Contributions and co-ordination of individual fingers in multiple finger prehension

HIROSHI KINOSHITA, SATORU KAWAI,* and KOMEI IKUTA
Faculty of Health and Sport Sciences, University of Osaka, 1-1 Machikaneyama-cho, Toyonaka City, Osaka 560, Japan

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The contributions and co-ordination of external finger grip forces were examined during a lifting task with a precision grip using multiple fingers. The subjects (n = 10) lifted a force transducer-equipped grip apparatus. Grip force from each of the five fingers was continuously measured under different object weight (200 g, 400 g, and 800 g) and surface structure (plastic and sandpaper) conditions. The effect of five-, four-, and three-finger grip modes was also examined. It was found that variation of object weight or surface friction resulted in change of the total grip force magnitude; the largest change in finger force, was that for the index finger, followed by the middle, ring, and little fingers. Percentage contribution of static grip force to the total grip force for the index, middle, ring, and little fingers was 42.0%, 27.4%, 17.6%, and 12.9%, respectively. These values were fairly constant for all object weight conditions, as well as for all surface friction conditions, suggesting that all individual finger force adjustments for light loads less than 800 g are controlled comprehensively simply by using a single common scaling value. A higher surface friction provided faster lifting initiation and required lesser grip force exertion, indicating advantageous effect of a non-slippery surface over a slippery surface. The results indicate that nearly 40% force reduction can be obtained when a non-slippery surface is used. Variation in grip mode changed the total grip force, i.e., the fewer the number of fingers, the greater the total grip force. The percent value of static grip force for the index, middle, and ring fingers in the four-finger grip mode was 42.7%, 32.5%, and 24.7%, respectively, and that for the index and middle fingers in the three-finger grip mode was 43.0% and 56.9%, respectively. Therefore, the grip mode was found to influence the force contributions of the middle and ring fingers, but not of the index finger.

1. Introduction
An understanding of the biomechanics of prehensile movements is of great importance in many professional fields. In the fields of medicine and physical therapy, data describing the normal function of the hand as well as the characteristics of functional abnormalities are essential. In the engineering and ergonomics fields, biomechanical data are necessary for designing handheld tools, hand prostheses, and robot hands.

According to Napier (1956), all prehensile activities can be classified into the two categories of 'power grips' and 'precision grips'. The precision grips are used for the purpose of fine control of prehensile forces on a manipulated object, which is usually held by the tips of the fingers and the opposing thumb. The precision grips may require different finger configurations depending on the movement purpose as well as the physical nature of the objects manipulated. If the movement purpose is simply to lift and hold the object without any further manipulation, or if the object is small, thin, fragile, or fairly light, the intended tasks may be accomplished in a two-finger mode.

*Tezukayama Junior College, Nara 631, Japan

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Individual finger forces during lifting task

The index or middle finger and the opposing thumb are often used in this case. If the object is to be manipulated in a more complex manner, or if the object is large, thick, rigid, and relatively heavy, a grip is formed using all five fingers.

Although various methods of measuring the kinetic features of prehensile activities have been developed, many researchers agree that the characteristics of grasping actions can be well described by the external forces acting between the fingers and the manipulated object. There have been a number of studies of the finger forces during grasping of an object using the two-finger precision grip (Buchholz et al. 1988, Cole and Abbs 1988, Gandevia and McCloskey 1974, Johansson and Westling 1984, 1987, 1988, 1992, Kinoshita and Forssberg 1989, Westling and Johansson 1984). However, investigation of the multiple finger precision grips has been limited to only one recent study by Radwin et al. (1992), who measured the grip forces from each of the five fingers during a stationary holding task. In their study, small conductive polymer force sensors were attached to the distal phalangeal pads to measure finger forces while the subjects lifted and held an object which weighed between 1 kg and 2 kg. They found that the average contribution of the index, middle, ring, and small fingers was 35%, 26%, 20%, and 19%, respectively. As object weight was increased from 1 to 2 kg, the contribution of the index finger was not constant, but decreased from 38% to 30%. Accordingly, a significant interaction of percentage finger force and load weight was present. They stated that external finger forces were not exerted in direct proportion to strength.

The individual finger forces may vary not only with the weight of the object grasped, but also with the frictional condition of the grip surface (Buchholz et al. 1988, Johansson and Westling 1984, 1987, Westling and Johansson 1984). Westling and Johansson (1984) reported that grip force applied between the index finger and thumb is critically balanced to optimize motor behaviour so that slipping between the skin and the object does not occur. To achieve this motor control, the nervous system relies on a mechanism that measures the frictional condition between the surface structure of the object and the fingers (Johansson and Westling 1992). There has been no attempt, however, to address the question of how the multiple fingers co-ordinate in order to generate appropriate grip force during holding of objects with varied surface frictional conditions.

