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Tactility as a Function of Grasp Force: Effects of Glove, Orientation, Pressure, Load, and Handle

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Contents

	Page
Introduction	1
Experiment 1: Tactility as a Function of Grasp Force: The Effects of Glove, Pressure, and Load	2
Method	3
Results	4
Discussion	6
Experiment 2: Tactility as a Function of Grasp Force: The Effects of Glove, Handle Size, Orientation, and Load	7
Method	7
Results	8
Discussion	15
Experiment 3: Maximal Exertion as a Function of Glove and Handle Size	17
Method	17
Results	17
Overall Discussion	19
References	20

Figures

1	Dynamometers used in these experiments	2
2	Glove box set-up for experiment 1	3
3	Gender effect on mean grasp force	5
4	Load effect on mean grasp force	6
5	Gloves used in this experiment	8
6	Glove effect on mean grasp force	10
7	Handle size effect on mean grasp force	10
8	Handle orientation effect on mean grasp force	11
9	Load effect on mean grasp force	11
10	Gender effect on mean grasp force	12
11	Glove*orientation interaction for the peak force	12
12	Glove*orientation interaction for the stable force	13
13	Glove*load interaction for the peak force	13
14	Glove*load interaction for the stable force	14
15	Handle*gender interaction	14
16	Load*gender interaction	15
17	Gender effect on maximum grasp strength	18
18	Glove effect on maximum grasp strength	18

Tables

1	Block Diagram of Conditions in Experiment 1	3
2	ANOVA Summary of Experiment 1	4
3	ANOVA Summary of Stable Grasp Data From Experiment 2	9
4	ANOVA Summary of Maximum Grasp Data From Experiment 2	17

Introduction

The hand offers probably the most effective means of accomplishing complex work, thanks to its ability to perform specialized tasks which require dexterity, manipulability, and tactile perception. This is especially true for work done in environments such as the vacuum of space, for which protective gloves must be worn. However, much evidence exists to show that performance decreases with the use of the protective EVA gloves. Numerous articles have been published in the area of the effect of gloves on task performance (Bishu and Klute, 1993a, Bishu and Klute, 1993b, Lyman and Groth 1958, and Cochran et al., 1986). The common finding in all these studies has been that gloves reduce both strength and dexterity performance.

It has been argued that a possible reason for this reduced performance could be reduced tactile sensitivity, or the feedback from the hand when gloves are donned. Bishu and Klute (1993a) attempted to measure the tactile sensitivity with gloves using a two-point discrimination test. This test consisted of having a subject sliding his finger along the gradually separating edges of a "v block." The distance between the starting point and the point at which the subject could discriminate two separate edges was to represent a measure of the tactile sensitivity of the subject. However, the results from this experiment revealed that this test was not quite appropriate. While the tactile sensitivity measure decreased with an added layer of the glove known as the thermal micrometeorite garment (TMG), the dexterity performance improved with the TMG. This type of relationship was not expected since reduced tactile sensitivity is generally associated with reduced dexterity. Either this may reveal that the relation between dexterity and tactility is not as it was thought to be, or the two-point discrimination test was inadequate under these test conditions.

As a follow-up to this experiment, it was hypothesized that grasp strength could represent a measure of tactile sensitivity. The logic behind this is that grasping force for a certain load will be a function of the weight to be lifted and the hand conditions. The differences in grasping force for various hand conditions will then be a correlate of the tactile sensitivity of the corresponding hand conditions. It was further reasoned that when a person grasps an object, a firm grasp is made initially followed by a slow release to reach an effort that would just hold the object. Humans, being natural optimizers, would always try to hold an object with as minimal an effort as possible. This minimal effort for each glove condition would be a correlate of the tactile feedback that the person receives while holding the object under that gloved condition. Therefore, the initial firm grasp force, the following minimal grasp force, and their ratio would represent the amount of tactile adjustment that is made when picking up an object, and this adjustment should vary with the use of gloves.

The objectives of this research were to determine whether a reduction in tactile sensitivity was in fact causing a reduction in gloved performance, and to measure this reduction in tactile sensitivity through grasp force at the hand/handle interface under a variety of performance conditions. The effects that glove type, pressure differential, load lifted, handle size, and handle orientation have on the initial grasping force and stable grasping force were determined, with the working hypothesis being that grasp force would be a function of all the above mentioned factors. The objectives were achieved through the three experiments described below.

