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Effect of Gloving on Perceptual and Manipulation Task Performance

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ABSTRACT

This study evaluates the effect of fingertip covering on the performance of perceptual and manipulation tasks. For the perceptual task, subjects were timed as they detected hard lumps in soft rubber models while barehanded and while wearing gloves of thickness 0.32 mm, 0.64 mm, 0.95 mm, 1.27 mm, 1.59 mm and 1.91 mm. Four lump sizes with diameters 3.2 mm, 4.8 mm, 6.4 mm and 7.9 mm were used. Analysis of the data yielded significant differences in lump detection time with glove thickness. Detection time variation was greatest for the 3.2 mm lump. Mean times were always best with bare hands and poorest with 1.91 mm glove thickness. The maximum force applied during palpation increased linearly with glove thickness. In the manipulation task, seven subjects were asked to lift a 460g object using the thumb and index finger while barehanded and wearing gloves of thickness 0.16 mm, 0.32 mm, 0.95 mm and 1.91 mm. The object was covered with three different surfaces with varying frictional conditions: sandpaper, suede and rayon. As glove thickness increased, the subjects' ability to adapt to new surfaces decreased and increasing levels of excess grip force were applied. Visual feedback did not play an important role in assisting lift for any glove thickness. The results of the perceptual and manipulation tasks suggest that the effects of gloving are both thickness dependent and highly task sensitive.

INTRODUCTION

Distributed sensations across the fingerpad are useful in the execution of many tasks. Certain applications, however, involve conditions where cutaneous information is either inhibited or non-existent. An ubiquitous example is the wearing of gloves in medical procedures or hazardous environments. Gloves have many relevant properties including thickness, stiffness and fit; the thicker the glove, for example, the less cutaneous information passes through. The question of how gloves with different properties impair task performance therefore becomes a relevant issue. This study analyzed glove thickness as a parameter.

Previous studies on the effects of gloving have indeed indicated that performance of certain tasks is impaired. A study on chemical gloves (Bensel 1993) found that wearing gloves of up to 0.64 mm thickness yielded significant differences in task performance time compared to bare hands. Tasks were chosen to test manual dexterity, such as rifle assembly and tool usage. Bensel also found that performance in these manual dexterity tasks could be improved significantly with practice.

Other studies have examined the effect of double gloving in surgery as a protective measure against infection and have found that two thin gloves have negligible effect on surgical technique (Webb and Pentlow 1993, Burke et al. 1989). Subjective studies have shown, however, that double gloving is uncomfortable and undesirable to the surgeon (Wilson et al. 1996) and that there is a high negative correlation between glove stiffness and subjects' assessment of tactile perception (Burke et al. 1989).

A limitation of these earlier works is that they only tested the effects of relatively thin gloves. The goal of the present study was therefore to quantitatively examine the effects of gloving for a much wider range of thicknesses. This was motivated by the hypothesis that beyond a certain thickness, glove interference may exceed a task-impairment threshold and lead to failure of effective manipulation. Tasks were chosen from the principal types of fingertip activities: a perceptual task (lump detection) and a manipulation task (object lifting using the precision grip).

Variations of these tasks have been studied in the past, although none of them have tested glove thickness as a variable. Lederman and Klatsky (1997) studied lump detection for both the barehanded case and fingers sheathed in a rigid fiberglass covering. The goal of this work was to assess the importance of incorporating spatially distributed fingertip forces in the design of haptic interfaces. These rigid coverings drastically impaired task performance.

Bloom et al. (1982) had subjects palpate silicone breast models containing lumps with different size, depth, hardness and fixation properties. The goal was to determine the relationship between optimum palpation skill and tumor characteristics in order to enhance breast self-examination technique. They found that for fixed lumps, size was the most important factor in detection ability whereas hardness and depth had little effect. For mobile lumps, both size and hardness contributed significantly to detection.

In light of Bloom et al.'s findings, this present study focused on fixed lumps and used size as a variable. Performance was evaluated in terms of the time required to find lumps and the maximum force applied.

Use of the precision grip in object lifting was researched extensively by Johansson and Westling (1984) for the barehanded case. They quantitatively examined the coordination of grip force and vertical lifting force and found that grip force was regulated to prevent slips based on both the weight of the lifted object and the frictional condition between the object and skin. In studies that investigated the underlying neural mechanisms, Johansson and Westling (1984, 1987) determined the importance of cutaneous feedback in slip prevention.

For this study, it was hypothesized that gloving would interfere with slip sensation because it occurs at the surface of the fingertips. To test the hypothesis, this study varied the frictional condition of the object to be lifted, and measured the excessive grip force applied.

METHODS

A. Lump detection

Apparatus

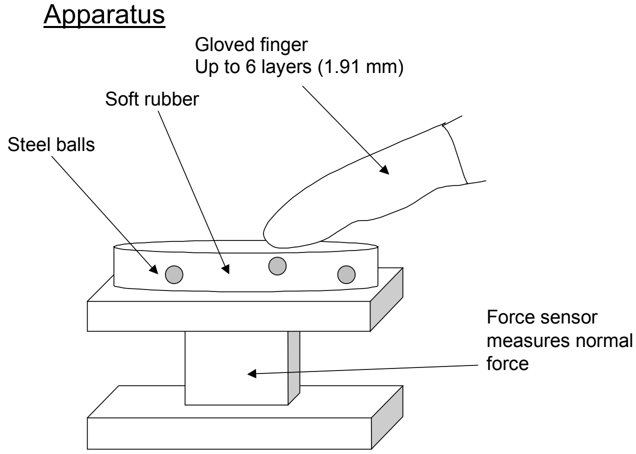


Figure 1. Experimental setup for the lump detection test

The experimental apparatus is shown in Figure 1. Ten healthy, right-handed subjects (5 female and 5 male, 20-49 years old) who were naïve with regard to the purpose of the experiments participated in this study. The subjects sat in a chair and palpated the tissue models on a table with their right index finger. A screen was placed in front of the rubber models to prevent visual cues from aiding in lump detection. A button to signal detection was placed on the table within reach of the subjects' left hand.

The "tissue" models were made of soft rubber (General Electric Co., GE6166, Young's Modulus≈4kPa) in a petri dish. Three steel balls of the same size were glued to the bottom of the petri dishes in a pseudo-random manner such that there was no discernable pattern across the dishes. Four "lump" sizes of diameters 3.2 mm, 4.8 mm, 6.4 mm and 7.9 mm were used. A rubber model containing no lumps was also made.

The fingers of a thick latex glove (Microflex Corp., UltraOne®, k≈90 N/m) were used for the fingertip covering. Thickness was achieved by layering different-sized glove fingers on top of each other. The full range was from zero thickness (bare hands) to a maximum of 1.91 mm (six gloves). Plaster molds of the gloves were used initially to determine the precise size of the fingers to ensure close glove fit without stretching as the layers were increased.

A force sensor was placed under the petri dish to measure normal forces applied during palpation. Calibration of the force showed that maximum error was less than about 8%. Data was recorded at 50 Hz. The first non-zero force signal was set as t=0.

Procedure

At the beginning of each study, subjects were instructed to palpate the rubber models and press the signal button when a lump was found. They were informed that each tissue sample contained either three equal-sized lumps or no lumps at all. To enable unbiased testing of all lump sizes at all glove thicknesses, both were presented in a pseudo-random order, *i.e.* no two consecutive tasks used the same lump size nor the same glove thickness. For each test, the normal forces applied during palpation and the signals from the detection button were recorded. A maximum time limit of 180 seconds was set for each test.