This study was designed to clarify external individual finger forces applied on a grasped object of relatively light weight during ordinary lifting tasks with the precision grip using multiple fingers. The specific purposes of this study were to acquire information concerning:

1. the contributions of individual finger forces to the total grip force during lifting, holding, and replacement of an object weighing between 200 and 800 g;
2. the differences between the five-finger mode and the four-finger or three-finger mode in the individual finger forces;
3. the effects of plastic and sandpaper surfaces, which provide different frictional conditions between the skin of the fingers and grip surface.

2. Methods

2.1 Apparatus

The experimental set-up consisted of an instrumented grip apparatus, position detecting unit, and miniature force platform (figure 1). The grip apparatus had a solid plastic plate as a core board (60 mm × 100 mm × 8 mm) on which five force transducers were
mounted. Each force transducer, which consisted of a thin steel plate on which four strain-gauges had been glued, measured the force generated perpendicularly to the apparatus by each finger. The transducers were constructed to allow three different maximum force levels. The transducer for the thumb could measure maximum force of 30 N within 0.5% error of linearity. The transducers for the index and middle fingers could measure maximum force of 15 N within 0.5% error of linearity, and those for the ring and little fingers that of 5 N within 0.5% error of linearity. Each transducer was calibrated by static application of a vertical load using weights of various magnitudes in 10–20 increments up to its expected maximum force level (30 N for the thumb, 15 N for the index and middle fingers, and 5 N for the ring and little fingers). The resolution of the transducer ranged from 0.1 N for the thumb, to 0.012 N, for the little finger. The crosstalk effect of the shear force on the perpendicular force for each transducer was assessed by simultaneous application of vertical and horizontal loading. Using a cable...
and pulley, weights of 0–500 g were applied horizontal to the grip surface to simulate
the gravitational force acting on the transducer. During this shear force application, 0 N
or 10 N was loaded vertical to the surface. It was found that there was a systematic
and linear change of the vertical force output with an increase of horizontal loading. A
regression equation was applied to the measured data, and based on average regression
data, the shear loading error (< 4%) was adjusted during subsequent data processing
according to the proportion of the gravitational force for each finger estimated from the
grip force distribution. The frequency response of the transducer was also estimated by
striking the transducer in situ. It was DC-200 Hz for all the force transducers.

A plastic plate (20 mm × 20 mm × 4 mm) was affixed to each transducer to provide
grip surface area. The surface material used in most experiments was plastic. In some
of the experiments sandpaper surface was also used. These surface materials represent
fairly slippery and non-slippery materials in our environment (Buchholz et al. 1988,
Westling and Johansson 1984). Grip surfaces for the index, middle, ring, and little
fingers were aligned vertically. The horizontal distance between the grip surfaces for
the thumb and those for the other fingers was 45 mm. The position of each transducer
on the centre plate was determined based on data obtained in 30 adult males who grasped
a plastic box with dimensions similar to those of the grip apparatus. Data for each finger
tip’s average centre position were obtained, and were used to determine the location
of the respective force transducer centre. In a right panel of figure 1 (the side-view of
the grip apparatus) the actual position of the transducers was illustrated. The apparatus
weight could be varied from 200 g to 800 g by attaching differently weighted boxes
underneath the apparatus. All the weight boxes had the same dimensions to minimize
size-weight illusion effect.

The miniature force platform consisted of four strain-gauge transducers (DC
235 Hz) fixed underneath a metal plate (15 cm × 15 cm × 0.4 cm). This provided data
for the table reaction force in the vertical direction.

Vertical displacement of the grip apparatus was measured with an infra-red emitting
diode attached to the grip apparatus and the position detection unit. This unit consists
of a position sensing diode (Hamamatsu Photosonic Co., S1352, DC-200 Hz) inside a
metal box and an ordinary 35-mm camera lens with an infra-red light filter (Kodak Co.,
No. 87 C, 100% wave length transmissibility < 900 nm). This position detection unit
was located 150 cm in front of the grip apparatus.

2.2 Subjects
Ten right-handed male volunteers (18–42 years old) were selected as subjects for the
study. Because the force transducers were fixed at a certain position, only those who
could comfortably position their digit tips on the centres of the force transducers during
lifting and holding tasks were selected as subjects.

2.3 Procedures
Five to ten minutes prior to the experiment, the subjects washed their hands with soap
and water to standardize their skin characteristics. The subject sat in a height-adjustable
chair and faced a testing table, upon which the force platform was affixed. The subject’s
right upper arm was parallel with his torso, and the forearm extended anteriorly. The
hand was held in a half-prone position, and all fingers were placed near the grip surface
of the grip apparatus on the table. The grip apparatus was located in front of the subject’s
right shoulder, and the distance from the shoulder to the apparatus was approximately 40 cm.

