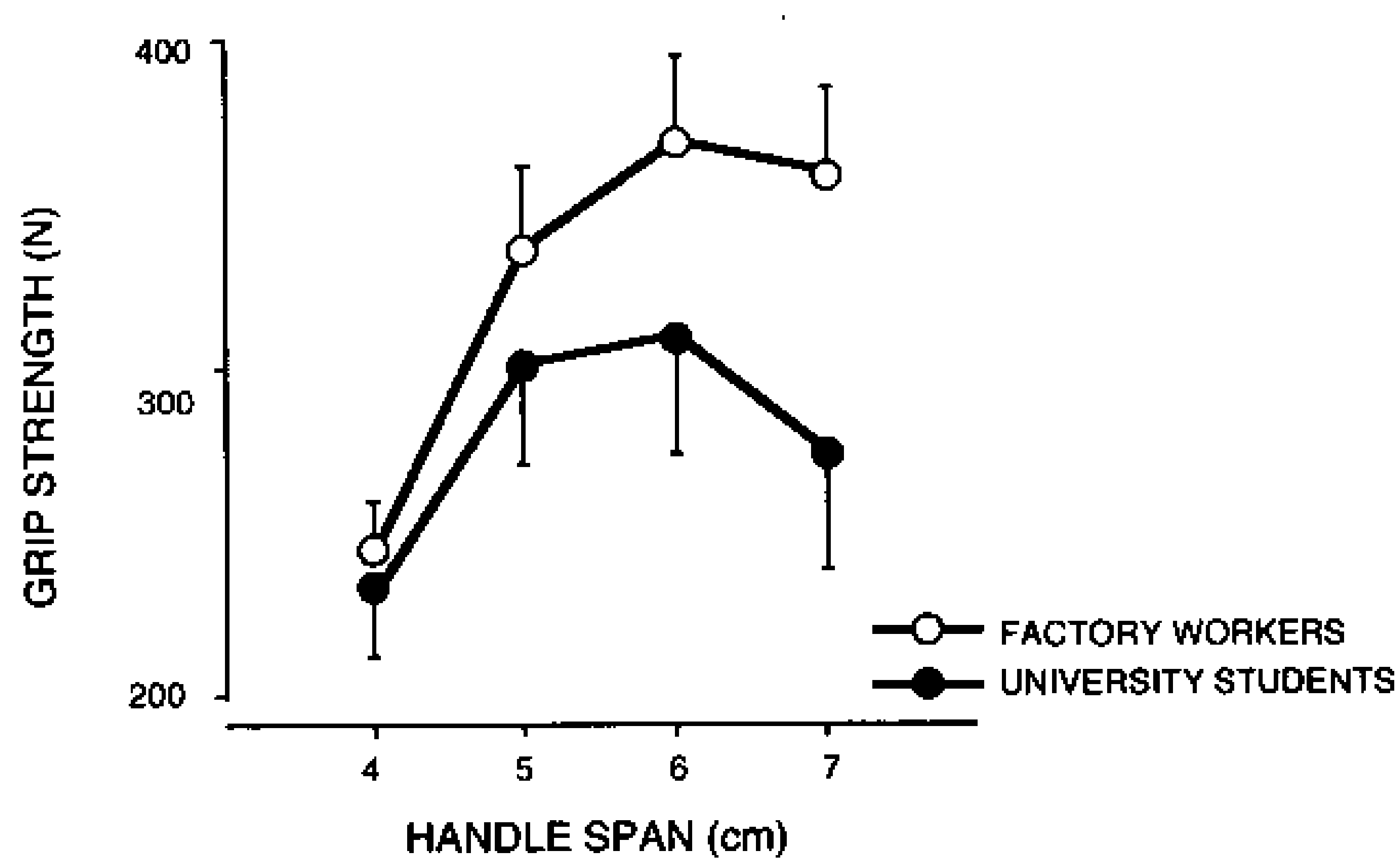

Figure 4. *Average grip strength plotted against handle span for university students and factory workers. Error bars represent standard error of the mean.*

TABLE 3

Summary of Significant ANOVA Effects for University Student Subjects

Variable	*Effect*	*Degrees of Freedom*		*F*	*p*
		Numerator	*Denominator*		
Grip strength	Length	2	15	11.1	0.001
	Span	3	45	14.1	<0.001
	Span × Length	6	45	3.3	0.009
Peak finger force	Type	1	15	8.4	0.011
	Span	3	45	8.4	<0.001
	Span × Length	6	45	2.3	0.051
Peak palmar force	Type	1	15	10.0	0.006
	Span	3	45	8.1	<0.001
	Span × Length	6	45	3.0	0.016
Peak finger exertion level	Type	1	15	4.9	0.042
	Span	3	45	4.5	0.008
Peak palmar exertion level	Type	1	15	4.8	0.045
	Span	3	45	4.8	0.005
Average finger holding force	Type	1	15	46.6	<0.001
	Span	3	45	6.2	0.001
Average palmar holding force	Type	1	15	46.6	<0.001
	Span	3	45	4.9	0.005
Average finger holding exertion level	Type	1	15	52.6	<0.001
Average palmar holding exertion level	Type	1	15	4.6	0.049
	Span	3	45	8.9	<0.001
	Span × Length	6	45	2.5	0.036

females and 50 males using a Jamar dynamometer. Among these subjects, 36 were light manual workers, 16 were sedentary workers, and 48 were manual workers. For a handle span of 6.4 cm, they reported 467 N for the male dominant hand and 241 N for the female dominant hand. All these strength levels exceeded the levels observed in the current study.