Preliminary Testing

Since learning during the course of repeated trials could interfere with data interpretation, preliminary testing on four naïve subjects determined the expected level of learning during this study. The same apparatus and procedure was used, and repeated palpation tests were performed for glove thickness 0 mm, 0.95 mm and 1.91 mm. Lump models were presented in sequential order from largest to smallest at each glove thickness. Each run consisted of a total of 12 trials (4 lump sizes at 3 glove thicknesses), and three runs were repeated for each subject. The data indicated that there was no significant learning across the three runs: detection time was improved in the third run for only 43% of the cases. The standard deviation in detection times across the three runs was 12% of the mean. As a result, it was assumed for the rest of the experiment that no adjustments were necessary to compensate for learning effects.

B. Precision Grip

Apparatus

The experimental apparatus is shown in Figure 2. Seven healthy, right-handed subjects (3 female, 4 male, 20-31 years old) who were naïve with regard to the purpose of the experiments participated in this study. The subjects stood and lifted the object that was placed on a table about waist high. The thumb and index finger were used to do the lifting.

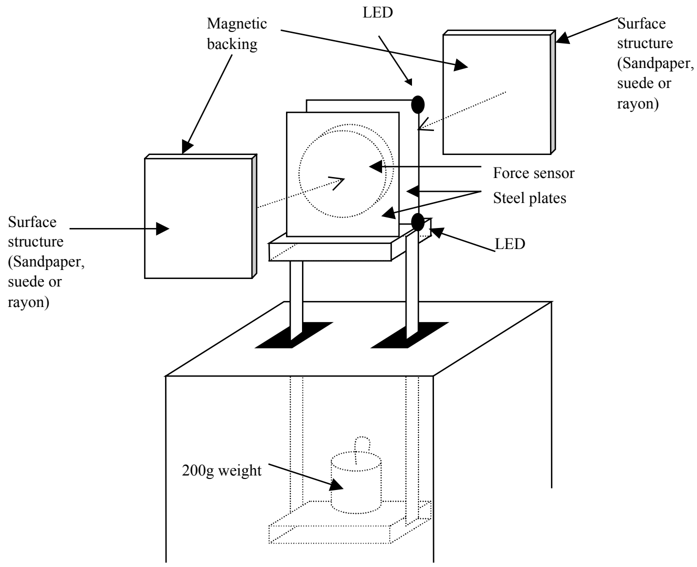


Figure 2. Experimental setup for precision grip

To provide a range of friction, three different surfaces (rayon, suede leather and no. 400 sandpaper) were used in this study. They were easily interchanged by a magnetic backing. A small notch prevented them from slipping vertically. The total load was constant throughout the study at 460 g. A force sensor (ATI, Mini F/T sensor) placed between the plates was used to measure the grip force on one finger and the vertical lifting force (load force). Two LEDs were used to track position and angle during the lifting motion. For the first half of the study, the lighting in the room was dimmed in order to prevent visual discrimination of the surfaces. In the second half, a screen was placed in front of the apparatus to preclude all visual feedback during the lifting process. All data were collected at 120 Hz.

The same gloves were used in this experiment as the lump detection study, layered in a similar manner. One (0.32 mm), three (0.95 mm) and six (1.91 mm) layers of gloves were tested, in addition to a single layer of a thinner latex glove at 0.16 mm (Microflex Corp., Evolution, k≈60 N/m). Only the fingertips of the gloves were used, and they were placed on the thumb and index finger.

The RMS variations of the force readings were independent of the force levels applied, and were 0.096N for the vertical lift force and 0.087 N for the grip force. Variations were determined by sampling both forces for 3 minutes under different known load conditions. During the experiment, load force equaled 4.6 N and all grip forces were greater than 5N, making the RMS variations less than 2% of the forces in either direction.

In addition, the RMS variations of the two position sensors were 0.0071 cm and 0.0083 cm in the horizontal direction and 0.014cm and 0.018 cm in the vertical direction. Since the object was raised 2.48 cm on average and moved 0.21 cm horizontally, the error contribution was less than 1% vertically, and about 4% horizontally. Again, these were measured by placing the object in known positions and recording its position data for 3 minutes.

Procedure

The same set of instructions was given to each subject at the beginning of each study. The subjects first washed their hands with soap and practiced lifting until they were comfortable with the procedure. They were instructed to grip the object with the thumb and index finger, lift it about 2 cm, hold for seven seconds and then slowly place back in its original position. This procedure, or trial, was repeated for a series of 60 lifts with different surface and glove thickness combinations. All subjects were presented with the trials in the same order. This ordering served several purposes. First, identical surface and thickness tests were given in sets of two. All data from the second of the two consecutive tests made up the standard case result, which was defined as the average across all trials that were preceded by the same glove and surface combination. This was done to ensure that certain unexpected effects, such as learning and adapting to new surfaces, did not factor into the mean values. Second, consecutive trials were performed involving different surface features while maintaining the same glove thickness. This tested for the presence of adaptation ability. Third, the trials were presented symmetrically with respect to glove thickness, *i.e.* in the first half of the experiment, subjects put on increasing glove layers, and in the latter half, they decreased layers. This last feature was to ensure that there were no learning advantages to either increasing or decreasing glove layers.

A screen was then placed in front of the apparatus and the subject was again asked to grip the object with the thumb and index finger, lift it about 2 cm, hold for seven seconds and then slowly place back in its original position. The same series of 60 trials was used.

Finally, the subjects were instructed to lift the object about 2 cm and then to slowly separate the thumb and index finger until the object was dropped. Since $f = \mu n$ at the point of initial slipping, these tests enabled the determination of the different frictional conditions between the finger and object surface. All combinations of surface textures (sandpaper, suede and rayon) and finger coverings (bare hands, Evolution® glove, and UltraOne® glove) were tested. By performing each combination twice, 18 such trials were performed on all subjects. These tests are henceforth referred to as the slow-release experiments.

As determined from the slow-release experiment (for technique, see Analysis below), the average coefficients of friction between bare hands and the three surface materials were 0.96±0.15 (mean±standard deviation) for sandpaper, 0.41±0.07 for suede and 0.20±0.04 for rayon. The coefficient of friction μ relates normal force n to the frictional force f: $f \le \mu n$. When the thin Microflex Evolution® gloves were worn, the coefficients of friction decreased to 0.78±0.03 for sandpaper, 0.21±0.01 for suede and 0.13±0.01 for rayon. For the thicker Microflex UltraOne® gloves, they were 0.77±0.04 for sandpaper, 0.17±0.01 for suede and 0.13±0.01 for rayon.

Analysis

For each trial, grip force, load force and the spatial position of the object were measured. The angle of tilt determined from the position of the two LEDs was used to decouple the grip and load forces in trials where the lift occurred at an angle.

$$f_x = f_x^m \cos\theta + f_y^m \sin\theta$$

$$f_y = f_y^m \cos\theta - \left| f_x^m \sin\theta \right|$$

In equation (1), f_x is the true load force and f_y is the true grip force, f_x^m and f_y^m are the measured load and grip forces, and θ is the angle from the vertical position. In most cases, the angles were less than 5 degrees, so this correction was quite small.

In addition, the ratio of grip force to load force was calculated for each trial. These ratios were used in conjunction with measures of slip ratio[1], which is defined as the ratio of grip force to load force just as the object begins to slip. Slip ratios were calculated from the slow-release experiments where the subjects allowed the object to slide. They are related to the coefficient of friction μ as[2]:

$$\mu = \frac{f_x}{f_y} = \frac{1}{2}\left(\frac{1}{Slip\ \ Ratio}\right)$$

Furthermore, safety margin[1] was defined as the ratio of grip force to load force less the appropriate slip ratio. Paired *t*-tests were performed on these safety margins to determine which trials were statistically different from each other.