EXPERIMENT 1: TACTILITY AS A FUNCTION OF GRASP FORCE: THE EFFECTS OF GLOVE, PRESSURE AND LOAD

The objective of this experiment was to investigate the effect of gloves, pressure differential, and load to be lifted on grasp force.

APPARATUS In order to accommodate the loads to be lifted by the subject, and also to simulate the space shuttle conditions as closely as possible, a device similar to a standard hand dynamometer was designed and fabricated. As shown on the right in figure 1, it consisted of two steel halves which, when placed together, formed the same elliptical shape of the EVA handrail on the shuttle payload bay. The dynamometer on the left which was added later in experiment 2, is identical to the one on the right, except the length of one inch was added to the long axis of the cross-section, yielding a handle larger in diameter. A small plate was attached to the bottom of the device so that weights could be added as needed (as is attached to the left dynamometer in figure 1). Between these two halves, at the top and bottom of the device, load cells were placed to measure the horizontal forces applied by the hand along the long axis of the cross section. The output of the load cells was channeled through a real-time data recording system, from which graphs of the applied force vs. time were obtained. Particular points of interest were taken from these graphs, recorded, and then analyzed using the Statistical Analysis Software.

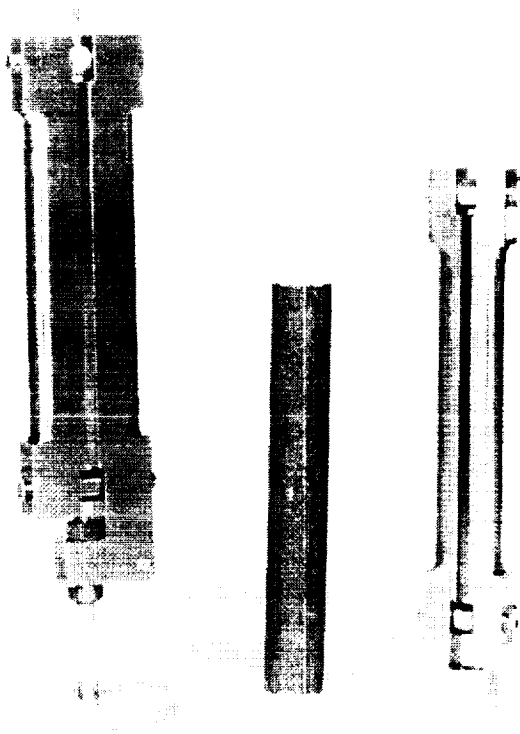


Figure 1. Dynamometers used in these experiments.

The actual performance tests for this experiment were conducted inside a glove box, as shown in figure 2. The glove box is designed to simulate the conditions felt inside a pressurized suit, so that astronauts can verify the fit and dexterity of their gloves inside a vacuum. It can be evacuated to any level, creating a pressure differential similar to that of a suit. It is cylindrical in shape and has an internal volume of 13ft³.

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Figure 2. Glove box set-up for experiment 1.

METHOD

The independent variables for this experiment were glove type, pressure, load, and gender as shown below, and were combined to form a set of 18 trials for the subjects, as shown in table 1.

Glove type: Shuttle, advanced, and bare handed
 Pressure: 0 PSID (pounds per square inch differential),
 4.3 PSID, and 8.3 PSID
 Load: 3.5 lb, 8.5 lb, and 13.5 lb
 Gender: Male and female

Table 1. Block Diagram of Conditions in Experiment 1

	0 PSID	4.3 PSID	8.3 PSID
Bare hand	1	not possible	not possible
Shuttle	2	3	not possible
Advanced	4	5	6

Eight subjects, four males and four females, ranging in age from 21 to 31, participated in this study. Each subject performed the 18 trials alternately with three minutes of rest time. The trial began with the adjustment of both the weight of the unit and the pressure of the glove box. The subject then donned the glove and adjusted the placement of the grip device so that it was comfortable. After resetting the computer, the subject was asked to grasp and hold the object as he/she normally would grasp something of that size and weight. The grip was held for 20 seconds and then the subject was asked to release the grasp as slowly as possible, so that the device would gradually slip through his/her hands. The order of the trials was randomized across all the conditions.

