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External finger forces in submaximal five-finger static pinch prehension

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Small conductive polymer force sensors were attached to the distal phalangeal pads for measuring individual finger forces exerted during submaximal static pinch. A linear force summing strain gauge dynamometer for measuring resultant five-finger pinch force was grasped vertically using a neutral wrist posture. Individual finger forces were measured at fixed total pinch force levels of 10%, 20%, and 30% of maximum voluntary exertion using pinch spans of 45 mm and 65 mm. Total pinch force and individual finger forces were also measured while similarly grasping the dynamometer and supporting fixed weights for 1·0 kg, 1·5 kg, and 2·0 kg loads using pinch spans of 45 mm and 65 mm. The index and middle fingers exerted more than 3 N greater average force than the ring and small fingers for the fixed total pinch force task. No significant individual finger force differences were observed at the 10% maximum voluntary exertion level, however both the index and middle fingers exerted more than 5 N greater force than the ring and small fingers at the 30% maximum voluntary exertion level. The average contribution of the index, middle, ring, and small fingers were 33%, 33%, 17%, and 15%, respectfully, for the fixed total pinch force task. As exertion level increased from 10% to 30%, the contribution of the middle finger was not constant increasing from 25% to 38%. Total pinch force increased from 15 N to 30 N when the load weight increased from 1·0 kg to 2·0 kg. The index finger exerted more than 1 N greater average force than the middle finger, and more than 3 N greater average force than the ring and small fingers during the static lifting task. The average contribution of the index, middle, ring, and small fingers were 35%, 26%, 20%, and 19%, respectfully, for the static lifting task. As load weight increased from 1·0 kg to 2·0 kg, the contribution of the index finger was not constant, decreasing from 38% to 30%.

1. Introduction

Measurement and prediction of individual finger forces during submaximal grip exertions are important for developing functional biomechanical models and for designing tools, work equipment and manual activities. Although individual finger forces have been studied in numerous investigations involving maximal grip exertion levels or strength (Swanson *et al.* 1970, Dickson *et al.* 1972, Hazelton *et al.* 1975, Ohtsuki 1981, Ejeskär *et al.* 1981, An *et al.* 1985, Amis 1987), surprisingly little data are available concerning submaximal pinch and grip exertions. A major difficulty in accurately predicting internal hand forces for biomechanical models is the determination of external finger forces for different joint configurations and grasping functions. This is probably because force sensors needed for measuring individual finger forces applied during grasping activities have not been available.

Various instruments have been devised and used for measuring individual finger forces during maximal voluntary pinch and grip exertions. Dickson *et al.* (1972) constructed a mechanical device for assessing postoperative individual finger strength by measuring displacement of a cantilever spring. Hazelton *et al.* (1975) studied the influence of wrist position on force produced by the individual finger flexors. Their instrument consisted of flexible straps attached to a strain gauge load ring for each finger while individual finger forces were measured simultaneously at the middle or distal phalanges. Ohtsuki (1981) similarly measured individual finger forces by restraining the forearm and placing rings tied to individual strain gauge load cells on each finger. Amis (1987) developed a dynamometer for simultaneously measuring both normal forces and tangential shear forces for each of the three phalangeal segments of finger when gripping a cylinder. The instrument, however, did not measure individual finger forces simultaneously. None of the above mentioned studies examined submaximal finger exertions.

Conventional methods for measuring exertion levels that are actually produced during grasping activities include subjective magnitude estimation, electromyography and directly instrumenting handles. Stevens and Mack (1959) demonstrated that individuals can subjectively estimate grip force according to power function of grip force. Magnitude estimation, however, is relatively low in resolution and depends on the objectivity of the participant. Electromyography has been used for studying power gripping, pinching, and precision handling at different exertion levels while handling objects of various weights and sizes (Long *et al.* 1970). Armstrong and Chaffin (1979) studied pinch and grip force exerted by workers performing various manual work activities, using electromyograms. Practical force measurement using surface electromyography, unfortunately, is limited to static exertions and fixed postures, is not specific to individual fingers or locations on the hand, and is not practical for measuring individual finger forces during complex manual work activities. Fellows and Freivalds (1989) measured grip force in the palm and fingers by attaching 14 resistive sensors to various locations on the handle of a garden tool. Instrumented handles, however, must be installed on every object handled, and are limited to measuring forces at locations specific to the handle rather than specific locations on the hand. Small force sensors that can be practically attached directly to the hand are needed for measuring hand forces during the wide variety of activities performed in manual work.