Since data were collected as time series, it was necessary to pick a point in time when making comparisons across different trials. Exactly three seconds into the lift (as determined by the onset of grip force) was arbitrarily chosen for this purpose. Since most grip and load forces had already stabilized within one second, forces at three seconds were static values. For the rest of the study, these measurements are referred to as static phase[1] values.

RESULTS

A. Lump Detection

A typical data set is shown in Figure 3.

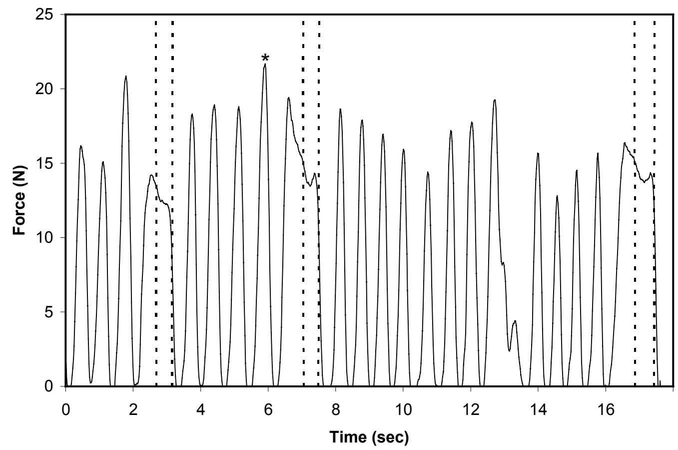


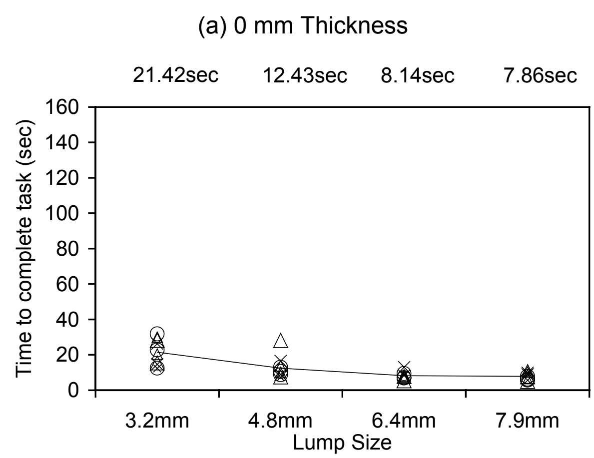
Figure 3. Typical data.

The dotted lines indicate the point of lump detection; the width between each pair is the duration that the button was pressed. As seen in this typical data set, peak force often tended to precede lump detection. * denotes the maximum force applied during this palpation task.

Relationship between glove thickness and task completion time

Spread in Data

The effect of handwear thickness on lump detection time was seen to vary considerably with lump size and among individuals (Figure 4). Each graph represents a different glove thickness, and data points from all ten subjects are displayed.



[1] Using terminology from Johansson and Westling (1984).
[2] See Johansson and Westling (1984) for a more detailed derivation.

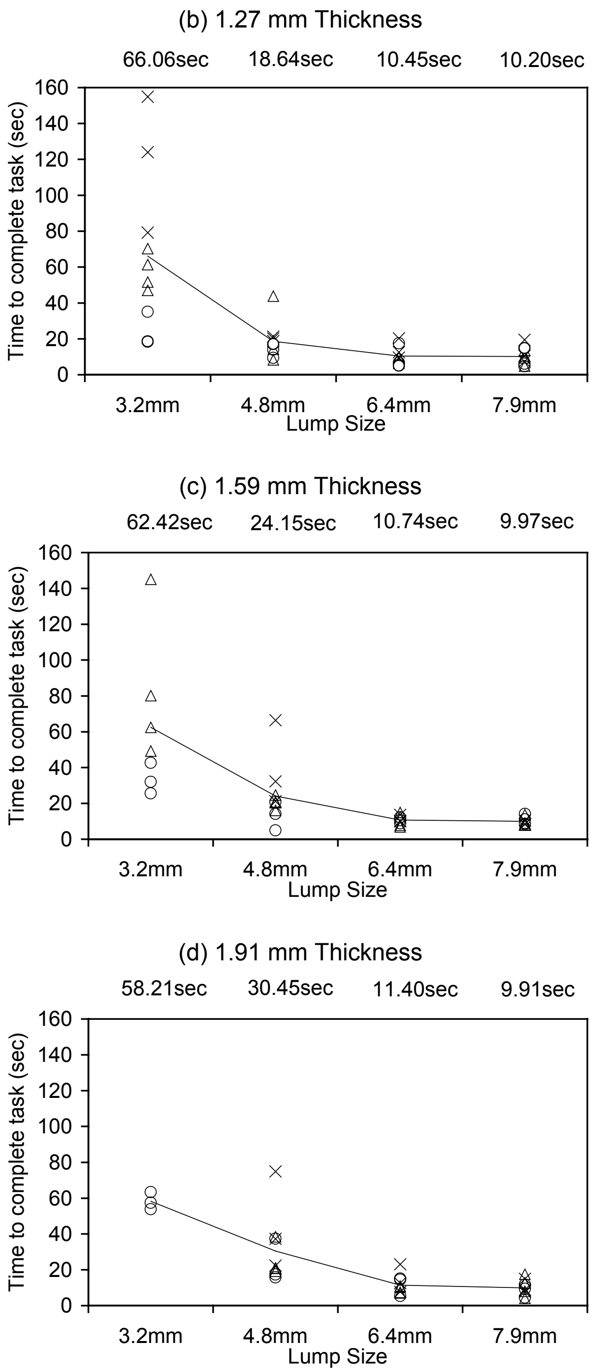


Figure 4. Relationship between glove thickness and lump palpation time across all subjects. *× denotes subjects who were unable to complete the 3.2 mm ball palpation task at glove thickness of 1.59 mm and 1.91 mm. △ were unable to complete it at 1.91 mm thickness. ○ successfully completed all tasks. For glove thickness 0.95 mm and under, the differences in detection time did not depend on the categorization ×, △, ○. For 1.27 mm and up, however, the detection time of the smallest lump clearly separated along these performance classes. Mean times are indicated above each plot and indicated by lines.*

Palpation Threshold

As indicated in Figure 5, three subjects were unable to complete the 3.2 mm lump palpation task for glove thickness of 1.59 mm and 1.91 mm. These subjects also took longer to complete the 3.2 mm lump palpation task at 1.27 mm (average 119 s vs. average 43 s for the other seven). Four other subjects were unable to detect the 3.2 mm lumps only for the 1.91 mm case. In addition, they took longer to detect lumps at 1.59 mm thickness than the remaining three subjects (average 84 s vs. average 33 s).

Mean Lump Detection Time

Figure 5 shows the mean task completion time of all ten subjects. There appeared to be very little distinction between the 6.4 mm and 7.9 mm lumps. Furthermore, palpation time for these lumps did not seem to vary significantly with glove thickness.

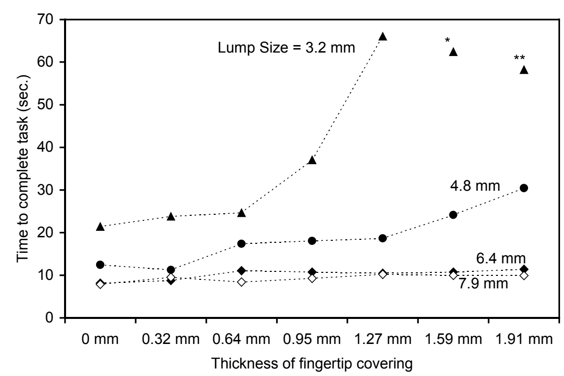


Figure 5. Task completion time averaged across ten subjects.