RESULTS

For purposes of analysis, and because each pressure differential was not possible with each glove condition, the independent variables of glove and pressure were combined to form one variable: glove-pressure. The six glove-pressure conditions consisted of 1) bare hand and 0 psid, 2) shuttle glove and 0 psid, 3) shuttle glove and 4.3 psid, 4) advanced glove and 0 psid, 5) advanced glove and 4.3 psid, and 6) advanced glove and 8.3 psid. Peak force, stable force, and the ratio of peak to stable force were the main dependent variables. An analysis of variance (ANOVA) was performed on the data and a summary follows in table 2.

Table 2. ANOVA Summary of Experiment 1

Dependent Variables	Glove-Pressure	Load	Gender	Glove-Pressure* Load
Peak	NS	**	**	NS
Stable	NS	***	***	NS
Peak/Stable	NS	***	**	NS

*** = $p < 0.0001$, ** = $p < 0.001$, * = $p < 0.01$, NS = not significant

Among the main factors, the gender effect and load effect were significant. Figure 3 shows a plot of the gender effect. On the average, females tended to use less force, with their stable force being 66% that of men and their peak force being 81% that of men. A larger ratio of peak to stable force was seen in the female subjects, however. On an average, the ratio for the females was approximately 125% that of the males.

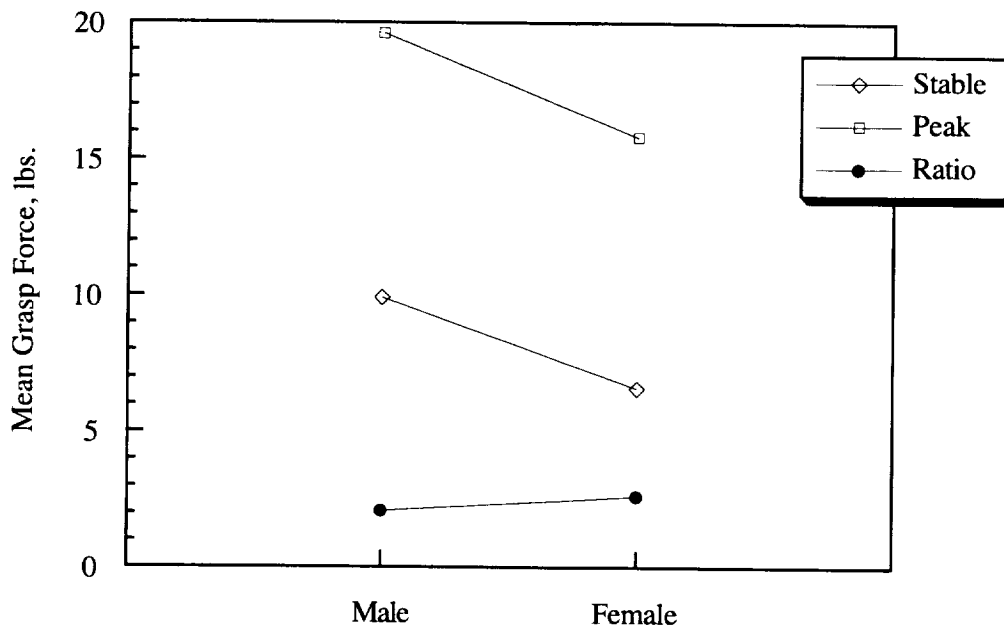


Figure 3. Gender effect on mean grasp force.

The load effect, as seen in figure 4, shows an increase in the force applied to the dynamometer as the load lifted increases, and this was expected. The ratio reduces slightly with increasing loads. The ratio seen at a load of 13.5 lb is only 73% that of the ratio at a 3.5-lb load.