Differences in maximum grip strength between previous studies and this investigation may be attributed to differences in the

TABLE 4

Summary of Significant ANOVA Effects for Industrial Factory Worker Subjects

Variable	*Effect*	*Degrees of Freedom*		*F*	*p*
		Numerator	*Denominator*		
Grip strength	Span	3	30	14.4	<0.001
Peak finger force	Span	3	30	13.5	<0.001
Peak palmar force	Span	3	30	9.2	<0.001
Average finger holding force	Type	1	9	145.1	<0.001
Average palmar holding force	Type	1	9	185.2	<0.001
Average finger holding exertion level	Type	1	10	134.8	<0.001
	Span	3	30	10.1	<0.001
Average palmar holding exertion level	Type	1	10	99.4	<0.001
	Span	3	30	8.8	<0.001

TABLE 5

Tukey Multiple Contrasts of Handle Span for University Student Subjects

Span (cm)	4	5	6	7
Grip strength (N)	231 (82)	302 (129)	310 (153)	274 (151)
Peak finger force (N)	106 (45)	131 (74)	131 (75)	131 (75)
Peak palmar force (N)	129 (63)	153 (90)	152 (86)	157 (94)
Average finger holding force (N)	20.1 (12.3)	24.6 (16.3)	24.8 (13.5)	24.1 (14.9)
Average palmar holding force (N)	28.0 (13.8)	33.7 (20.0)	33.2 (15.6)	33.5 (17.0)
Peak finger exertion level (%MVC)	48.9 (20.0)	46.4 (21.7)	45.9 (21.2)	53.1 (22.5)
Peak palmar exertion level (%MVC)	59.7 (26.9)	54.2 (25.6)	54.3 (25.3)	63.7 (27.1)
Average palmar holding exertion level (%MVC)	14.1 (9.5)	11.1 (7.4)	13.2 (9.5)	15.9 (11.2)

One standard deviation is listed in parenthesis. MVC = maximum voluntary contraction. Underlining indicates no significant difference (p = 0.05).

particular handles used and the methods used for collecting strength data. Grip strength data often used for handle design are based on the Jamar dynamometer, Smedley dynamometer, or similar instruments (Schmidt and Toews, 1970; Young et al., 1989) rather than on a handle representative of an actual tool. In most previous cases, only one dimension (handle span) was controlled, and the other handle dimensions were not necessarily similar to those of a tool handle. The Jamar and Smedley dynamometers have smaller circumferences and narrower widths than the tool handle used in this study. Also, the tool handle curvature is straight, whereas the Jamar dynamometer has a curved surface at the grip center. The handle used in this study closely represented an actual tool handle circumference and width. These size and curvature differences can affect the position of the fingers and grip posture. Dimensional differences must therefore be considered when designing handles based on strength using published grip strength data.

Another difference between previous studies and this study is the method used for measuring grip strength. In the current study subjects were required to exert a maximum

TABLE 6

Tukey Multiple Contrasts of Handle Span for Industrial Factory Worker Subjects

Span (cm)	4	5	6	7
Grip strength (N)	244 (53)	336 (84)	369 (86)	360 (85)
Peak finger force (N)	142 (34)	190 (38)	193 (59)	184 (47)
Peak palmar force (N)	185 (37)	224 (47)	233 (69)	226 (53)
Average finger holding exertion level (%MVC)	13.0 (5.3)	11.0 (5.1)	8.8 (3.1)	8.8 (3.7)
Average palmar holding exertion level (%MVC)	16.8 (6.2)	14.1 (7.2)	11.4 (3.9)	11.4 (4.7)

One standard deviation is listed in parenthesis. MVC = maximum voluntary contraction. Underlining indicates no significant difference (p = 0.05).

power grip for 3 s. Grip strength was then calculated by averaging the force for 1.5 s after a full exertion was developed. Because the Jamar- and Smedley-type dynamometers record peak force, grip strength may seem somewhat greater in studies using those instruments, though great differences are not expected.

Grip strength significantly increased as hand length increased for the university student subjects (see Table 3). Average grip strength was 182 N (SD = 46 N) for the small hands, 249 N (SD = 106 N) for the medium hands, and 407 N (SD = 114 N) for the large hands. Figure 5 illustrates the interaction of Length × Span for the student group. Maximum grip strength occurred at a handle span of 5 cm for the small- and medium-size hands and at a span of 6 cm for the large-size hands.

Submaximal Forces during Tool Operation

Peak finger and palmar forces, averaged over the two trigger types, are plotted against handle span in Figure 6. Peak finger and palmar forces significantly increased as handle span increased for both subject groups (see Tables 3 and 4). Both peak finger and palmar forces were significantly less for a handle span of 4 cm than for handle spans of 6 cm and 7 cm (see Tables 5 and 6). Average peak finger and palmar force did not significantly increase ($p > 0.05$) when increasing handle span from 5 cm to 7 cm for either student or worker groups. Trigger type had a significant effect on peak finger and palmar forces for the student group (see Table 3). Average peak forces were consistently greater for the conventional trigger than for the extended trigger (see Table 7).