The apparatus was grasped with all of the fingers of the right hand and lifted at the subject's natural lifting speed to a height of 10 cm above the surface of the force platform, mainly by flexing the elbow. It was then held in space for 6 s, and replaced on the force platform at the subject's natural descending speed. A small 1 cm-wide marker placed on a target plate served to indicate the target zone for the lifting height. The subject was instructed to grasp and lift the apparatus so that a small pointer on the top left side of the apparatus fell within the range of the target zone. To become accustomed to all the experimental conditions and acclimatized to the experimental environment, all subjects underwent a practice session for about 1 h one day prior to the data collection session and for about 20 min on the data collection day. Data were collected under the 200 g, 400 g, and 800 g weight conditions with the plastic surface material. During the 400 g trials, the subject was asked to perform the same task without the little finger, and without the ring and little fingers. The surface material was then replaced with sandpaper, and the subject performed the same task. Finally, the subject was asked to lift the apparatus to the target as fast as possible under the 200 g, 400 g, and 800 g weight and plastic surface material conditions. The subjects performed 10–20 practice trials prior to each experimental condition followed by 8 trials for data collection under each set of conditions. Prior to each experimental condition, the subjects rested for a few minutes, and, between trials, they rested for about 10 s.

In this study, each experimental condition was presented to the subjects in a sequential manner rather than a random manner because the results of our pilot study as well as the findings of the previous studies (Johansson and Westling 1984, 1988) suggested that the carry-over effect of object property in the previous condition on the grip force was negligible after an adequate period of practice at a given condition.

2.4 Data acquisition methods
All force data were amplified using a six-channel strain gauge amplifier (Kyowa Co., DPM-612A) and stored on a 14-channel FM tape recorder (TEAC Co., XR-510). The position data were amplified using a PSD amplifier (Hamamatsu Photosonic Co., C3683) and also stored on the FM tape recorder. The data were subsequently processed with an NEC personal computer (PC-9801 DA) via a 12-bit A/D converter sampling at 300 Hz for each channel.

2.5 Data analysis
Data were analysed with a laboratory software package developed by the present authors. The output from this program consists of 12 temporal, 20 force, and two velocity parameters (figure 2). The parameters are defined following the definitions of Johansson and Westling (1984, 1988). The duration from the moment of finger-surface contact to the lifting force initiation for each of the five fingers was termed 'preload phase'. The preload phases for the thumb, index, middle, ring and little fingers are shown as PP1–5 in figure 2. The duration between the lifting force onset and apparatus lift-off from the support was termed 'loading phase', and the duration between the moment of resupport (the force platform contact moment) and the zero lifting force moment was termed 'unloading phase'. The duration from the lifting force end moment to the grip force end moment for each of the five fingers was termed 'release phase'. The release phases for all fingers are shown by RP1–5.
Figure 2. Grip forces, table reaction force, vertical displacement, and vertical velocity as a function of time in a sample trial. The parameters evaluated, following the definition by Johansson and Westling (1984, 1988), are: PP1–PP5—preload phase; RP1–RP5—release phase; TOF1–TOF5—take-off grip force; PKF1–PKF5—peak grip force; STF1–STF5—static grip force; TDF1–TDF5—touch-down grip force.

The force parameters evaluated were 'take-off grip force', 'peak grip force', 'static grip force', and 'touch-down grip force'. The take-off grip forces (TOF1–5 in figure 2) were the forces at the moment of apparatus lift-off from the support. The peak grip forces (PKF1–5) were the maximum forces which occurred during lifting of the apparatus. The static grip forces (STF1–5) were the average grip forces while the object was held stationary in space for 2 s (between 5 and 7 s from the object lift-off moment). The touch-down grip forces (TDF1–5) were the grip forces at the moment of resupport.

The vertical velocity was calculated by differentiating the vertical displacement data after low-pass filtering using a 4th order Butterworth filtering method at a cutoff frequency of 30 Hz. From the velocity curves, peaks (PV1 and PV2 in figure 2) during lifting and replacement phases are obtained.

2.6 Statistical analysis
The mean value for each parameter for the eight trials for each set of experimental conditions was computed for each subject and used to calculate the average values for all subjects given herein. Depending on the purpose of comparison, a separate two-way analysis of variance (ANOVA) with repeated measures (digit × weight load, and digit × surface material) or one-way ANOVA with repeated measures was conducted on each parameter, and post hoc tests using a single factor ANOVA with repeated measures were performed (Keppel 1973). Statistical significance was accepted at $p < 0.05$. 
3. Results

3.1 Variation of object weight

3.1.1 Lifting and replacement velocities: The average peak velocity during lifting phase at 200 g, 400 g, and 800 g weight load with the plastic surface material was $39.9 \pm 12.6 \text{ cm/s}$, $33.3 \pm 10.3 \text{ cm/s}$, and $29.6 \pm 6.2 \text{ cm/s}$, respectively. Comparisons between pairs of single means using a separate one-way ANOVA with repeated measures revealed a significant difference only between the 200 g and 800 g conditions ($F(1,9) = 9.34$, $p < 0.05$). The average peak velocity for the respective weight loads when the subjects lifted the apparatus as fast as possible was $121.9 \pm 27.1 \text{ cm/s}$, $114.9 \pm 17.4 \text{ cm/s}$, and $98.3 \pm 22.6 \text{ cm/s}$, respectively. Thus, the subjects’ natural lifting speed for all weight loads fell within the range of 29% and 33% of their fastest lifting speed. The average peak velocity during replacement phase at 200 g, 400 g, and 800 g weight load was $26.5 \pm 6.0 \text{ cm/s}$, $27.0 \pm 4.5 \text{ cm/s}$, and $24.9 \pm 4.9 \text{ cm/s}$, respectively. The difference between any of these velocities was not significant ($p > 0.1$).