Due to a lack of force measurement instruments, attempts to model the finger and hand internal forces biomechanically have had to resort to making assumptions concerning external finger force distribution. Armstrong (1982) assumed that individual finger forces are distributed in proportion to the relative strength of the fingers. An *et al.* (1985) assumed that the force of extrinsic finger flexor muscles were distributed in proportion to their physiological cross-sectional areas. A complicating factor in predicting external finger forces is that individual finger exertions are not independent of one another. Ohtsuki (1981) concluded that activation of one finger may inhibit the activity of adjacent fingers during maximal voluntary exertions. Hence use of these assumptions do not take into account these interactions.

Recent technological advances have provided small, thin sensors having promise for use in directly measuring individual finger forces during normal grasping activities. Sorab *et al.* (1988) developed a system for measuring fingertip applied forces during delivery of newborns, using piezoresistive silicon sensors that were placed on the clinician's fingertips. These sensors were highly fragile and brittle and not suitable for measuring forces during manual work and activities of daily living. A conductive polymer force sensor for attaching to the palmar surface of the hand has been developed and rigorously tested (Jensen *et al.* 1991). Although somewhat limited in range and resolution, these sensors are highly durable and practical for measuring individual finger forces exerted during submaximal pinch.

The objective of this study was to investigate the contribution of individual fingers during submaximal pinch prehension tasks by directly measuring individual finger forces. Small, thin sensors were attached to the distal finger pads for measuring actual finger forces exerted during pinch grip tasks consisting of varying exertion levels, loads and sizes. The operating hypothesis was that individual fingers contribute to the total finger pinch force at the same proportion for increasing exertions levels and pinch spans.

2. Methods

2.1. *Apparatus*

Figure 1 contains a block diagram of the experimental apparatus and laboratory organization for this study. Individual finger forces were measured using thin conductive polymer force sensors taped to the distal phalangeal pads of the index, middle, ring and small fingers. The sensors were constructed using conductive polymer sensing elements manufactured by Interlink Electronics (Santa Barbara, CA). They consist of a conductive organic film screen-printed on a Mylar sheet placed against another Mylar sheet having a printed silver ink pattern. Applied pressure increases contact between the conductive elastomer and a sensing electrode. As the contact area increases, the contact resistance decreases. Therefore the resistance of the sensor decreases with increasing pressure until the resistance reached a minimum. The sensor had a 12 mm diameter pressure sensing area. A 1 mm high epoxy dome was placed over the sensing area to equally distribute applied forces over the pressure sensitive element, turning it into a force sensor. Microfoam® tape (3M Company, Minneapolis, MN) was used for attaching the transducers directly to the fingers.

A strain gauge dynamometer served as the object pinched and lifted (see figure 1). A cable was attached to the dynamometer for suspending weights and increasing its effective load. The dynamometer was constructed for measuring the transverse force acting within an aluminium beam causing a shear stress in the cross-section (Pronk and Niesing 1981; Radwin *et al.* 1991). This resulted in a force measurement instrument that was independent of point of application, permitting the individual finger forces to sum linearly. The dynamometer was calibrated by suspending weights from the handle in the plane of greatest sensitivity. Two 16 mm × 16 mm × 120 mm instrumented beams were mounted in parallel and 38 mm × 117 mm aluminium plates were attached for increasing the pinch surface area. The span between the outer surfaces of the parallel plates was continuously adjustable.

Static force sensor calibration was performed after every sensor was attached to the fingers by opposing the finger against the strain gauge dynamometer with the thumb. Maximum pulp pinch force was first measured for each finger and then ten static calibration points were selected at equally spaced intervals up to 50% maximum voluntary contraction (MVC). The reference level was displayed on an oscilloscope so when subjects pinched the dynamometer at the desired force level the beam remained within a target area on the screen. During this time both the sensor and dynamometer outputs were sampled. Force levels were presented for each sensor