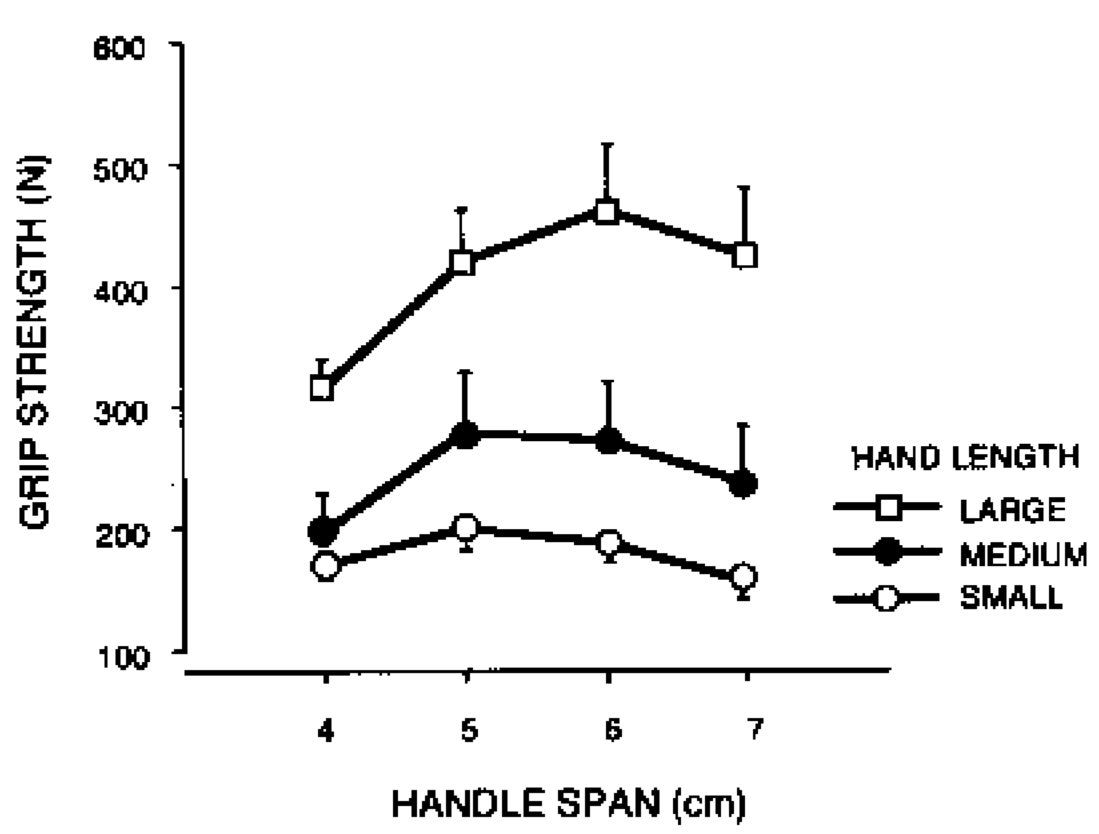

Figure 5. *Average grip strength plotted against handle span for the three hand size categories for university students. Error bars represent standard error of the mean.*

The dynamometer used in this experiment had its sensitivity directed along the horizontal axis, parallel to the tool trigger and spindle. Because the peak forces were less for the small handle span than for the larger handle spans, it may be possible that the fingers could wrap further around the handle, directing forces away from the dynamometer axis of sensitivity. However, because subjects were required to squeeze the trigger in order to operate the tool, the position of the distal index finger was controlled throughout the experiment regardless of the handle span. This means that it was unlikely that additional force components were directed away from the dynamometer axis of sensitivity and that the decreased forces observed for the small handle span resulted from force vectors directed away from the axis of sensitivity of the force transducer.

In order to replicate these findings, a follow-up pilot study was performed to further investigate how grip force may be affected by handle span. Three university students participated. They were instructed to grip a strain gauge dynamometer and lift it off a platform. A cable was attached to the dynamometer for suspending different weights. Subjects were allowed to select a finger position that was easily reproducible. Distal finger location at the dynamometer was kept the same for all handle spans. The locations of the distal fingers were marked on the dynamometer using a water-soluble marker.