3.1.2 Force parameters: Table 1 presents average values for take-off, static, and touch-down grip force parameters. Figure 3 shows average total take-off, peak, static, and touch-down grip force under each object weight condition. All grip force parametric values showed nearly linear increase with increasing weight load. A one-way ANOVA with repeated measures revealed that the effect of weight load on each of the four total grip force parameters was significant ($p < 0.001$). These four parametric values were compared at each weight load level using a separate one-way ANOVA with repeated measures. It was found that they were all significantly different ($p < 0.05$), i.e., for all weight loads, the touch-down grip force was the smallest, the average grip force was
Table 1. Average and standard deviation values for varied weight load conditions and summary of the ANOVA for the selected force parameters.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Take-off grip force</th>
<th>Static grip force</th>
<th>Touch-down grip force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOF1</td>
<td>TOF2</td>
<td>TOF3</td>
</tr>
<tr>
<td>200 g</td>
<td>2.84</td>
<td>1.10</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>0.40</td>
<td>0.23</td>
</tr>
<tr>
<td>400 g</td>
<td>5.10</td>
<td>2.14</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>0.78</td>
<td>0.36</td>
</tr>
<tr>
<td>800 g</td>
<td>10.55</td>
<td>4.50</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>2.56</td>
<td>1.35</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Weight effect: $F(2,18) = 122.90^{***}$  
Finger effect: $F(3,27) = 43.29^{***}$  
Interaction effect: $F(6,54) = 35.16^{***}$

**Notes**

Average and standard deviation values are all in Newtons.
The grip surface used is plastic.
TOF1–5, STF1–5 and TDF1–5 are defined in figure 2.

*** $p < 0.001$
always smaller than the take-off grip force, and the peak grip force was always larger than the take-off grip force.

Figure 4 illustrates the average static grip force for each of the four fingers at different weight loads. There was a significant interaction of digit with weight load (ANOVA results in table 1), indicating that the effect of weight load was different for each finger. With an increase of the weight load from 200 g to 800 g, the index, middle, ring, and little finger forces increased 3.2 N, 1.9 N, 1.3 N, and 0.9 N, respectively. The increase of the index finger force was therefore about 3.5 times larger than that of the little finger. The main effect of finger and that of weight load were also significant (table 1). Concerning the finger effect, post hoc analyses using a one-way ANOVA with repeated measures revealed that, at all weight load levels, the differences in the grip forces of adjacent fingers were all significant ($p < 0.05$). Post hoc analyses for the weight effect revealed that, for each finger, the grip force was significantly different under any two different weight load conditions ($p < 0.001$).

The percentage contribution of each finger grip force to the total grip force at take-off, holding, and touch-down is shown in figure 5. A two-way ANOVA with repeated measures revealed that, for the take-off grip force parameter (figure 5 A), the main effect of finger was significant ($F(3, 27) = 72.61$, $p < 0.001$), but neither the interaction effect of finger with weight load ($F(6, 54) = 2.18$, $p > 0.05$) nor the main effect of weight load ($F(2, 18) = 0.63$, $p > 0.5$) was significant. Consequently, the average percentage value over all weight loads was computed for each finger. The percentage force contribution of each finger was as follows: index—40.6 ± 6.0%; middle—25.8 ± 4.9%; ring—18.4 ± 2.4%; and little—15.2 ± 3.0%.

Percentage finger force contribution to static grip force is shown in figure 5 B. Contributions by the index and middle fingers were 42.0 ± 6.9% and 27.4 ± 6.4%, respectively. Average percent forces for the ring and little fingers were 17.6 ± 2.9% and 12.9 ± 4.5%, respectively. A two-way repeated measure ANOVA revealed that the main effect of finger was significant ($F(3, 27) = 59.15$, $p < 0.001$), but neither the
interaction effect ($F(6,54) = 1.16, p > 0.1$) nor the main effect of weight load ($F(2,9) = 0.11, p > 0.5$) was significant.

For the touch-down grip force, the index, middle, ring, and little finger contributions were $44.5 \pm 7.5\%$, $24.4 \pm 5.4\%$, $17.9 \pm 2.9\%$, and $13.1 \pm 4.1\%$, respectively. The main effect of finger was significant ($F(3,24) = 78.07, p < 0.001$), but the weight load effect ($F(2,9) = 2.49, p > 0.1$) and the interaction effect ($F(6,54) = 1.5, p > 0.1$) were insignificant.