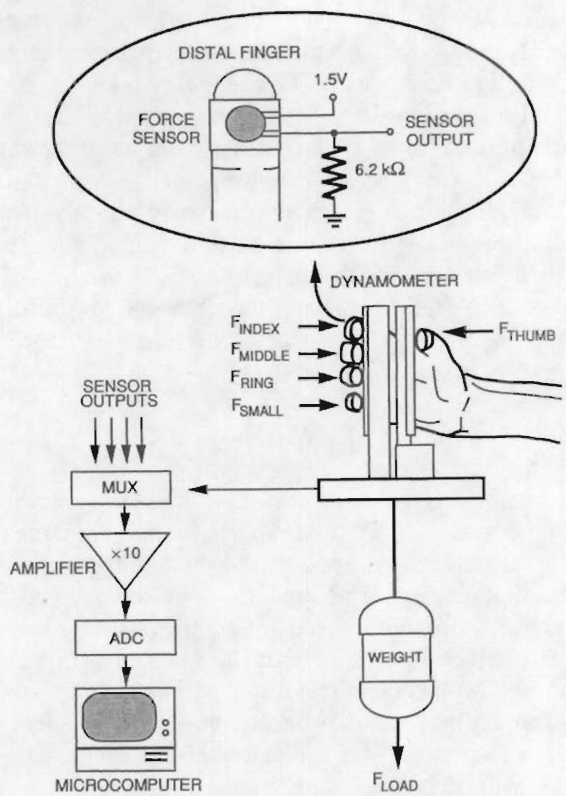

Figure 1. Experimental apparatus and laboratory organization.

in random order. The outputs were each averaged over a 2 s sampling interval beginning after the pinch force stabilized and were used as pairs of static calibration points. A second-order polynomial calibration curve was fit for each sensor using linear regression.

The finger force sensors had a useful range of 0 N to 30 N with a resolution of 1 N. The sum of the distal phalangeal finger forces, measured using the force sensors, was compared to the force measured using the dynamometer for each trial as an internal reliability check. The two values should have been the same, within an acceptable level of error. Sources of error included inadvertent variation in pinch posture and pinching using the medial phalangeal pads. The absolute average error between the dynamometer and sum of the four force sensors was 13% for Experiment 1 and 17% for Experiment 2. Outliers that resulted in more than a 40% difference between the sum of the individual finger forces and the dynamometer force, indicating all the sensors were not completely contacting the dynamometer surface, were discarded.

A 12-bit analog-to-digital converter (ADC) was used for recording sensor and dynamometer outputs. A microcomputer controlled all data acquisition, display, and storage of the collected data. Finger and dynamometer forces were sampled at 40 Hz for a sampling period of 2 s.

2.2. *Experiment 1: fixed total pinch force*

Experiment 1 measured individual finger forces for three levels of static total pinch force and two pinch spans in a full-factorial experimental design. The five-finger pinch grip total exertion levels were controlled at 10%, 20%, and 30% of each subject's MVC level. The two pinch spans were 45 mm and 65 mm. Every force and span condition was replicated three times for each subject and averaged.

Subjects were instructed to pinch the dynamometer using all five fingers of the dominant hand as illustrated in figure 1, while seated. They were permitted to select particular finger positions that felt comfortable and were easily reproducible. Subjects were reminded to grip the dynamometer in the same manner for each trial. The locations of the fingers and thumb against the dynamometer were marked using a water soluble marker. This allowed the experimenter to visually monitor the grip during each trial and check for consistency of grip posture between trials. Every time the dynamometer was grasped, placement of the sensors were inspected to ensure they were positioned correctly. The dynamometer was held using a 90° elbow angle and the upper arm was positioned parallel to the upper torso. The dynamometer was grasped so that the parallel plates were held vertical with the forearm held in neutral rotation.

Visual force feedback was provided using an oscilloscope for controlling total five-finger pinch force exertion levels when gripping the dynamometer. The difference between the dynamometer ouput and a voltage corresponding to the reference force were subtracted using a differential amplifier. Similar to the calibration procedure, a target at the centre of the oscilloscope screen represented the reference force level and the position of the oscilloscope beam corresponded to the difference between reference level and the actual total pinch force exerted. Subjects were instructed to maintain the beam position inside the target area by adjusting their grip. The dynamometer and sensor outputs were sampled for 2 s using the ADC after the force level stabilized and only the average forces over the sample period were retained for each trial.

2.3. *Experiment 2: fixed load weight*

Total pinch compression force and individual finger forces were measured while lifting three load levels and pinching two pinch spans in a full-factorial experimental design. The load levels included 1·0 kg, 1·5 kg, and 2·0 kg, and the spans were 45 mm and 65 mm. Every condition of load level and span was replicated three times and presented in random order for each subject and averaged.

Subjects were instructed to pinch the dynamometer using all five fingers of the dominant hand. They were permitted to select particular finger positions that felt most comfortable and were easily reproducible. The locations of the fingers and thumb were marked on the dynamometer using a water soluble marker so the experimenter could visually monitor the grasp during each trial and check for consistency between trials.

Seated subjects lifted the dynamometer off the top of a platform. Load weights were suspended from a cable attached to the dynamometer, which passed through a hole in a platform, so the load weights were hidden from the subject's sight to avoid visual cues. The dynamometer was grasped using a 90° elbow angle, the upper arm parallel to the upper torso, and the wrist deviated so the parallel plates were held vertical.