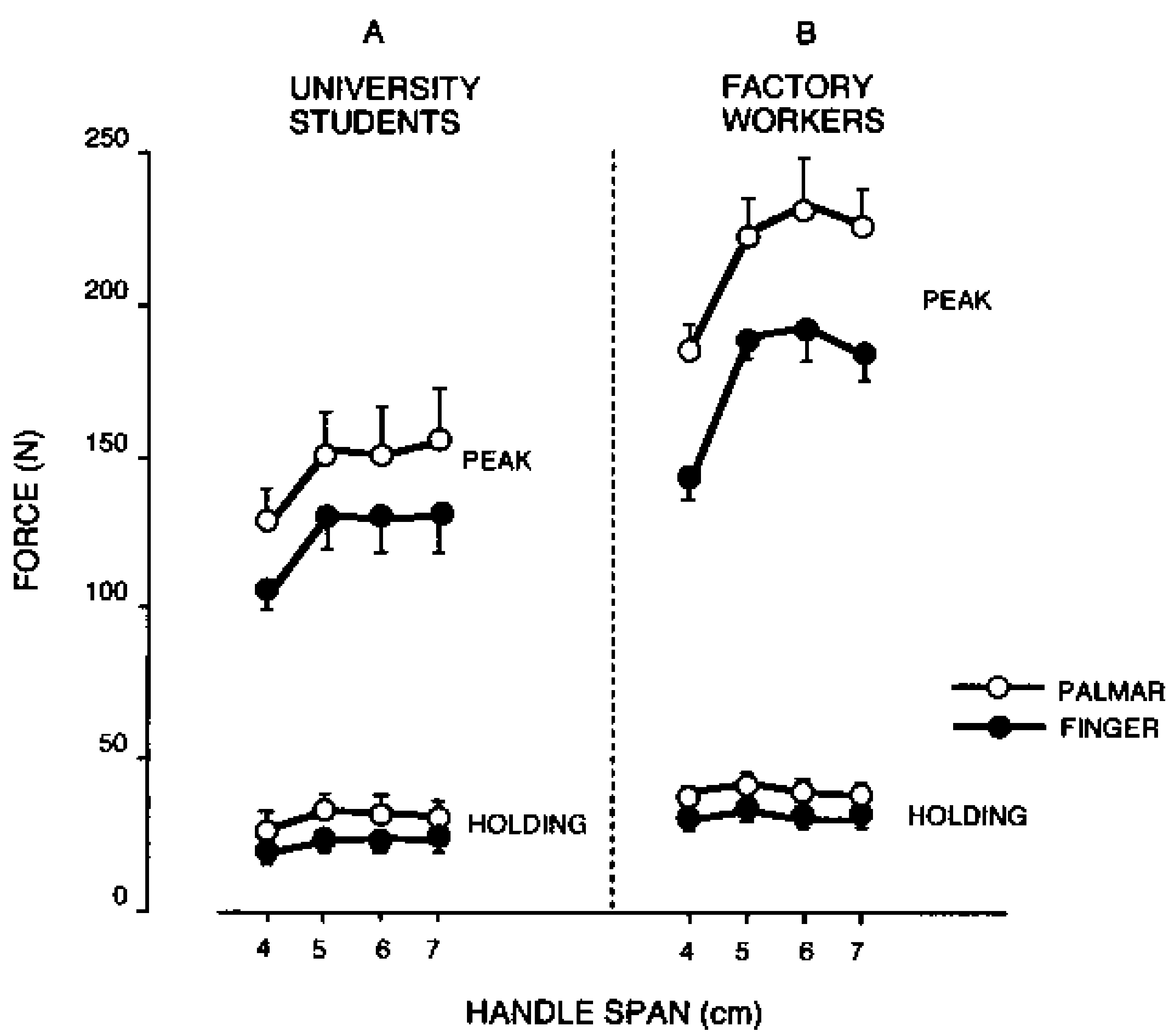

Figure 6. *Average peak force and holding force plotted against handle span: (A) university students and (B) factory workers. Error bars represent standard error of the mean.*

Subjects were presented with random combinations of two load weights (0.3 kg and 1.3 kg) and two handle spans (4 cm and 7 cm). Three replications were made for each experimental condition, and the results were averaged. The outcome of that study showed that subjects produced greater grip forces for the large handle span, $F(1,2) = 82.1$, $p < 0.01$. The force averaged over two load weights was 130 N ($SD = 49$ N) for a handle span of 4 cm

TABLE 7

Summary of Significant Trigger Effects

Subjects	Variable	Conventional Trigger		Extended Trigger	
		Finger	Palmar	Finger	Palmar
University students	Peak force (N)	130 (71)	153 (85)	119 (66)	142 (83)
	Peak exertion (%MVC)	50 (22)	60 (27)	47 (21)	56 (26)
	Average holding force (N)	29 (16)	38 (18)	18 (10)	26 (12)
	Average holding exertion level (%MVC)	13 (9)	14 (10)	8 (6)	13 (9)
Factory workers	Average holding force (N)	38 (11)	47 (13)	26 (9)	35 (12)
	Average holding exertion level (%MVC)	12 (5)	16 (6)	8 (4)	11 (5)

One standard deviation is listed in parenthesis. MVC = maximum voluntary contraction.
$^{*}p = 0.06$.

and 150 N (SD = 47 N) for a handle span of 7 cm. This pilot experiment replicated the results of the current study using even more carefully controlled finger positions than when operating the power tool.

The significant Length × Span interaction for the student group for peak finger and palmar forces (see Table 3) is illustrated in Figure 7. Tukey pairwise contrast tests showed that the small hands produced significantly less peak finger force ($p < 0.05$) and palmar force ($p < 0.01$) than did the medium and large hands, regardless of the handle span.

Peak finger and palmar exertion levels (defined as the ratio of peak force to MVC), averaged over the two trigger types, are plotted against handle span in Figure 8. Peak finger and palmar exertion levels for a handle span of 5 cm and 6 cm were less than for a handle span of 7 cm ($p < 0.05$) for the student group (see Table 5). Although hand forces for students were at a minimum for a handle span of 4 cm, exertion level was greater for 4 cm than it was for 5 cm and 6 cm (see Figure 8). This was likely because the minimum grip strength, which was used in the denominator, occurred for a handle span of 4 cm. Trigger type also had a significant effect on exertion level for the student group (see Table 3). On average, finger and palmar exertion levels for the conventional trigger were significantly greater than for the extended trigger (Table 7).