3.1.3. Temporal parameters: The average preload phase for all fingers (PL1–5) ranged from 74 to 117 ms for all weight loads (figure 6 A). Large inter-subject variability was observed for all fingers for all weight loads. While there was some increase of this phase with an increase of weight load, due to the large variability, a two-way repeated measure ANOVA revealed that the main effect of weight load was statistically insignificant ($F(2,9) = 1.32, p > 0.1$). The interaction effect of finger with weight load ($F(8,72 = 0.76, p > 0.5$) as well as the main effect of finger ($F(4,36) = 1.10, p > 0.1$) were also insignificant.

The average loading phase was $128 \pm 34$ ms when the weight was 200 g, and increased almost linearly with weight load (figure 6 B); at 400 g and 800 g weight loads, it was $200 \pm 59$ ms and $305 \pm 74$ ms, respectively. The unloading phase duration also increased from $255 \pm 94$ ms at 200 g weight load to $323 \pm 69$ ms at 400 g, and to $446 \pm 109$ ms at 800 g. At all weight loads, the unloading phase was about 130 ms longer than the loading phase. ANOVA revealed that the effect of weight load on both the loading and unloading phases was statistically significant ($p < 0.05$).

The average release phase (RL1–5) for all fingers except for the little finger ranged from 107 ms to 150 ms at 200 g weight load, from 72 to 92 ms at 400 g, and from 55
to 67 ms at 800 g (figure 6 C). The average release phase for the little finger was 54 ms at 200 g, 31 ms at 400 g, and 24 ms at 800 g. At all weight loads, the release phase for the thumb was the longest, and that for the little finger the shortest. ANOVA revealed that the interaction of finger with load was insignificant ($F(8,72) = 1.21, p > 0.1$). The effect of weight load ($F(2,9) = 6.31, p < 0.05$) and that of finger ($F(2,36) = 5.59, p < 0.01$) were significant. A post hoc analysis using a single factor repeated measure ANOVA revealed that the release phase for the 200 g condition was significantly longer than that for either of the other two weight conditions ($p < 0.05$). As for the effect of finger, only the little finger had significantly shorter phase duration than any other finger ($p < 0.05$).

3.2. Variation of grip mode

3.2.1. Lifting and replacement velocities: The average peak lifting velocity in the four-finger and three-finger modes was $32.2 \pm 13.2 \text{ cm/s}$ and $32.1 \pm 12.6 \text{ cm/s}$, respectively. These values were not significantly different from that in the five-finger
Figure 7. Effects of grip mode variation: A—average static grip forces for individual fingers in relation to grip mode variation. The total grip force shown is the summation of the index, middle, ring, and little finger forces. B—average percentage contribution to the total grip force for each finger in relation to grip mode variation.

mode ($p > 0.5$). The average peak replacement velocity in the four-finger and three-finger modes was $26.4 \pm 7.3$ cm/s and $28.1 \pm 8.9$ cm/s, respectively; and these values were not significantly different from that in the five-finger mode ($p > 0.5$). These results indicated that the lifting and replacement speeds were nearly the same for all grip modes.

3.2.2. Force parameters: For the four-finger mode, the average value of the static grip force was $1.98 \pm 0.58$ N for the index finger, $1.51 \pm 0.56$ N for the middle finger, and $1.14 \pm 0.39$ N for the ring finger (figure 7 A). The average total grip force was $4.62 \pm 1.09$ N. Comparisons with the results for the five-finger mode using a one-way ANOVA with repeated measures revealed that the values for the middle and ring finger forces were significantly larger than those for the five-finger mode ($p < 0.05$ and $p < 0.001$, respectively). In the three-finger mode, the average static grip force was $2.11 \pm 0.77$ N for the index finger and $2.78 \pm 0.65$ N for the middle finger, and the average total grip force was $4.90 \pm 1.25$ N. The latter two values were significantly larger than those in the five-finger mode ($p < 0.001$ and $p < 0.05$), respectively. The middle finger force for the three-finger mode was also significantly larger than that for the four-finger mode ($p < 0.001$).

The percentage force contribution of individual fingers in the different modes is shown in figure 7 B. The percentage force contribution for the middle and ring fingers in the four-finger mode was significantly larger than that in the five-finger mode, by 6% and 7%, respectively ($p < 0.05$ and $p < 0.01$, respectively). In the three-finger mode, the middle finger contribution increased by 30% and 25% compared with those in the five-finger and four-finger modes, respectively, and these increases were significant ($p < 0.001$). In all finger modes, the index finger contribution was nearly constant.
3.2.2. **Temporal parameters:** The average duration of the preload phase ranged from 101 ms to 132 ms in the four-finger mode, and from 103 ms to 141 ms in the three-finger mode. These phases were slightly longer than those in the five-finger mode. However, comparisons of the preload phase for each finger using a one-way ANOVA with repeated measures revealed that there was no significant difference between the five-finger and four- or three-finger mode \((p > 0.1)\).