Several practice trials were provided prior to the actual experiment until subjects reported they felt comfortable performing the task. Subjects were reminded to grip the dynamometer in the same manner before each trial. The experimenter continuously monitored subjects for correct posture and observed the output of the dynamometer on an oscilloscope. When a steady dynamometer output was observed, the dynamometer and sensor outputs were sampled and averaged over a 2 s sample period.

2.4 *Subjects*

Subjects were solicited by posting announcements on bulletin boards in university buildings or recruited by invitation of the experimenters. The criterion for acceptance required that subjects indicated they were healthy adults who had no history of neuropathies or injuries to the dominant hand. Subjects were paid for their participation on an hourly basis.

Eight subjects participated in this study. Four were male and four were female. Their ages ranged from 18 years to 33 years old. All subjects described themselves as right-handed individuals. The average hand length was 18·6 cm (SD=1·4 cm) and average hand width was 8·1 cm (SD=0·6 cm). Only seven subjects were included in Experiment 1 because of equipment difficulty with one subject. Finger length and hand dimensions of the dominant hand were measured for every subject. Five finger pulp pinch grip strength and individual finger pinch strength were measured using the dynamometer for the two grip spans after the sensors were attached to the fingertips. The angles of the MCP, PIP, and DIP finger joints were also recorded using a Preston finger goniometer. The order subjects performed Experiment 1 and Experiment 2 were counterbalanced so half performed Experiment 1 first and half performed Experiment 2 first.

3. Results

3.1. *Pinch and finger strength*

Average maximum voluntary five finger pinch strength for eight subjects using the same posture when performing submaximal pinch exertions was 100 N (SD=26 N). The effect of pinch span on strength was not statistically significant $F(1,7)=0{\cdot}03$, $p>0{\cdot}8$). Average pulp pinch strength measured for each individual finger opposing the thumb, is summarized in table 1. The effect of individual finger strength was significant ($F(3,21)=38{\cdot}00$, $p<0{\cdot}001$) however no significant differences were observed between the index finger and middle finger strength or between the ring finger and small finger strength using Tukey multiple contrasts ($p>0{\cdot}1$). Both the index finger and middle finger strength were significantly greater than the ring finger and small finger strength ($p<0{\cdot}01$).

Table 1. Comparison of finger strength data from this study with previous investigations.

Study	Average finger strength (N) Index	Middle	Ring	Small
Current study	61 (SD=15)	58 (SD=21)	36 (SD=13)	28 (SD=11)
Swanson *et al.* 1970	52	55	37	23
Dickson *et al.* 1972	45	43	31	27
Average	53	52	35	26

3.2. *Experiment 1: fixed pinch force*

Average total pinch force, measured using the strain gauge dynamometer, is plotted against corresponding required pinch exertion levels in figure 2. Pinch force exterted by each individual finger, measured using the finger force sensors and averaged over all exertion levels and pinch span conditions, is plotted in figure 3. The effect of individual fingers on average total pinch force was significant ($F(3,18)=11{\cdot}10$, $p<0{\cdot}001$). Tukey pairwise multiple contrasts indicated no significant difference ($p>0{\cdot}1$) between average index finger and middle finger forces, or between the ring finger and small finger forces. The average ring finger force, however, was 3 N less ($p<0{\cdot}01$) than the average index and middle finger forces, and the average small finger force was 4 N less ($p<0{\cdot}01$) than the average index and middle finger forces.

Average force exerted by individual fingers are plotted against the required total pinch exertion levels in figure 4. The interaction between finger × level was significant ($F(6,36)=4{\cdot}74$, $p<0{\cdot}005$). As exertion level increased from 10% MVC to 30% MVC, the average middle finger force increased 7 N ($p<0{\cdot}01$), the average index finger force increased 5 N ($p<0{\cdot}01$), and the average ring finger force increased 4 N ($p<0{\cdot}01$). Although the average small finger force also increased 2 N, this increase was not statistically significant ($p>0{\cdot}1$). No significant differences ($p>0{\cdot}1$) were observed between individual finger forces at the 10% MVC exertion level when using Tukey pairwise multiple contrasts. At the 20% MVC exertion level both the index finger and middle finger force were 4 N greater than the ring finger and small finger forces ($p<0{\cdot}01$). At the 30% MVC exertion level the average index finger force was 3 N greater ($p<0{\cdot}01$) than the average ring finger force and 5 N greater ($p<0{\cdot}01$) than the average small finger forces, and the average middle finger force was 5 N greater ($p<0{\cdot}01$) than the average ring finger force and 7 N greater ($p<0{\cdot}01$) than the average small finger force. Although the interaction between finger × span was statistically significant ($F(3,18)=4{\cdot}15$, $p<0{\cdot}05$), the magnitude of this effect was small. The average force exerted by the middle finger only decreased only 1 N when the pinch span increased from 45 mm to 65 mm, while the exertion levels for the remaining fingers were unchanged.