The times for the 3.2 mm lump at glove thickness of 1.59 mm and 1.91 mm were omitted from this figure because the number of subjects who were able to complete the task dropped from 10 to 7 and 3 respectively. The mean completion time for the 7 subjects with 1.59 mm thick gloves was 62 seconds. For the 3 subjects with 1.91 mm thick gloves, the mean was 58 seconds.

Paired *t*-tests were performed on the ten original sets of data to confirm the significance of the times observed in Figure 5 for the 3.2 mm and 4.8 mm lumps (Table 1).

Glove Thickness	Lump Size: 3.2 mm	Lump Size: 4.8 mm
0 mm		10
0.32 mm	23	
0.64 mm		
0.95 mm	37	20
1.27 mm	66	
1.59 mm		
1.91 mm		23

Table 1. Significance testing on task completion time

Statistically similar times are represented within dotted lines. The numbers refer to average task completion times in seconds.

For the 4.8 mm lump, there were three sets of significant time differences. Performance time was similar for bare hands and the 0.32 mm glove and more than doubled through the thickest glove. For the smallest 3.2 mm lump, the changes in performance were most dramatic. Although there was no significant difference in lump detection time between bare hands and gloves up to 0.64 mm, changes were rapid beyond this thickness. The 0.95 mm glove increased detection time by 161%, and the 1.27 mm glove by another 178%. At and above thickness 1.59 mm, some of the subjects failed to complete the task. For this reason, significance was not evaluated for these thicknesses.

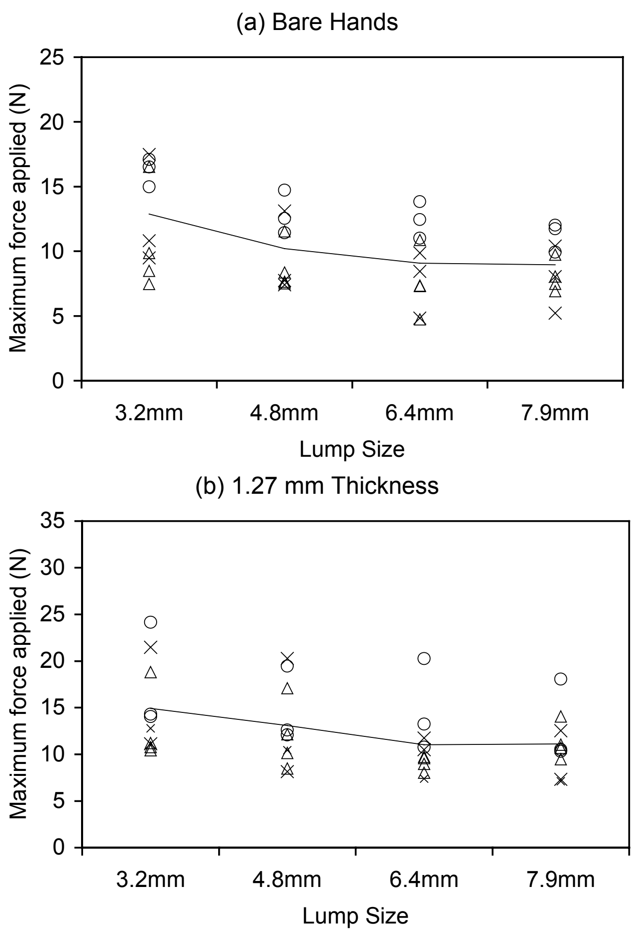


Figure 6. Relationship between glove thickness and maximum force applied during palpation. *The data point markers ×, △, ○ are equivalent to those of Figure 5. × denotes subjects who were unable to complete the 3.2 mm ball palpation task at glove thickness of 1.59 mm and 1.91 mm. △ were unable to complete it at 1.91 mm thickness. ○ successfully completed all tasks. The straight line connects mean values.*

Relationship between glove thickness and forces applied during palpation

The typical range of maximum forces applied during palpation as a function of lump size is shown in Figure 6. Maximum force corresponds to the highest force peak reached during palpation (* in Figure 3). For this experiment, these maximum forces were used as a relative measure of the effect that glove thickness has on palpation task execution. Maximum forces were found to be quite symmetric about the mean with average standard deviation at 30% the value of the mean, consistent for all glove thicknesses and lump sizes.

Mean Forces Applied During Palpation

The mean maximum force as a function of glove thickness across all subjects was found to be closely linear, as shown in Figure 7. The r^2 ranged from 0.88 to 0.99.

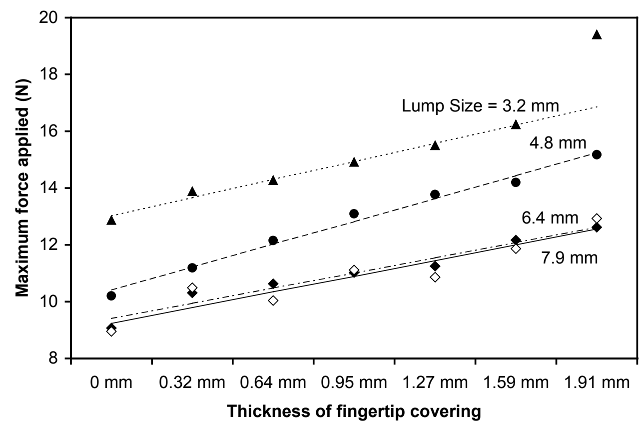


Figure 7. Linear dependence of palpation force on fingertip covering thickness. *For glove thickness 1.91 mm, the smallest lump was excluded from the line estimation because the sample size was small.*

Relationship between applied force and lump detection time

Finally, the correlation between task completion time and the forces applied during palpation was determined. The correlation, $\rho_{f,t}$, was calculated as:

$$\rho_{f,t} = \frac{Cov(F,T)}{\sigma_f \sigma_t}$$

where

$$Cov(F,T) = \frac{1}{n}\sum_{j=1}^{n}\left(f_j - \mu_x\right)\left(t_j - \mu_y\right)$$

f_j and t_j represent force and time data of each subject for a given lump size and glove thickness combination. F and T are sets containing all subjects' data. The results in Table 2 indicate that pressing harder did not lead to faster lump detection times.

Correlation		Lump Size				Mean
		3.2 mm	4.8 mm	6.4 mm	7.9 mm	
Glove Thickness	0 mm	-0.12	0.40	-0.01	-0.22	0.01
	0.32 mm	0.16	0.22	0.17	0.18	0.18
	0.64 mm	-0.04	0.64	0.31	0.08	0.25
	0.95 mm	0.14	-0.41	0.07	0.33	0.03
	1.27 mm	0.00	0.28	-0.16	0.09	0.05
	1.59 mm	-0.24	0.15	0.07	0.62	0.15
	1.91 mm	0.11	0.38	0.49	0.08	0.27
Mean		0.00	0.24	0.13	0.16	0.13

Table 2. Correlation between detection time and applied force is low.

B. Precision Grip

Standard Case

Typical data for the standard case is shown in Figure 8. **A** corresponds to the preload phase, or the initial phase during which only the grip force increases. **B** is the loading phase, where the grip force and load force increase in parallel until the load force reaches its maximum value of 4.6 N. **C** is the point where the object is initially lifted. **D** is onset of the static phase, where the grip force remains stable – for this experiment, static phase measurements were taken at 3 seconds.

Spread in Data

Variability across subjects was analyzed using individual force data. Both grip force and load force across subjects were compared by setting the onset of grip force as t=0 for each trial, as a non-zero grip force marked the very beginning of all lift efforts.