The average loading phase in the four-finger and three-finger modes, 216 ± 58 ms and 217 ± 70 ms, respectively, was not significantly different from that in the five-finger mode \((p > 0.5)\), nor was the average unloading phase, 332 ± 111 ms and 333 ± 92 ms, respectively \((p > 0.1)\).

The average release phase for the four-finger and the three-finger modes ranged from 66 ms to 33 ms and from 70 ms to 57 ms, respectively. The release phase for each finger was also not significantly different from that for the five-finger mode \((p > 0.5)\).

3.3 **Variation of grip surface material**

3.3.1. **Lifting and replacement velocities:** The average peak lifting velocity and peak replacement velocity with the sandpaper surface, 34.9 ± 8.8 cm/s and 27.8 ± 5.1 cm/s, respectively, were not significantly different from those with the plastic surface \((p > 0.05)\).

3.3.2. **Force parameters:** The results for the sandpaper surface are summarized in table 2. In all force parameters, there was a significant interaction effect of finger and surface material. The index finger showed the largest force change with surface material change, followed by the middle, ring, and little finger. A two-way ANOVA with repeated measures revealed a significant main effect of finger and that of surface material in all force parameters (table 1). Analysis of the main effect of finger using a separate one-way ANOVA with repeated measures revealed that, for both surfaces, any two adjacent finger forces were significantly different \((p < 0.05)\). Concerning the main effect of surface material, a one-way factor ANOVA with repeated measures revealed that all values for the sandpaper surface were significantly smaller than those with the plastic surface \((p < 0.01)\). The total grip force for the sandpaper surface was about 60% of that for the plastic surface.

The percentage contribution of each finger to the total static grip force was 41.2 ± 6.5%, 28.1 ± 5.1%, 18.7 ± 2.3%, and 11.8 ± 4.0% for the index, middle, ring, and little fingers, respectively. Change in the surface material from plastic to sandpaper was accompanied by a slight decrease of the index and middle finger contributions and a slight increase of the ring and little finger contributions. However, none of these changes were significant \((p > 0.05)\).

3.3.3. **Temporal parameters:** The average preload phases with the sandpaper surface for all fingers including the thumb ranged from 49 ms to 71 ms (figure 8 A). There was neither an interaction effect of finger and surface \((F(4,36) = 0.84, p > 0.5)\) nor a main effect of finger \((F(4,36) = 0.86, p > 0.5)\) for this parameter, but a main effect of surface was found \((F(1,9) = 9.55, p < 0.05)\). Comparisons between individual means using a one-way ANOVA with repeated measures revealed that the preload phases for the thumb, index, middle, and little fingers with the sandpaper surface were significantly shorter than those with the plastic surface \((p < 0.05)\).

The average loading phase and unloading phase with the sandpaper surface was
Table 2. Average and standard deviation values for the sandpaper surface condition and summary of the ANOVA for the selected force parameters.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Take-off grip force</th>
<th>Static grip force</th>
<th>Touch-down grip force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOF1</td>
<td>TOF2</td>
<td>TOF3</td>
</tr>
<tr>
<td>AV</td>
<td>3.26</td>
<td>1.29</td>
<td>0.85</td>
</tr>
<tr>
<td>SD</td>
<td>0.77</td>
<td>0.41</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Surface effect: $F(1,9) = 43.96^{***}$
Finger effect: $F(3,27) = 35.71^{***}$
Interaction effect: $F(3,27) = 8.48^{***}$

$F(1,9) = 81.03^{***}$
$F(3,27) = 43.91^{***}$
$F(3,27) = 9.92^{***}$
$F(6,54) = 32.57^{***}$

Notes
Average and standard deviation values are all in Newtons.
Load weight used was 400 g.
TOF1–5, STF1–5 and TDF1–5 are defined in figure 2.
ANOVA was carried out with the 400 g weight and sandpaper surface condition.

$^{***} p < 0.001$
Figure 8. Average temporal parametric values under the two grip surface conditions: A—preload phases; B—release phases. Vertical bars describe ± 1 standard deviation range.

212 ± 79 ms and 343 ± 70 ms, respectively. These values were not significantly different from those with the plastic surface (p > 0.5).

The average release phases for the thumb, index, middle and ring fingers with the sandpaper surface ranged from 48 to 68 ms (figure 8 B). An interaction effect of finger and surface was insignificant for this parameter (F(4,36) = 0.47, p > 0.5). The main effects of finger (F(4,36) = 8.87, p < 0.001) and surface (F(1,9) = 7.69, p < 0.05) were significant. A post hoc analysis using a one-way ANOVA with repeated measures demonstrated that the phases for the thumb, index, middle, and ring fingers with sandpaper surface were significantly shorter than those with the plastic surface (p < 0.05). The average release phase for the little finger with the sandpaper surface, 28 ms, was not significantly different from that with the plastic surface (p > 0.1). The main effect of surface indicated shorter finger release time for the sandpaper than the plastic.