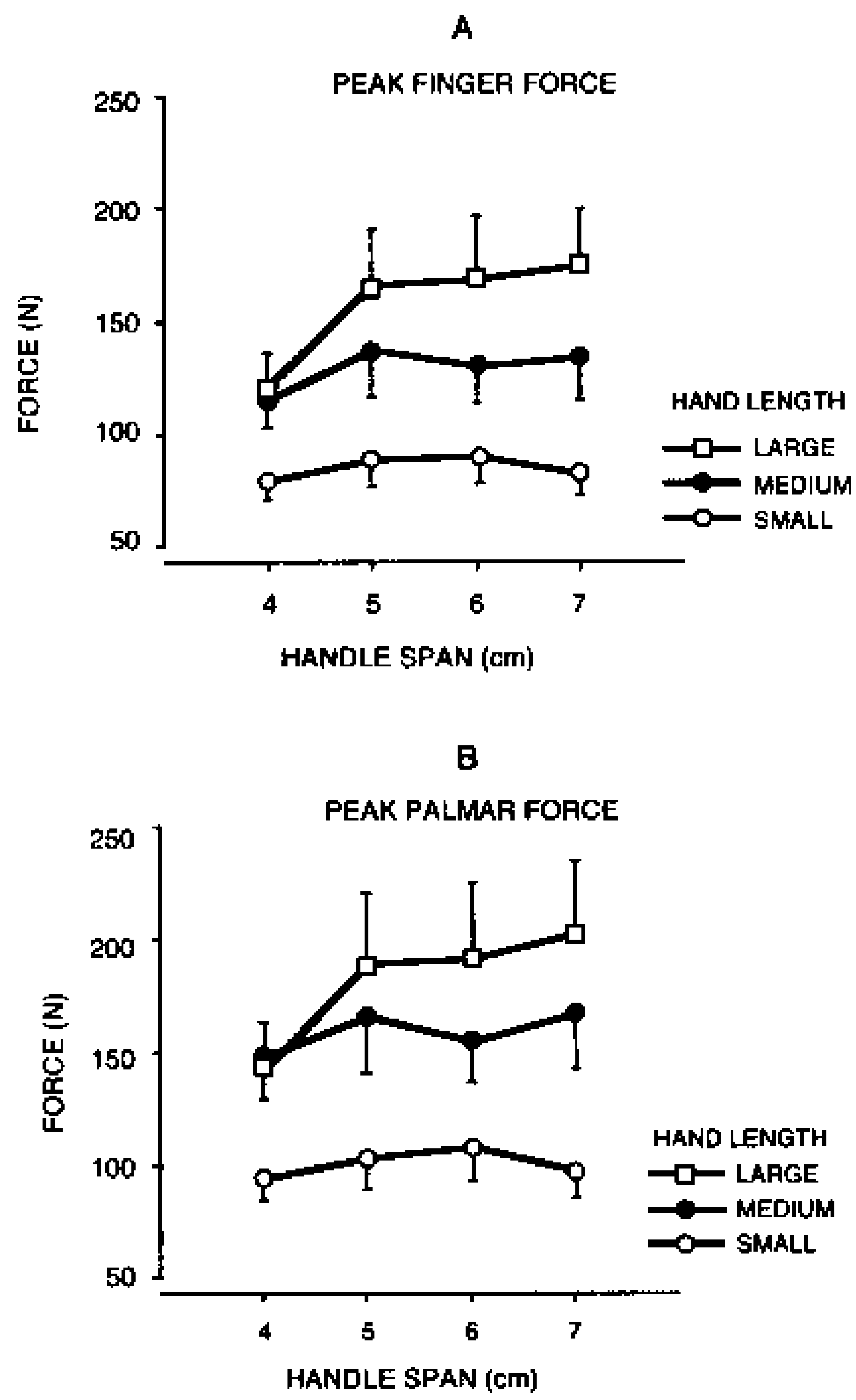

Figure 7. *(A) Average peak finger force and (B) average peak palmar force plotted against handle span for the three hand size categories for university students. Error bars represent standard error of the mean.*

Tennis players are often warned not to choose a racquet grip that is too small (Brown, 1977; Gothard, 1990). Based on anecdotal evidence, Gothard (1990) explained that if a grip is too small, it causes more stress and strain on the arm because the player has to "squeeze harder" in order to hold the racquet properly. The results of this experiment indicated that although subjects used less grip force, they produced greater exertion levels for the small (4 cm) handle span than for any other span. This may explain why tennis players perceive that they squeeze harder when the racquet grip is too small.

Exertion levels were computed as the ratio of rapidly building submaximal peak forces to fully developed static strength measured after maximum force build-up has occurred. The faster a muscle shortens, the less tension it produces. Kroemer and Marras (1981) showed that the rate of force build-up is faster for maximum isometric exertions than for submaximal isometric exertion. Hence it is possible that exertion levels reported

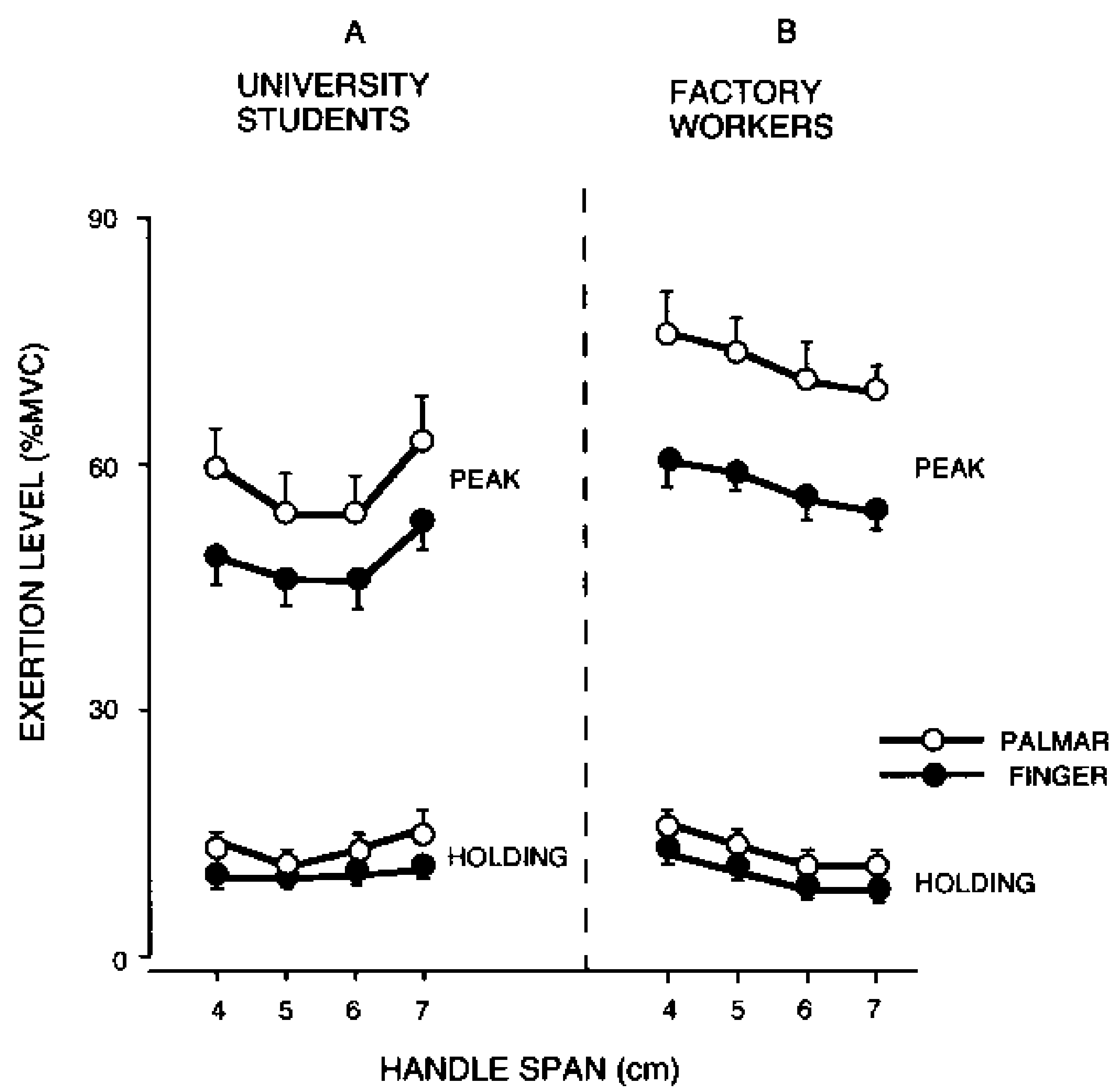

Figure 8. *Average finger exertion level and palmar exertion level plotted against handle span for (A) university students and (B) factory workers. Error bars represent standard error of the mean.*

in this study are underestimated. Fully developed isometric static strength (MVC) was chosen as a reference level in the current study because it is easy to control and measure.