Averaged across all trials, the value of the load force was 4.60±0.03 (mean±standard deviation) during the static phase. There was small variation because the vertical lift force exactly matched the force of gravity pulling the object down (4.60 N). For the grip force, there was more variation across individuals, as expected, since the only constraints that existed were slip prevention (lower bound) and physical strength or fatigue (upper bound). On average, during the static phase, grip force standard deviation was 18% of the value of the mean force calculated across all subjects. This spread, when stated as a percentage of mean force, did not vary with glove thickness, but varied with surface material. It tended to be greater for sandpaper, which averaged 26%, in contrast to 15% for suede and 14% for rayon. Since sandpaper had a lower slip ratio than either suede or rayon, there was a greater range of allowable forces.

Similar to the lump detection test, there were individual tendencies present in the data. Subject who tended to squeeze harder did so for all trials while those who were barely above the slip ratio maintained that tendency throughout (Figure 9).

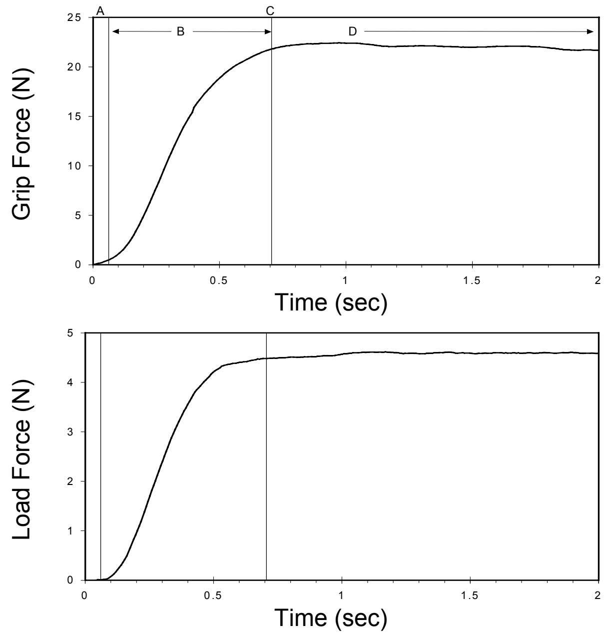


Figure 8. Force changes during a single lift
A single data set from a rayon-0.16 mm thickness trial illustrates the timing of force changes.

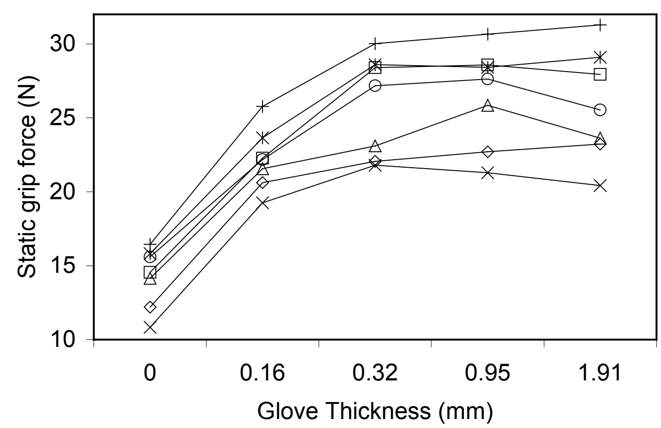


Figure 9. Static grip force vs. glove thickness for rayon.
Each line represents data from a different subject.

Profiles of average grip force and load force

Average grip and load forces across subjects were obtained by setting the onset of grip force for each trial as t=0 and then taking their average. The force profiles during the lifts indicated that average grip force varied considerably across the different surface and fingertip conditions (Figure 10). The lowest static phase grip force of 5.7N was observed for the sandpaper-no glove combination. The highest was 26.5N for the rayon-1.91 mm glove combination. It is important to note, however, that this range in grip force was not caused solely by changes in glove thickness. Because the gloves themselves affected the frictional condition of the lift, both thickness and friction effects were present.

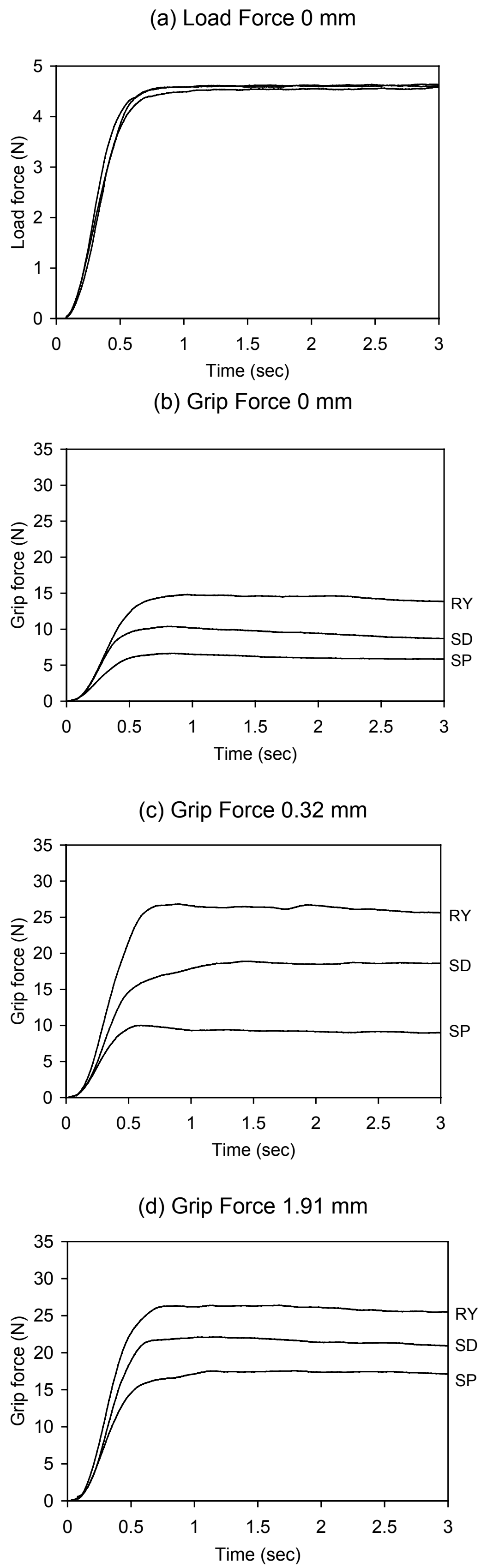
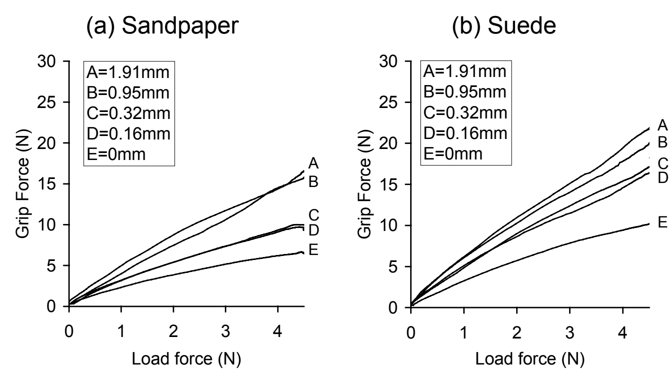


Figure 10. Time series of load and grip force – mean data. In this figure and throughout the rest of the paper, RY refers to rayon, SD refers to suede and SP refers to sandpaper. (a) shows typical load force profiles for rayon, suede and sandpaper. All trials, regardless of glove thickness and surface condition, look similar. (b)-(d) show how grip force varied with surface material and increased considerably with glove thickness

Loading phase

During the loading phase, both the grip force and load force increased in parallel for 0.65±0.02s (mean±standard deviation). This phase was found to be similar in duration for all trials, independent of glove thickness and frictional condition.