4. Discussion

4.1. Object weight effect
The findings for weight load variation clearly demonstrated the strong interactive nature of the absolute grip forces for individual fingers in relation to weight load. The increase of exerted grip force as the object weight changed differed for each finger. The index finger showed the largest increase, followed by the middle, ring, and little fingers. Clearly the functional roles of individual fingers differ in the generation of various magnitudes of total grip force in lifting objects of different weights. The heavier the weight, the larger the index and middle finger contributions. The results further demonstrated that there was a significant difference between any two finger forces at all object weights. Radwin et al. (1992), who examined the finger forces during holding of an object weighing between 1 kg and 2 kg, also reported a similar result. However, in their study, no significant difference between the ring and little finger forces was found. This discrepancy cannot be accounted for by a difference in the weight load used, since our 800 g condition would not be expected to differ substantially from their 1 kg
condition. One explanation may be the resolution difference of the force sensors used. The resolution level of their finger-mounted conductive polymer force sensors was 1 N, which is nearly 100 times greater than that of our force transducer. Since the observed difference in the average static grip forces of the ring and little fingers, even at the 800 g weight load, was only 0.45 N, fairly high resolution of the force sensor is essential to detect a difference at this level of precision.

The individual finger force contribution to the total grip force was different for all fingers. For static grip force, it was 42.0% for the index, 27.5% for the middle, 17.6% for the ring, and 12.9% for the little finger. Radwin et al. (1992) reported that, when a 1 kg weight was lifted, the contributions of the index and middle fingers were 38% and 25%, respectively, but when the weight load was 2 kg, these values decreased to 30% and 28%, respectively. This was accompanied by a significant interaction of finger with load. Radwin et al. therefore stated that the assumption that individual finger external forces were exerted in direct proportion to strength was not correct. In this study, such recruitment interaction between force distribution and weight load was not evident within the weight load range examined. Therefore, the concept that change in finger force contribution depends on the grip force may be applicable only under conditions requiring relatively high grip force (> 1 kg). Such conditions may include lifting objects heavier than a few kg or those with an extremely slippery surface.

The force distribution at the take-off moment was nearly the same as that during the holding phase, suggesting that this pattern was already formed at a fairly early stage of the grasping action. According to Johansson and Westling (1984, 1988), the timing and magnitude of the grip and lifting forces in the two-finger precision grip mode are generated in an anticipatory or programmed manner with object weight and surface friction taken into consideration. Adequate anticipatory force action in accordance with object weight is essential because feedback from the corresponding motor commands cannot take place until after the lifting movement has begun. The findings of this study suggest that adequate programming of individual finger force contribution is also essential, so that the summation of the four finger forces is the same as the thumb force prior to the lifting movement.

With respect to the temporal parameters, it was found that the preload phases for all the fingers did not differ at any load level. This finding indicates that no one particular finger serves the function of leading the finger-surface contact action. The release phase for the thumb and index finger was often more prolonged than that of the others, while only that of the little finger was significantly shorter than that of the others. The release phase of the little and ring fingers sometimes had a negative value, indicating that these fingers were released before the object was fully supported by the table. The release phase is related to the stability of the support; the less stable the support, the longer the phase. The results for the finger difference during the release phase, then, suggest that the thumb and index finger have a greater role in the final assurance of support stability, while the ring and little fingers apparently have a lesser role. The finding that the release phases shorten as the weight load increases can also be accounted for by the stability difference. The weight load was varied by simply replacing the weight underneath the grip apparatus, and therefore the 800 g condition, in which the centre of mass was lower, was more stable than the 200 g condition.

4.2. Grip mode effect
Variation in the grip mode significantly changed the magnitude of total grip force. The
total grip force increased as the number of fingers decreased. This total grip force increase may be attributable to psychological factors. We asked each subject about whether there was any perceived difference among the grip modes. The majority responded that it was easier and more comfortable to lift and hold the apparatus with four or five fingers than with three fingers. Object physical properties, such as size (volume), surface friction, and weight, could have influenced the perceived difference. The apparatus used in this study was of an appropriate size for gripping with five fingers. The surface material used was plastic with low friction, and the object weight was 400 g. All of these physical properties would favor the use of all five fingers. A difference in area of contact may also have contributed to the perceived difference. Johansson and Westling (1987) reported that the high innervation density of mechanoreceptors found in the tips of the fingers provides a strong afferent input to control the grip force. Indeed, local anesthesia of one of the fingers during gripping produced a degradation of the grip force control capacity (Johansson et al. 1992). A larger contact area therefore may have facilitated more precise force control capacity.

The grip mode difference was also revealed by the distribution of individual finger forces. That is, when an object was held without the little finger, the little finger force proportion was distributed between the middle and ring fingers. When neither the little nor ring fingers was used, these finger force proportions were transferred to only the middle finger. Accordingly, the middle finger force exertion exceeded that of the index finger. The index finger force was kept nearly constant, regardless of the finger mode. These results suggest that, similar to that for the five-finger grip mode, there is also a relatively fixed finger force distribution pattern for each of the other grip modes for the load levels studied. Because these grip modes are also quite commonly used in carrying out everyday tasks, they may be considered to be well-learned and to thus rely heavily on centrally programmed motor actions, which can probably be accessed for usage in a virtually unconscious fashion.