The average contribution of each finger to the total five-finger pinch force is summarized in table 2 and the finger effect was significant ($F(3,18)=12{\cdot}43$, $p<0{\cdot}001$). Tukey pairwise multiple contrasts indicated the average index finger and middle finger contributions were both 16% more ($p<0{\cdot}01$) than the average ring finger contribution and 18% more than the small finger contribution. The interaction between finger × level for percent contribution of each finger is shown in figure 5, and was also significant ($F(6,36)=4{\cdot}34$, $p<0{\cdot}01$). As exertion level increased, the middle finger contribution increased from 25% to 38% ($p<0{\cdot}01$). At the 10% MVC exertion level Tukey pairwise multiple contrasts indicated the index finger contribution was 10% more than the middle finger contribution ($p<0{\cdot}05$). At 30% MVC, however, no significant difference ($p>0{\cdot}1$) between the index finger and middle finger percent contribution was observed. Although the interaction between finger × span was statistically significant ($F(3,18)=3{\cdot}95$, $p<0{\cdot}05$), the magnitude of this effect was small. The average force contribution from the middle finger decreased by only 3% when the pinch span increased from 45 mm to 65 mm.

3.3. *Experiment 2: fixed load weight*

Figure 6 contains the average total pinch force exerted for the three load weight conditions. Average total pinch force increased from 15 N (SD=4 N) to 31 N

Table 2. Per cent contribution of individual fingers to the total pinch force.

Finger		Experiment 1 Fixed pinch force (%)	Experiment 2* Fixed load weight (%)
Index	Mean	33·1	34·7
	SD	7·5	9·3
Middle	Mean	32·5	26·4
	SD	9·7	7·5
Ring	Mean	17·2	20·1
	SD	7·1	5·8
Small	Mean	15·3	18·8
	SD	7·8	5·1

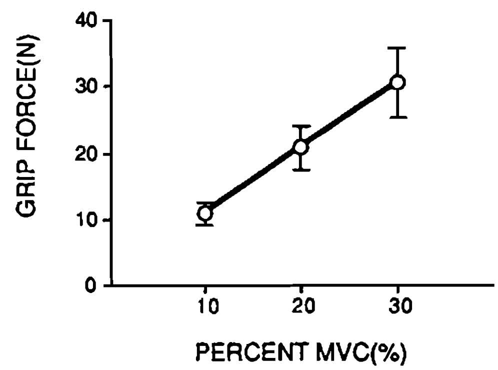

Figure 2. Average total grip force plotted against exertion level in Experiment 1 (seven subjects). Error bars represent ±one standard deviation.

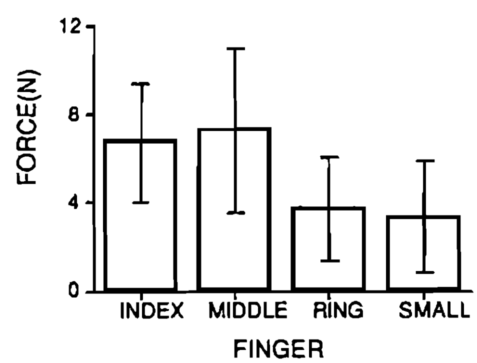

Figure 3. Individual finger forces averaged over all exertion levels and span conditions in Experiment 1 (seven subjects). Error bars represent ±one standard deviation.

(SD=6 N) when doubling the load weight from 1·0 kg to 2·0 kg ($F(2,14)=183$, $p<0{\cdot}001$). Average total pinch force also increased 2 N when increasing the grip span from 45 mm to 65 mm ($F(1,7)=6{\cdot}38$, $p<0{\cdot}05$), however the magnitude of this effect

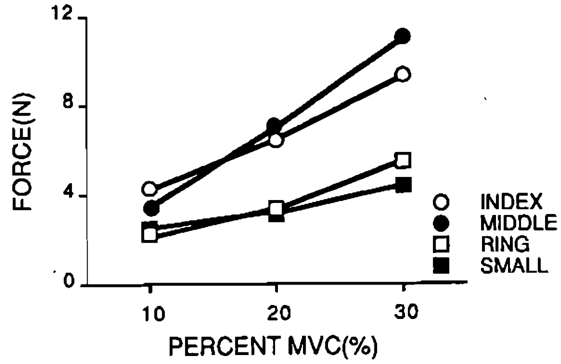

Figure 4. Average individual finger forces plotted against exertion level for Experiment 1 (seven subjects).