The relationship between grip force and load force during the loading phase was found to be approximately linear across all glove thickness (r^2=0.983 to 0.993) (Figure 11). This trend implied that subjects anticipated very early during the lift process the forces needed to lift the object and prevent it from sliding. Once the required ratio of grip force to load force was determined, both were increased proportionately until the desired levels were reached simultaneously. Note, however, that these trials were preceded by trials with identical friction and thickness features. As a result, there was no element of uncertainty: subjects correctly anticipated force requirements based on the preceding trial.



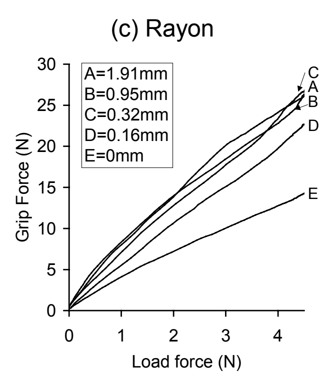


Figure 11. Grip force vs. load force during the loading phase. As glove thickness increased, so did the overall level of grip force, but the linearity of the loading phase was unchanged. Note grip force saturation due to strength limitation for rayon at thickness greater or equal to 0.32 mm.

Static phase

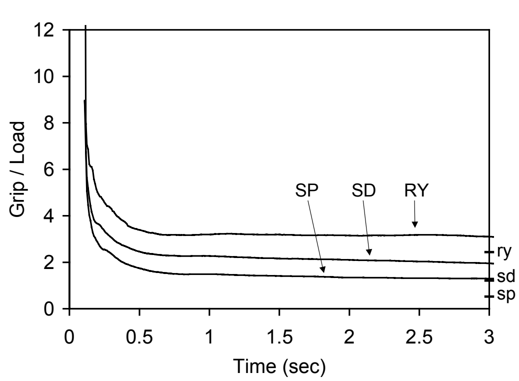
The grip forces during the static phase were maintained above a certain minimum value such that slip did not occur. Comparisons between these values were not made in terms of grip force, however, because the slip conditions differed across the various trials. Instead, the ratios of grip force to load force were used in conjunction with the different slip ratios obtained experimentally. The slip ratios for the different combinations of surface structures and fingertip coverings are presented in Table 3.

	Sandpaper		Suede		Rayon	
	Ratio	S.D.	Ratio	S.D.	Ratio	S.D.
Bare hands	0.52	0.09	1.21	0.32	2.44	0.42
0.16 mm glove	0.64	0.03	2.36	0.08	3.73	0.10
≥0.32 mm glove	0.65	0.02	2.89	0.14	3.98	0.17

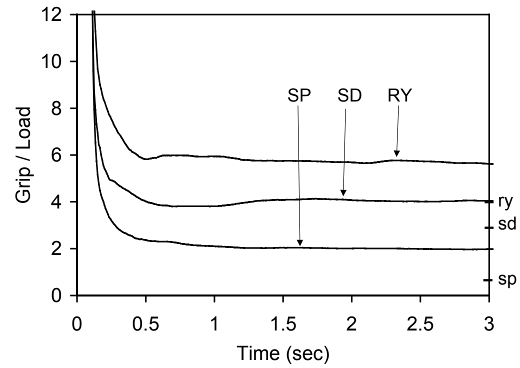
Table 3. Experimentally obtained slip ratios Means of all seven subjects. Ratio is the slip ratio, and S.D is standard deviation.

Figure 12 shows the average ratio of grip force to load force. The high ratios in the beginning were due to the preload phases, where the load forces were still very close to zero. As the load forces increased, the ratios decreased to their final stable values. Notice that the ratios were maintained well above the slip ratios, preventing any risk of slipping. The slip ratios are denoted by smaller case symbols in Figure 12. Furthermore, there appeared to be a physical strength or fatigue limit preventing the ratio from becoming too high. From Figure 12, that upper limit seemed to be around 6. Trials involving rayon, which was the most slippery surface, reached the peak ratio first (at 0.32 mm thickness) while trials involving the other two surfaces gradually caught up as glove thickness was increased.

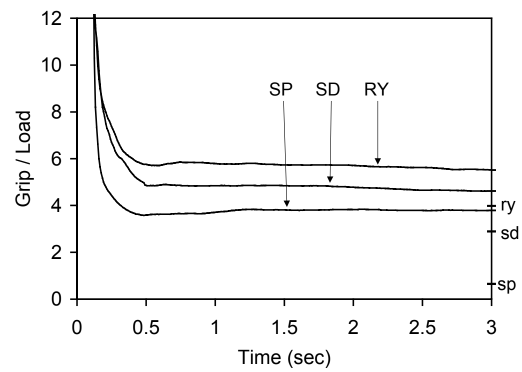
(a) 0 mm Thickness



(b) 0.32 mm Thickness



(c) 1.91 mm Thickness



(d) Static Ratio

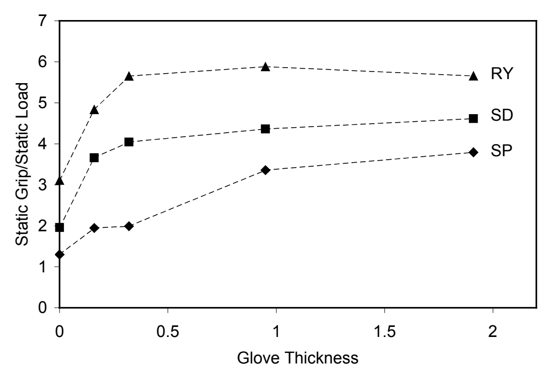


Figure 12. Ratios of grip force to load force. As glove thickness increased, the ratio of grip force to load force became significantly higher than the slip ratios. In (d), the grip force to load force ratio during the static phase is compared across glove thickness. The ratio appears to plateau beyond the 0.32 mm glove for rayon, while suede and sandpaper slowly catch up.

Safety Margin

Subtracting the slip ratio from the grip force-to-load force ratio provides a measure of safety margin. This measure makes it possible to compare the effect of glove thickness alone, since the frictional effect is subtracted out. Figure 13 shows the changes in slip margins with glove thickness. Table 4 indicates which changes were statistically significant.

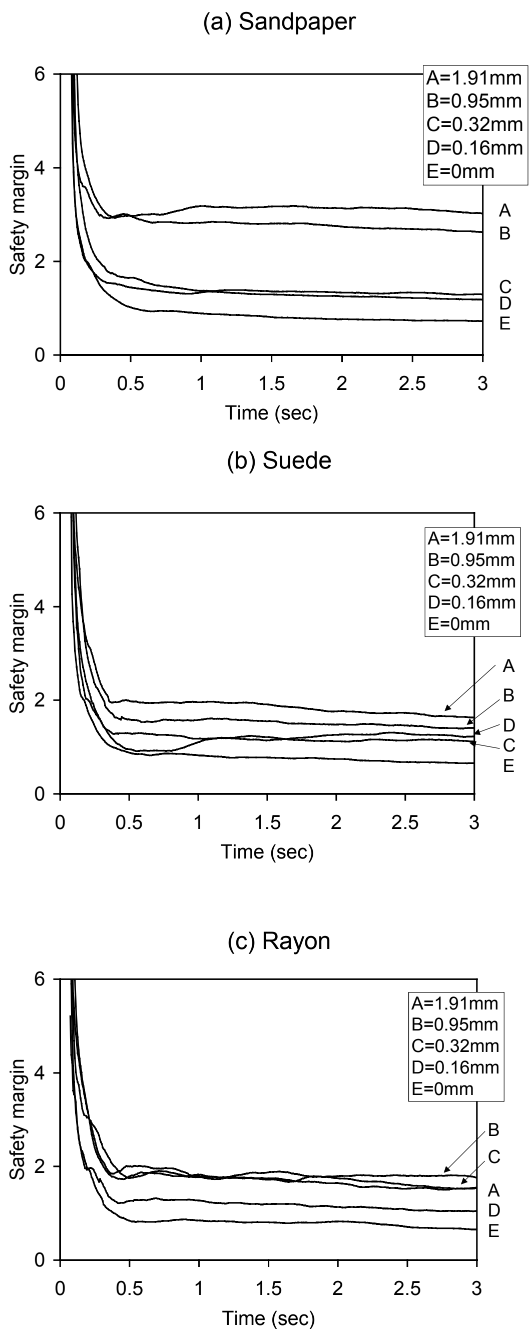


Figure 13. Changes in safety margin with glove thickness. The safety margins were higher overall for sandpaper, but all three surfaces demonstrated increases in safety margin with higher glove thickness.