In this study, a two-finger precision grip mode was not included because the force transducer for any of the fingers could not be positioned directly opposite the thumb grip force transducer (figure 1 B), and therefore accurate measurement of the grip forces in opposing two finger position was not possible. This difficulty could be solved by constructing a grip apparatus equipped with adjustable transducer position. Use of such an apparatus also can provide an opportunity to study subjects with a larger range of hand anthropometry.

4.3. Surface friction effect
Friction between the fingers and the grip surface has been reported to play an essential role in determining the grip force exertion level (Buchholz et al. 1988, Johansson and Westling 1984, 1987, Westling and Johansson 1984). Westling and Johansson (1984) reported that the change of static grip force in the two-finger precision grip was almost proportional to the coefficient of friction of the surface material. It was also demonstrated in the present study that the grip force with the sandpaper surface, which should have a higher friction coefficient value, was significantly smaller than that with the smooth plastic surface. Indeed, the force with the sandpaper surface was approximately 60% of that with the plastic surface, highlighting the advantageous effect of higher surface friction.

Buchholz et al. (1988) have provided regression equations to estimate the static friction coefficient for various materials against the skin of the human palm. According
to the equation for a sandpaper surface, the coefficient of friction at the static grip force level of 2.81 N is 0.769. A smooth plastic surface was not included in their surface material samples, and the aluminum surface which they examined may be the most similar sample which they examined. Using the equation for aluminum, the friction coefficient is 0.416 at the static grip force level of 4.42 N. The sandpaper surface is, therefore, about 54% less slippery than the plastic surface, and may also require the static grip force 54% less than that for the plastic surface. Since the static grip force for holding the object with the plastic surface was 60% of the sandpaper surface, the plastic material used in this study may have been slightly more slippery than aluminum.

While the magnitude of each individual finger force was significantly changed in relation to the frictional condition, the force contribution for each finger was constant, even under different friction conditions. Therefore, the individual finger forces were scaled at the same proportion to the total grip force required for the adaptation to different surface conditions.

Under the sandpaper surface condition, the preload phases for all fingers were shortened, allowing earlier start of lifting force application. This can be regarded as another advantage of higher surface friction. Probably by using stored information gained through the sensory experience of non-slippery surface condition in the previous lifting trials, the subjects could initiate the lifting force generation earlier than they could with the relatively slippery plastic surface condition.

4.4. Possible control strategy and mechanisms
The finding that the force contribution of each finger remained fairly constant, while total grip force varied suggests that the force distribution is governed by a relatively simple control strategy for the load levels and frictional properties studied. The generation of the total grip force required to lift various weight loads and to adjust to various surface frictions requires adjustment with only a single scaling value. This undoubtedly simplifies the control of a complex multiple finger system. According to Schieber (1990), this kind of finger control can be accomplished by the central mechanisms directly driving a rudimentary synergy. In accurate adjustment of force at the individual finger level, however, a higher neural system seems to take a primary role.

5. Conclusions
Object weight variation produced a change in total grip force. The largest change was noted in the index finger force, followed by the middle, ring, and little finger forces, respectively. The largest contributions to total grip force variation were those by the index and middle fingers. The percentage contribution to the total grip force during static holding of the object was 42.0%, 27.5%, 17.6%, and 12.9% for the index, middle, ring, and little fingers, respectively. These values were fairly constant for all weight conditions between 200 g and 800 g as well as for all surface friction conditions. Therefore, the individual finger grip force adjustments might be controlled comprehensively and simply by using a single scaling value. Variation in grip mode changed the total grip force; the fewer fingers used, the greater the total grip force. This suggests that a larger contact area may facilitate more precise adjustment of the finger force required for holding an object. Therefore, it can be concluded that the five-finger mode provides better control of the object than does the four- or three-finger mode. Higher surface friction provided earlier lifting initiation and lower grip force exertion,
highlighting the advantageous effect of a non-slippery surface over a slippery surface. The results suggest that the exerted force can be reduced by almost 40% by the use of a non-slippery surface. The information provided describes the mechanical function of the normal human hand, and may be used for the evaluation of functional abnormality of the hand, and in the design of hand prostheses, robot grippers, and handheld tools.

In daily tasks, more complex manipulation of a handheld object is often required. Further studies are needed to examine the external finger forces during complex prehensile actions such as orientation in various directions including a shaking action and rotation in different axes. A study is also needed to examine the effects of loads heavier than 800 g.

Notes

1 In order to facilitate comparison with previous work (Johansson and Westling 1984, 1987, 1988; Radwin et al. 1992, Westling and Johansson 1984), and to differentiate between weight loads and grip forces, all object weights are expressed in units of mass (200 g, 400 g, and 800 g) rather than units of force.

References