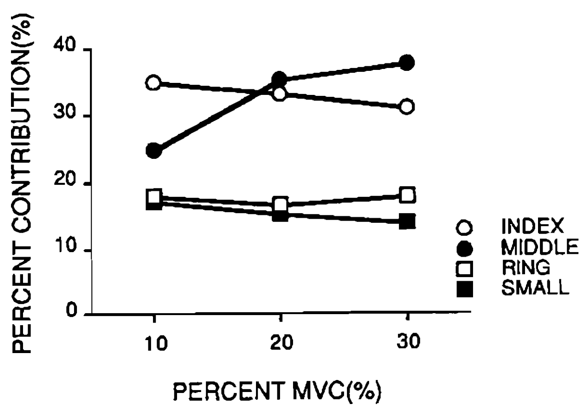

Figure 5. Average finger contribution to total pinch force measured at each exertion level in Experiment 1 (seven subjects).

was relatively small (7% increase). No significant effect on total pinch force was observed for the interaction between load × span ($F(2,14)=1{\cdot}11$, $p>0{\cdot}3$).

The effect of individual fingers on force exerted during the static lifting task was significant ($F(3,21)=8{\cdot}27$, $p<0{\cdot}001$). Finger forces averaged over all load weight and grip span conditions are shown in figure 7. Tukey pairwise contrasts indicated the average index finger force was 1 N greater than the middle finger ($p<0{\cdot}05$), and more than 3 N greater than the ring finger ($p<0{\cdot}01$) and small finger ($p<0{\cdot}01$). The average middle finger force was also 2 N greater than the average ring finger force and 2 N greater than the average small finger forces ($p<0{\cdot}01$). No significant difference, however, was observed between the average ring finger and small finger forces ($p>0{\cdot}1$). The interaction between span × load was not significant ($F(2,14)=1{\cdot}25$, $p>0{\cdot}3$).

The average percent contribution to total pinch for individual fingers is summarized in table 2 and the effect of fingers was significant ($F(3,21)=9{\cdot}33$, $p<0{\cdot}001$). Tukey pairwise contrasts indicated the average index finger contribution was significantly ($p<0{\cdot}01$) greater than all the other fingers, and the average middle finger contribution was significantly ($p<0·01$) greater than the average ring finger and small finger contributions. No significant effects on percent contribution were observed for the main effects of grip span ($F(1,7)=0·1$, $p>0·7$) and load weight ($F(2,14)=0·64$, $p>0·5$). The interaction between finger×load on percent contribution to total pinch force was significant ($F(6,42)=4·16$, $p<0·01$). Figure 8 illustrates the percent contribution to total pinch force for each finger as a function of load weight. As load weight increased from 1·0 kg to 2·0 kg the index finger contribution decreased ($p<0·1$) from 38% (SD=10%) to 30% (SD=7%). Tukey pairwise multiple comparisons indicated that the index finger percent contribution was 13% greater than the middle finger ($p<0·01$) for the 1·0 kg load weight, however no significant difference ($p>0·1$) was observed at the 2·0 kg load weight.

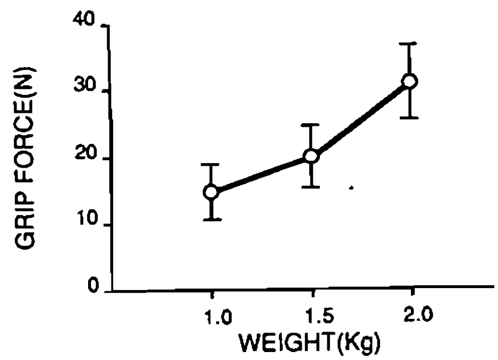

Figure 6. Average total grip force plotted against load weight in Experiment 2 (eight subjects). Error bars represent ±one standard deviation.