Submaximal Forces While Holding the Tool between Operations

Tool-holding forces, averaged over the two trigger types, are plotted against handle span in Figure 6. Finger and palmar holding forces for the student group were significantly affected by handle span (see Table 3); however, these effects were small (see Figure 6). Finger and palmar holding forces for a handle span of 4 cm were significantly less than holding force for the other handle spans (see Table 5).

Finger and palmar holding exertion level, averaged over two trigger types, are plotted against handle span in Figure 8. Span had a significant effect on palmar holding exertion level for the student group (see Table 3). Palmar holding exertion level for a handle span of 7 cm was significantly greater than for other handle spans (see Table 5). Span had a significant effect on both finger and palmar holding exertions for the worker group (see Table 4). Worker finger and palmar tool-holding exertion levels for smaller spans were greater than were exertion levels for larger spans (see Table 6).

Finger and palmar holding exertion levels for the extended trigger were significantly less than for the conventional trigger for both student and worker groups (see Tables 3 and 4). Exertion levels, stratified on trigger type, are included in Table 7. These results indicated that trigger type affected the manner in which the tools were handled, even when the tools were not being operated. When using the extended trigger, operators may have shifted more of the tool weight over the crotch of the first and second digits, thereby reducing the grip force requirements.

The Length × Span interaction (see Figure 9) for the student subjects was significant for palmar holding exertion level (see Table 3). Tukey pairwise contrast tests showed that palmar holding exertion level for a handle span of 7 cm was significantly greater for the small-handed group than palmar holding exertion level for other spans ($p < 0.01$). Palmar holding exertion level for the small- and the medium-handed subjects was significantly greater than palmar holding exertion level for the large-handed subjects, regardless of handle span ($p < 0.05$).

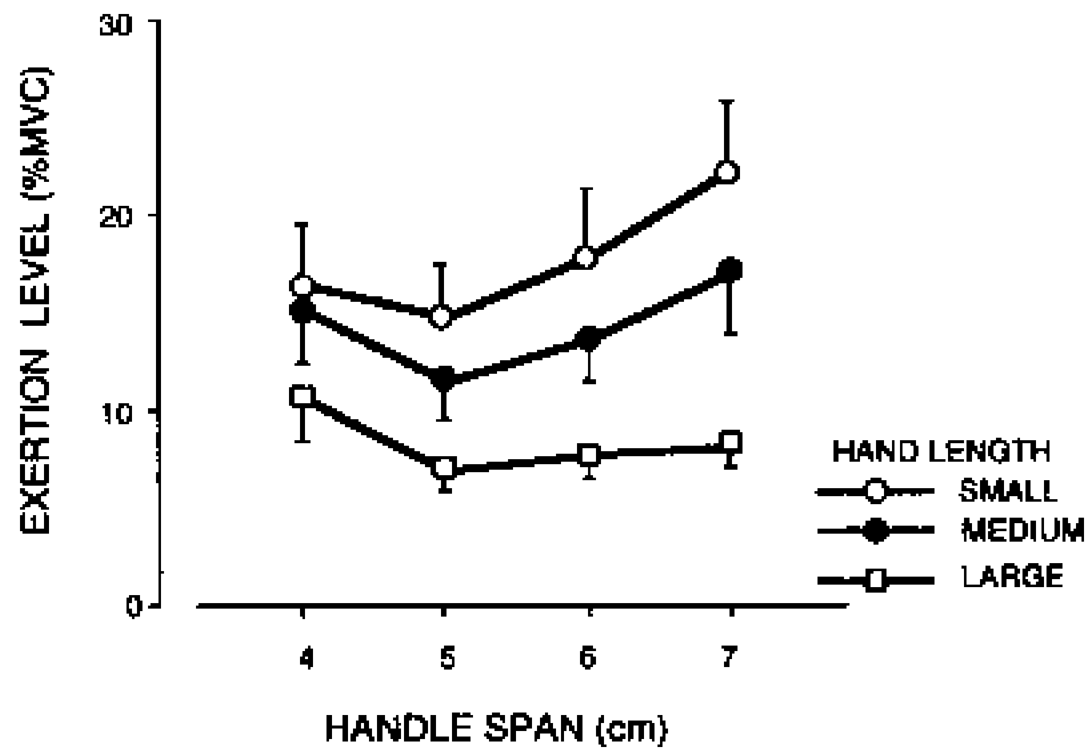

Figure 9. *Palmar holding exertion level plotted against handle span for university students. Error bars represent standard error of the mean.*

Comparison between Finger and Palmar Hand Force Components

Peak palmar force was significantly greater than peak finger force for students, $F(1,286) = 6.4, p = 0.01$, and factory workers, $F(1,174) = 25.8$, $p < 0.001$. Regression analysis showed that peak finger force was linearly related to peak palmar force when regressed over all experimental conditions for students, $F(1,142) = 4467, p < 0.001$, and factory workers, $F(1,86) = 161, p < 0.001$.