Sandpaper		Suede		Rayon	
	Margin		Margin		Margin.
0 mm	0.74	0 mm	0.68	0 mm	0.75
0.16 mm	1.21	0.16 mm	1.26	0.16 mm	1.06
0.32 mm	1.32	0.32 mm	1.21	0.32 mm	1.58
0.95 mm	2.65	0.95 mm	1.41	0.95 mm	1.78
1.91 mm	3.08	1.91 mm	1.66	1.91 mm	1.54

Table 4. Significance testing of safety margins. The dotted lines separate sets of results which were significantly different from each other. The significance level in the paired *t*-test was set at 0.05. Margin is safety margin.

The results here can be summarized as follows: (a) bare hand always produced the least amount of excess force; (b) the thinnest 0.16 mm glove produced significantly less force than the two thickest gloves but more than bare hands. (c) the force used for 0.32 mm gloves depended on the contact surface. (d) 0.95 mm and 1.91 mm gloves were significantly different from the thinnest 0.16 mm glove in all cases and produced the greatest force.

Adaptation Case

Adapting to new surface materials

Earlier in the results, it was established that the rate of increase of grip force during the loading phase was proportional to the rate of increase of load force. So far, this result was limited to trials that were preceded by similar trials, i.e. with the same friction and thickness conditions. In this next experiment, the surface material was changed between trials. Subjects therefore had to adapt to a new surface during the lift. Here, adaptation, or learning, was defined as the extent to which the end values of the new forces matched that of the appropriate standard cases. 100% learning at the end of the loading phase therefore meant that the grip force of the adapted trial exactly matched the grip force of the standard trial of the current surface; 0% learning indicated that the end value of the "adapted" trial still equaled the standard trial end value for the previous surface.

Results indicated that both the speed and extent of adaptation were affected by glove thickness. In the barehanded case, when the surface was changed from rayon (slippery) to suede (less slippery), a brief period of zero adaptation lasted until load force reached about 0.5 N (Figure 14). Subsequently, the slope of the ratio line changed, and limited learning took place (49%). When the 0.16 mm glove was worn and the same experiment repeated, there was no learning until the load force reached about 1.5 N. There was again a change of slope, followed by limited adaptation. As glove thickness was increased to 0.32 mm and 0.95 mm, the trends were similar. With each increase in glove thickness, the onset of learning was delayed and the level of adaptation decreased. Finally, with the 1.91 mm glove, there was very little distinction between standard rayon and suede preceded by rayon. This indicated that subjects could not adapt to the new surface. The level of learning here was 1%

In the reverse case, where sandpaper (less slippery) was replaced with suede (more slippery), subjects started learning immediately for the zero glove trials, and the grip force almost reached that of standard suede by the end of the loading phase (93% learning). With 0.16 mm gloves, learning only started after about 0.5 N of load force, and the final grip force fell short of the standard suede level at 86% learning. The results of the 0.32 mm, 0.59 mm, 0.95 mm and 1.59 mm gloves were qualitatively similar to that of the 0.16 mm glove. Learning started after about 0.5 N to 0.8 N of load force was reached, and learning was incomplete. By the 1.91 mm glove, the level of learning had decreased to 67%

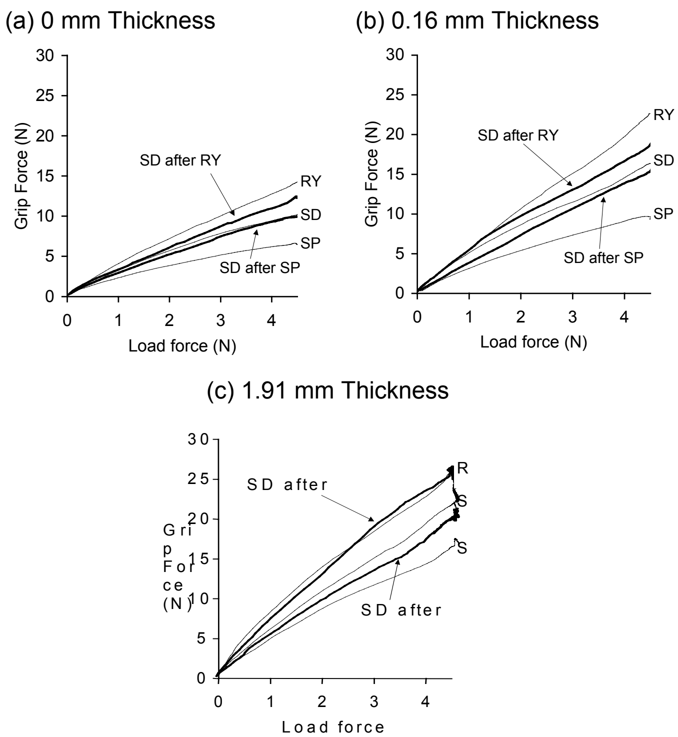


Figure 14. Grip force vs. load force in suede trials that follow sandpaper or rayon. The fine lines represent the standard trials, introduced earlier in Figure 11. The bold lines are the adaptation cases.

No visual feedback

So far, the experimental setup prevented visual discrimination of the surface structures but it did not prevent visual discrimination of slip. The next experiment used a screen to block view of the apparatus. This was used to test whether the presence of visual feedback was a factor in determining grip force level.

Grip and load force profiles similar to the standard cases were observed, again generated by using trials that were preceded by the same glove and surface combinations (Figure 17). Compared to the cases with visual feedback, these new force profiles had longer preload phases on average, and greater variation among trials (Figure 13). For zero gloves, the average preload time was 0.12±0.06 s, in contrast to the original time of 0.073±0.03 s. The preload phase increased further with glove thickness.

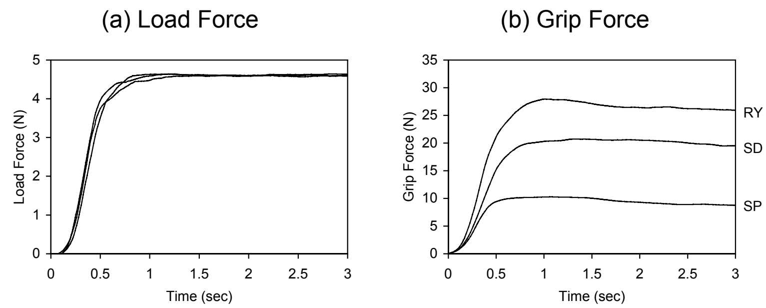


Figure 15. Average load force and grip force in trials with no visual feedback Compared to Figure 10, the grip forces tended to be higher, and they were not as stable even during the static phase. (b) is average data for the 0.32 mm glove, which may be compared directly to Figure 10(c).