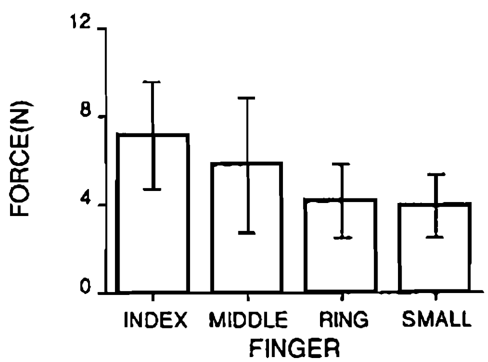

Figure 7. Individual finger forces averaged over all load levels and span conditions in Experiment 2 (eight subjects). Error bars represent ±one standard deviation.

4. Discussion

The relative magnitude of individual finger maximum voluntary exertion levels measured in this investigation were consistent with pinch strength data previously reported by others (see table 1). Swanson *et al.* (1970) measured the average pulp strength for 50 male subjects using individual digits opposing the thumb of the dominant hand and concluded, as in this study, that the index and middle fingers

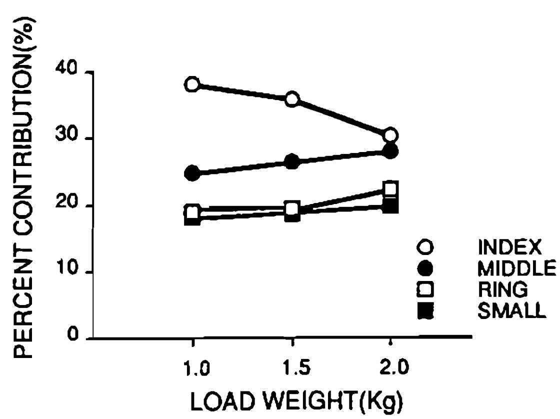

Figure 8. Average finger contributions to total pinch force measured at each load level in Experiment 2 (eight subjects).

were stronger than the ring and little fingers. Dickson *et al.* (1972) also measured mean flexion finger strength for the dominant hand finding similar results. Ejeskär *et al.* (1981) reported that the middle finger was the strongest, followed by the index finger, ring, and little finger. The two strongest fingers observed in this study, which were the index and middle fingers, also produced the greatest average forces at submaximal exertion levels (see figures 3 and 7).

Average contribution to five-finger pinch force at submaximal exertion levels in this study (see table 2) corresponded closely to the average individual finger contribution at maximal exertion levels measured by previous investigators. Hazelton *et al.* (1975) reported the index finger produced approximately 25%, the middle finger 33·5%, the ring finger 25·0%, and the little finger 16·5% of the total grip force at maximal exertion levels. Amis (1987) found the mean contribution of each finger during maximum voluntary exertions was 30% for the index finger, 30% for the middle finger, 22% for the ring finger, and 18% for the small finger. Ohtsuki (1981) also reported the relative share of individual fingers during maximal grip exertions was 24%–25% for the index finger, 33% for the middle finger, 27%–28% for the ring finger, and 15% for the little finger.

When adding the average individual finger strengths, the sum was 183 N, which exceeded the average pinch strength using all five fingers simultaneously by 83%. The apparent outcome that pinch strength was diminished when all four fingers participated indicated that profundus muscle recruitment may be inhibited when the fingers act synergistically. Ohtsuki (1981) observed this phenomenon and reported that individual finger strength decreased in proportion to the number of other fingers participating when performing simultaneous exertions. Therefore submaximal exertion levels used for this study were likely greater than 30% individual finger MVC since these levels were based on finger strength measured independently of other fingers.

For submaximal exertions studied in this investigation it was found that as the force requirement increased, individual finger contributions were not maintained constant even though individual finger forces increased in proportion to the total force requirement (see figure 4). It was observed that at low exertion levels (10% MVC) the index finger contributed 35% while the middle finger contributed 25% of the total pinch force (see figure 5). Conversely at the high exertion level (30% MVC) the index finger contribution decreased to 31% while the middle finger contribution increased to 38% of the total pinch force. Similarly for the small load weight (1·0 kg) the index finger contributed 38% but for the large load weight (3·0 kg) the index finger contributed only 30% (see figure 8). In contrast the middle finger contributed only 25% of the total grip force for the small load weight and 28% of the total pinch force for the large load weight. These recruitment interactions were apparently dependent on grip exertion level. Hence the assumption that individual finger external forces are exerted in direct proportion to strength is not correct. Controlled prehension in the fingers is the function of the delicate balance of flexor and extensor muscles indicating the presence of rapidly responding reciprocal innervation mechanisms (Hazelton *et al.* 1975). Muscle recruitment for synergistic fingers in co-ordinated grasping activities are apparently balanced in a similar manner.