Finger and palmar forces are mostly affected by the force needed to resist the torque reaction forces produced by the power tool. This is apparent from the large differences in peak forces produced during tool operation and tool-holding forces exerted between tool operations (see Figure 6). The holding force represents the force necessary for holding the tool in the hand while supporting the weight of the tool and air line (minus the counterbalancing force of the spring balancer). The difference between the finger and palmar forces represents the feed force necessary for keeping the tool socket engaged. The actual forces exerted by an operator may exceed the minimum forces required for holding and overcoming reaction forces. The handle span and trigger effects, therefore, represent the forces exerted by an operator in excess of the minimum force requirements.

Trigger Preferences

Of the total sample, 11 of the 18 student subjects (61%) and 5 of the 11 factory workers (45%) indicated that they preferred using the handle with the extended trigger. Use of the extended trigger resulted not only in less peak finger and palmar forces during tool operation but also in less finger and palmar tool-holding forces exerted between tool operations (see Table 7). The effect of trigger type was significant for finger and palmar holding forces for both student and worker subject groups (see Tables 3 and 4). Average finger tool-holding force for the student group was 65% greater for the conventional trigger than for the extended trigger, and average palmar tool-holding force was 48% greater for the conventional trigger than for the extended trigger.

Similarly, finger holding force for the industrial worker group was 45% greater for the conventional trigger than for the extended trigger, and palmar holding force was 37% greater for the conventional trigger than for the extended trigger. Because the amount of operating time spent holding the tool was 76% in students and 65% in industrial subjects, using an extended trigger may be considerably beneficial throughout the work cycle.

Five of the seven students and four of the six workers who reported they preferred the conventional trigger explained that their decision was based on the concave curvature of the conventional trigger, rather than on trigger length (see Figure 2). These subjects indicated that if the extended trigger had a concave surface, they would have preferred the extended trigger. Two of the six workers who preferred using the conventional trigger said that their choice was based on the current tool they operated. Individual finger force was not measured. Therefore, it is not possible to see how force distribution among fingers is changed as trigger design changed.

Hand Size and Handle Span Preference

Hand anthropometry was considered as a factor for determining the optimum handle span. The size of tennis racquet handles is sometimes determined by the distance from the tip of ring finger to the long line that crosses the center of the palm (Gothard, 1990). In this experiment hand length, palm length, and hand width were all significantly related to the subjectively preferred handle span and to the span resulting in the maximum grip strength for the student group (see Table 8).

The relationship between hand length and preferred handle span for the student group is illustrated in Figure 10. Because no significant difference was observed between preferred handle spans for the conventional trigger and the extended trigger, $F(1,34) = 0.1$, $p > 0.7$, pooled preferred handle spans were used for the regression analysis. No anthropometric measurements were related to the span resulting in the minimum peak exertion level. No significant relationship was observed between preferred span and the span resulting in the minimum peak exertion level, based on either finger force ($p > 0.6$) or palmar force ($p > 0.9$), regardless of trigger type and subject group.

These results suggest that selectable size handles may be more desirable than having only a single size handle for power hand tools. Average exertion level when holding the tool was less for the large-size hands than for the small-size hands (see Figure 9).

TABLE 8

Summary of Regression Relationships between Hand Anthropometry and Handle Span

Dependent Variable	*Independent variable*	*Slope*	*Intercept*	R^2	*p*
Preferred handle span	Hand length	0.48	−3.21	0.59	0.00
	Palm length	0.89	−3.85	0.60	0.00
	Hand width	0.98	−2.59	0.48	0.00
Span at maximum grip strength	Hand length	1.41	10.31	0.27	0.03
	Palm length	0.85	5.73	0.33	0.01
	Hand width	0.59	4.96	0.24	0.04

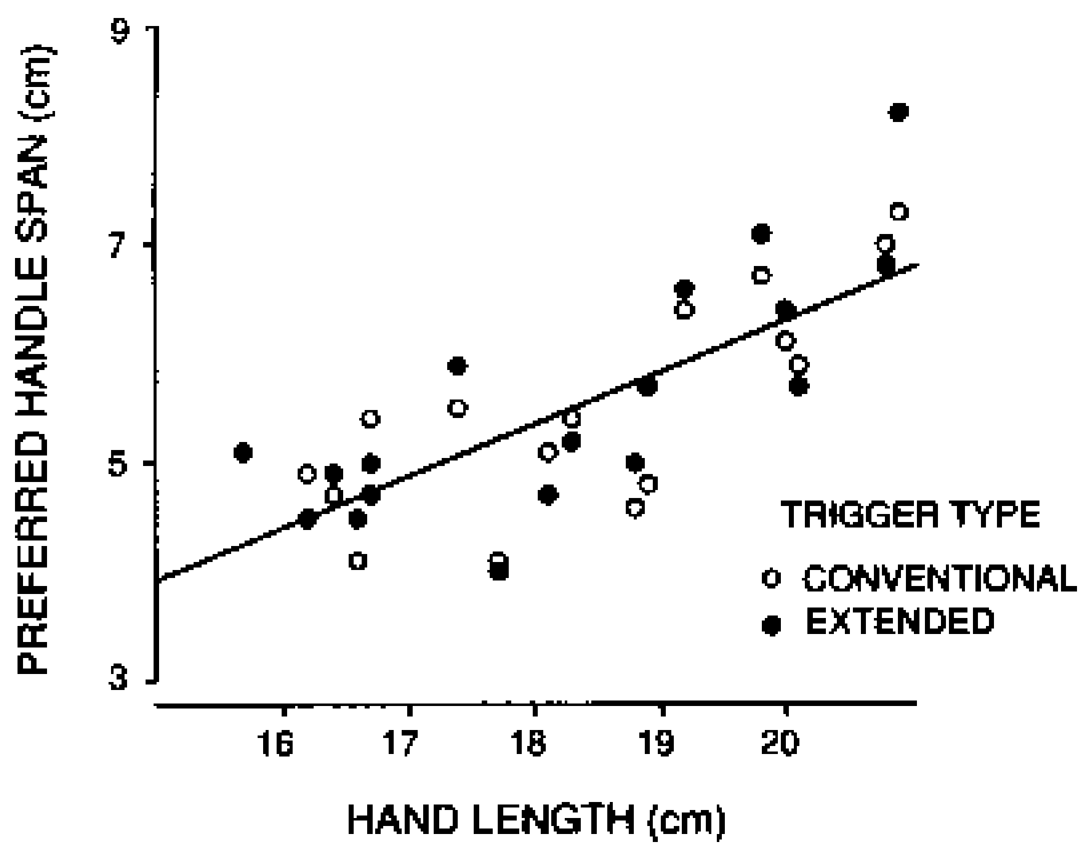

Figure 10. *Preferred handle span plotted against hand length for university students.*