The duration of the loading phase also increased. The average loading phase lasted 0.94±0.18s, which was both higher in average and greater in spread than the original 0.68±0.02s. Even with this significant increase in loading phase, the linear relationship between the rates of increase of grip force and load force was unchanged: the new r^2 of the line fits ranged from 0.984 to 0.999. This meant that people did not change their proportionate loading behavior, but merely changed its rate.

DISCUSSION

The present results indicate that increasing the thickness of gloves significantly affects the performance of perceptual and manipulation tasks. In both the lump detection and precision grip tests, the effects of gloving could be distinguished into two categories. The first set of effects were those whose magnitudes depended solely on the thickness of the glove. The second set of effects depended on both glove thickness and the specifics of the task, which, for the lump detection study consisted of the different lump sizes, and for the precision grip study were the different surface conditions. The lump sizes and surface conditions provided several difficulty levels to the task.

A. Lump Detection

In lump detection, the forces applied during palpation were observed to increase linearly with glove thickness (Figure 7). All lump sizes showed similar linear relationships, suggesting that force application was more dependent on the level of stimulus at the skin of the fingertips, rather than on task difficulty, *i.e.*, subjects pressed until the fingertip deformed to a desired extent (Peine 1999). Force increase was therefore an overall effect of gloving, and its average effect was 2.0 N per millimeter of thickness increase.

In contrast to the applied forces, task completion time varied by lump size as well as glove thickness. On one hand, the detection time for the two largest lumps was found to vary little with glove thickness. Gloving only added a total of 2 s to the performance time between bare hands and 1.91 mm thick gloves (25% increase). For the medium 4.8 mm lump, the corresponding increase in performance time was 13 s, or 230%. At the other extreme, when the task required very fine sensing ability (the 3.2 mm lump), increasing the glove thickness beyond 0.95 mm had a very dramatic effect on task completion time. The completion time for 1.27 mm gloves was 287% greater than the completion time for zero gloves. Beyond this thickness, several subjects failed to complete the test. This indicated that for the most difficult perceptual task, gloves of thickness 1.91 mm and greater effectively prevent task completion.

Performance differences across subjects suggested that perceptual thresholds vary across individuals. Furthermore, the inability of 70% of the subjects to palpate the 3.2 mm lumps at glove thickness 1.91 mm indicated that this combination of glove thickness and lump size had exceeded the perceptual threshold for most people.

Finally, although both detection times and forces varied among subjects, there was very little correlation between the two. Pressing harder did not necessarily lead to better detection times or increased detection levels. This again supported the observation that individual palpation thresholds vary.

B. Precision Grip

There were two task and thickness dependent effects observed during manipulation. The first was the subjects' ability to adapt to new surfaces. When the surface was changed from more slippery to less (rayon to suede), the extent of learning fell from 49% to 1% as gloving increased from zero to 1.91 mm. In contrast, when the change in surface was from a less slippery to a more slippery one (sandpaper to suede), initial adaptation was more complete and its deterioration with glove thickness was less dramatic. From zero gloves to 1.91 mm gloves, the total change in learning decreased from 92% to 67%. These results indicated that although glove thickness hindered adaptation ability overall, the extent of its effect was likely dependent on the level of stimulus received at the fingertip, making some adaptation tasks more difficult than others. More specifically, the process of adapting to a lower friction surface may have involved some slipping, which, if felt would have alerted the subject that the level of force application was insufficient. No such signal would have been present as subjects adapted to a higher friction surface.

The second effect was the amount of safety margin employed. The changes in safety margin from zero gloves to 0.16 mm gloves were relatively similar: 160% for sandpaper, 185% for suede and 141% for rayon. However, for greater changes in thickness, the increase in safety margin was greatest for sandpaper. The total change in safety margin between zero gloves and 1.91 mm gloves was 416% for sandpaper, 244% for suede, and 205% for rayon. Since sandpaper had a lower slip ratio than rayon, it was possible for subjects to grip significantly harder than the minimum slip condition before being limited by physical strength. These observations suggested that the subjects' natural reaction was to increase grip force with glove thickness, and that the primary factor preventing continued force increase for all surfaces was strength or fatigue limitation.

Finally, tests depriving subjects of visual feedback indicated that even under limited haptic feedback conditions, visual feedback played a secondary role. Differences between these tests and the standard case existed, but were limited in extent. First, the preload phase increased by an average of 0.15 ± 0.07s from the standard case. The likely cause for this increase in duration and spread was merely the difficulty involved in properly gripping the object when no vision is allowed. Second, the loading phase increased by 0.26 ± 0.20s. Perhaps subjects were more cautious when increasing forces because they could only rely on haptic feedback to judge when the force loadings were sufficient for lift, and hence when they could stop applying more grip force. A slower force loading process therefore compensated for the lack of visual feedback in determining successful completion of the lift. Finally, static phase force values were 6.1% higher, and also 35% more variable. These differences indicated that the complete lack of visual feedback had some effect, but perhaps not as great as might have been expected: obstructing vision certainly increased variability among individual trials, but the averages did not change considerably. Moreover, the effects were present across all glove thickness. This implied that even when haptic feedback was limited due to the thickest gloves, subjects did not (or could not) depend more on visual feedback to complete the lift task. Force application was regulated via sensations at the fingertips. Again, this pointed to the importance of haptic feedback in the performance of certain tasks: its deprivation could not be replaced with other forms of sensation.

CONCLUSION

The findings from this study suggest that even though there are some effects of gloving that are purely thickness driven, many effects are dependent on the nature and difficulty of the task. For this reason, every effort should be made to select the thinnest glove material possible if the goal is to introduce maximum versatility in the usage of the glove. If, however, it is possible to carefully restrict glove usage to certain tasks that are sufficiently above perceptual threshold and manipulation ability, then minimal thickness may no longer be a crucial factor in securing performance.

REFERENCES

Bensel, C.K., "The Effects of Various Thicknesses of Chemical Protective Gloves on Manual Dexterity," *Ergonomics* **36**(6), pp.687-696, 1993.

Bloom, H.S., Criswell, E.L., Pennypacker, H.S., Catania, A.C., and Adams, C.K., "Major Stimulus Dimensions Determining Detection of Simulated Breast Lesions," *Perception and Psychophysics* **32**(3), pp.251-260, 1982.

Burke, F.J.T., Watte, D.C., and Wilson, N.H.F., "Some Physical Factors Influencing Tactile Perception with Disposable Non-sterile Gloves," *J. Dent.* **17**, pp.72-76, 1989.

Johansson, R.S., and Westling, G., "Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip When Lifting Rougher or More Slippery Objects," *Exp. Brain Res.* **56**, pp.550-564, 1984.

Johansson, R.S., and Westling, G., "Signals in Tactile Afferents From the Fingers Eliciting Adaptive Motor Responses During Precision Grip," *Exp. Brain Res.* **66**, pp.141-154, 1987.

Lederman S.J. and Klatzky R.L 1997, "Designing haptic interfaces for teleoperational and virtual environments: should spatially distributed forces be displayed to the fingertip?" Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition, Dallas, Nov. 15-21, 1997, in G. Rizzoni, ed., Proceedings of the ASME Dynamics Systems and Controls Division, DSC-Vol. 61, 11-15.

Peine, W.J., "Remote Palpation Instruments for Minimally Invasive Surgery," Ph.D. Thesis, Division of Engineering and Applied Sciences, Harvard University, 1998.

Webb, J.M., and Pentlow, B.D., "Double Gloving and Surgical Technique," *Ann. Royal Coll. Surg. Engl.* **75**(4), pp.291-292, 1993.

Westling, G. and Johansson, R.S., "Factors Influencing the Force Control During Precision Grip," *Exp. Brain Res.* **53**, pp.277-284, 1984.