Westling and Johansson (1984) showed that grip force applied between the index finger and thumb was critically balanced to optimize motor behavior so that slipping between the skin and the gripped object did not occur. Using local anaesthesia they found that information from skin mechanoreceptors in the fingers were primarily involved and grip force control was heavily influenced by the weight of the objects held plus a safety margin factor specific to individual subjects. Similar to Westling and Johansson's results for gripping small objects between the index finger and thumb, when using all five digits in this study, average finger and total pinch force increased with increasing load weight (see figure 6). It was surprising that the variability in average force exerted when supporting loads without force feedback was not any greater than when visual force feedback was provided (see figure 2).

In Experiment 2, the weights were supported by virtue of the friction of the finger force sensors with the dynamometer. Its been shown that these sensors primarily respond to compression and are relatively insensitive to shear, having error due to shear less than ± 1 N (Jensen *et al.* 1991). The coefficient of friction between the dynamometer and the Microfoam® tape was likely to be greater than for bare skin and aluminium, indicating that without the sensors the normal forces may be greater than those measured. The subjects presumably adjusted the pinch sufficiently to prevent slipping. The different normal forces of each digit suggests a turning moment could be generated in the vertical plane. Since the hand orientation was not adjusted in order to achieve a balance and keep the dynamometer from tilting, this moment was countered by a reaction force produced by the thumb. The use of intrinsic muscles in the hand (i.e., interossei) was probably very different between the two experiments.

In normal precision grip an object is pinched between the flexor aspects of the fingers and the opposing thumb (Napier 1956). The extent to which the fingers are flexed and axially rotated depends largely on the size and shape of the object. Precision handling requires exact control of the finger and thumb position which is also determined, to some extent, by the size and shape of the object (Long 1970). Amis (1987) found that although grip strength decreased as cylinder diameter increased, individual finger force contributions did not vary significantly for cylindrical grip diameters between 31 mm to 116 mm. No significant effect on strength was observed between the 45 mm and 65 mm pinch spans in this investigation. Moreover no large effects on average grip force were observed at submaximal exertion levels between the two grip spans, and grip span did not greatly affect the percent contribution of individual fingers during submaximal exertions.

Although the finger × span interaction on average finger force in the fixed pinch force task was statistically significant, force exerted by the middle finger only decreased slightly (1 N), and consequently the average middle finger force contribution decreased only 3% when the pinch span was increased from 45 mm to 65 mm. Average total pinch force increased only slightly (7%) when increasing the grip-span from 45 mm to 65 mm in the fixed load weight task. The absence of span effects in this study may be attributed to the span range used. Moments at the distal interphalangeal joint, proximal interphalangeal joint, and metacarpophalangeal joint were estimated based on the force and anthropometry data, however, no significant ($p > 0 \cdot 1$) span effect on finger joint movements were observed for either experiment. Increasing the span range may have increased the magnitude of these effects.

This study measured distal phalangeal pinch forces during five finger static pulp pinch using a relatively simple prehension pattern. Palmar prehension is perhaps the most commonly used grasp for both picking up and holding small objects (Brunnstrom 1980). In palmar prehension the thumb opposes one or more of the other digits. This grip is often used for picking up and holding small or large objects by widening the grip. Palmar pinch prehension and the tasks used for this investigation may be observed during numerous common industrial activities. The fixed total pinch force task used in Experiment 1 is representative of assembling two mating parts using compression force, or for squeezing handles on a hand tool such as pliers. The fixed load weight task used for Experiment 2 is similar to the grip often used for lifting large thin objects such as sheets of material, or for carrying tote pans that do not provide cut-outs for handles by pinching the sides.

More complex prehension patterns as well as interphalangeal forces will be studied in future investigations. Sensors are now being developed in our laboratory for attachment to other locations on the fingers and hands for studying more complex grip postures. These sensors will be useful for studying static and dynamic forces involved with activities of daily living as well as manual work activities such as holding handles and tools.

5. Conclusions

The two strongest fingers, the index and middle fingers, exerted the greatest average submaximal finger forces. Although individual finger force contributions were equivalent to individual finger relative strength on the average for total pinch force exertion levels between 10% and 30% MVC, or force loads between 1·0 kg and 2·0 kg, individual finger force contributions were not constant for increasing force requirements. As exertion level increased from 10% to 30% MVC the middle finger contribution increased from 25% to 38%. Similarly as load weight increased from 1·0 kg to 2·0 kg, the index finger contribution decreased from 38% to 30%. These observed recruitment interactions are not included in biomechanical analyses that assume external finger forces are exerted in proportion to relative finger strength or muscle physiological cross-sectional areas.

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