Holding exertion level for the large hands was maximum for the 4-cm handle span, whereas holding exertion level for the small hands was maximum for the 7-cm handle span. Furthermore, the tendency was for large-handed subjects to subjectively prefer larger handle spans (see Figure 10).

University Student versus Industrial Factory Worker Subject Groups

Significant differences were observed between student and worker groups, including grip strength, peak forces, exertion levels, and holding forces.

A post hoc ANOVA showed that there was a significant difference in grip strength between students and workers, $F(1,108) = 4.8, p < 0.05$. Grip strength, averaged over handle span, was 279 N (SD = 133 N) for the student group and 327 N (SD = 90 N) for the worker group. There were no significant grip strength differences, however, between student and worker groups within each hand size, $F(3,108) = 0.5, p > 0.6$.

Peak finger, $F(1,230) = 39, p < 0.001$, and palmar forces, $F(1,230) = 48, p < 0.001$, were less for the student group than for the worker group (see Figure 6). The difference between peak palmar force and peak finger force was significantly greater, $F(1,230) = 24, p < 0.001$, for workers than for students (see Figure 6). Peak finger exertion level, $F(1,230) = 13, p < 0.001$, and palmar exertion level, $F(1,230) = 21, p < 0.001$, were also less for the student group than for the worker group (see Figure 8). Finger holding force, $F(1,230) = 23, p < 0.001$, and palmar holding force, $F(1,230) = 19, p < 0.001$, were greater for the industrial workers than for the university students (see Figure 6). No significant differences were observed between the student group and the worker group for either finger holding exertion level ($p > 0.8$) or for palmar holding exertion level ($p > 0.9$).

No significant span effects for either finger or palmar exertion levels were observed for the worker group; however, there was a significant span effect for the student group (see Figure 8). Furthermore, the effect of trigger type was not significant (see Table 4) for the worker group, whereas it was marginally significant (see Table 3) for the student group.

Differences between student and worker groups may result from distinct differences in their anthropometric characteristics and strength distribution (see Tables 1 and 2). There were no subjects with small hands ($L \leq 17$ cm) included in the worker sample, whereas there were six subjects with small hands in the student population. Average grip strength for the workers was 17% greater than for the students. Of the student subjects, 61% were female, whereas only 27% of the worker subjects were female. Other differences were the subject sampling methods used between the two subject populations and differences in experience using pistol grip power tools. Factory worker subjects were recruited based on their experience using power hand tools and on the similarity between the tools they had used and the tool in this experiment. Biased sampling is represented well by the anthropometric differences and gender distribution.

It is also possible that the workers' previous experience operating pistol grip power hand tools influenced the results. Many operators were accustomed to push-to-start pistol grip power hand tools using a conventional trigger. Their behavior operating these tools in their jobs may have transferred over to this experiment. Push-to-start tools require exerting additional palm force in addition to squeezing the trigger in order to operate the tool. This would explain the high palmar forces exerted by the industrial subjects (see Figure 6). Although 15 min were given for training and three replications were made for each condition, this preparation may not be long enough. Workers' experience may also have influenced their selection of the preferred handle span. The range of preferred handle spans for the worker group was smaller (4.7 cm to 6.5 cm) than that of the medium and large hands for the student group (4.0 cm to 8.2 cm). Of 11 workers, 8 commented that their preferred handle size was similar to the tool handle size they currently used in their job. Therefore, it is recommended that future studies provide a more suitable period of training and time to become accustomed to these differences.

CONCLUSIONS

This study investigated the effect of handle size and trigger type on forces and exertions produced during pistol grip pneumatic power tool operation using university student and industrial worker subjects. The results of these experiments led to the following conclusions.

1. Handle span affected submaximal finger and palmar forces. Peak finger force increased 24% for the student group and 30% for the worker group as handle span increased from 4 cm to 7 cm. Similarly, peak palmar force increased 22% for both the student and worker groups as handle span increased from 4 cm to 7 cm. Although peak finger and palmar forces were minimum for a handle span of 4 cm, grip exertion levels were minimum for a handle span of 5 cm to 6 cm. Handle span also influenced average finger and palmar tool-holding forces. Both finger and palmar holding force increased 20% as handle span increased from 4 cm to 7 cm for student subjects.

2. Hand size affected grip strength, hand force, and exertion level. Large-handed subjects produced their maximum grip strength for a handle span of 6 cm, whereas medium- and small-handed subjects produced their maximum strength for a handle span of 5 cm. Small-handed subjects exerted significantly less peak finger force and palmar force than did medium- and large-handed subjects, regardless of handle span. Holding exertion level for large-handed subjects was maximum when using a 4-cm handle and maximum for the small-handed subjects when using a 7-cm handle. Hand size was also proportional to preferred handle span.

3. Use of an extended trigger affected how the tool was handled. The extended trigger may be beneficial in terms of reduced hand force and exertion levels during tool operation. Average peak finger and palmar forces during tool operation for the student group were 9% and 8%, respectively, and less for the extended trigger than for the conventional trigger. Average finger and palmar tool-holding force between tool operations was 65% and 48%, respectively, and less for the extended trigger than for the conventional trigger. Similar effects were observed for industrial subjects.

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