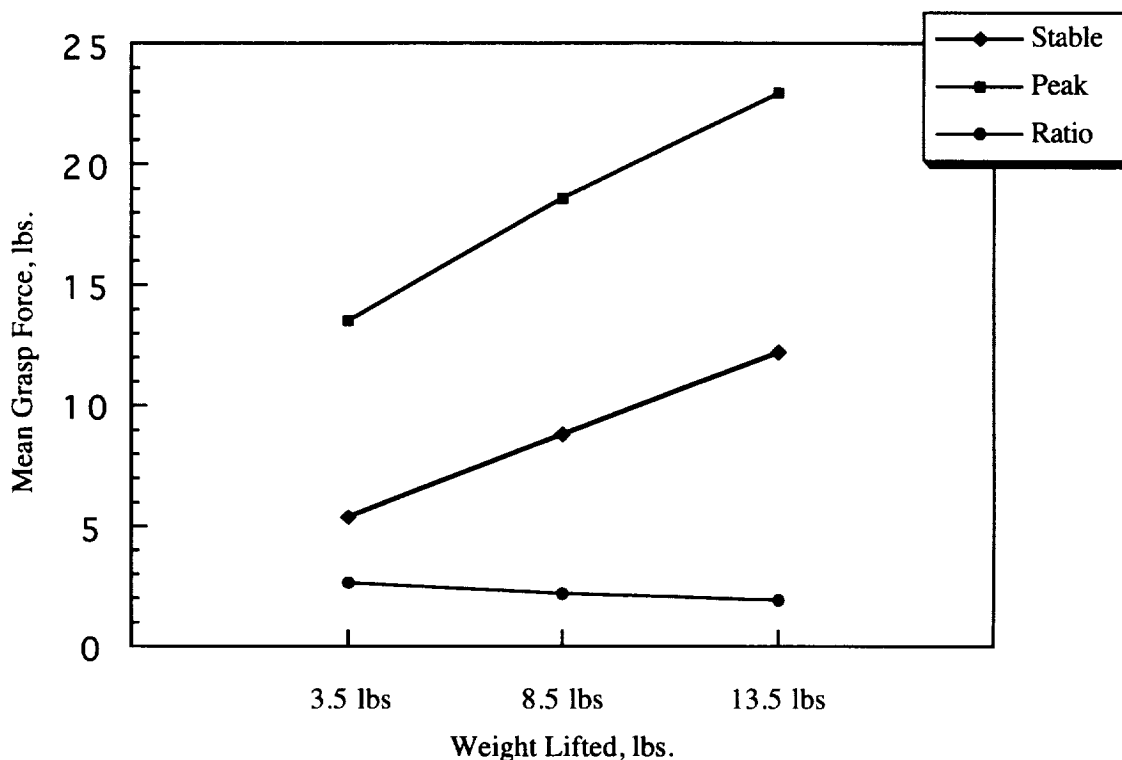


Figure 4. Load effect on mean grasp force.

DISCUSSION

The main results of this experiment were lack of glove-pressure effect, increasing load effect, gender effect, and decreasing ratio effect. While the load effect was expected, the gender effect was interesting and not intuitive. It is possible that the males were over-controlling as compared to the females in similar test conditions. Decreasing ratio effect is perhaps the most interesting result of this experiment. This could be due to either over perception of peak load, or to under perception of stable load. Overexertion and inadequate exertion are both harmful to the person. More research is definitely needed on this. Lack of glove-pressure effect is the most surprising result of this experiment. Both glove and pressure effects were expected. A reason for this could be the visual cue provided to the subjects in this experiment. Because the subject could see prior to each trial how much weight he or she would be lifting, some adjustments of the grasp force in lifting may have been made unconsciously. It is also possible that the gloves actually help in holding if they have a large enough coefficient of friction, while they deter in peak grasp strength. Another issue is that if the subjects were exerting the same peak and stable force in all the pressure-glove conditions, then were the muscles in the upper arm, which are the energy providers for the hand action, acting to the same exertion level? The current series of experiments was not geared to answer this question. However, the absence of glove-pressure effect led to the next experiment being performed outside the glove box with the visual cue and with a larger number of glove conditions.

EXPERIMENT 2: TACTILITY AS A FUNCTION OF GRASP FORCE: THE EFFECTS OF GLOVE, HANDLE SIZE, ORIENTATION, AND LOAD

The objective of this experiment was to investigate the effects of glove, handle size, handle orientation, and load on grasp force. Visual cues were eliminated in the trials.

METHOD

A set-up similar to that of experiment 1 was used here, but with a few exceptions. Because pressure was not found to be a significant independent variable in the previous experiment, this study was performed outside the glove box in 0 psid conditions. In addition, it was hypothesized that a possible reason for the lack of glove and pressure effects found in experiment 1 could have been the visual cue. Therefore trials were held without a visual cue. A divider, which separated the subjects from the grasp load measuring apparatus, was fabricated. The subjects lifted and held the load on the other side of a divider, outside the glove box. The divider was positioned in between the body and right arm of the subject, and in no way altered the subject's grasping ability. As the grab bars in the Shuttle payload bay area are elliptical in cross section, it was of interest to determine if the grasp forces depended on holding orientation. Therefore two orientations of the handle were studied this time, both lateral and transverse (shown in figure 9), as opposed to only the lateral orientation used in the first experiment. To add more diversity in the type of gloves, a pair of common industrial gloves (henceforth called meat packing gloves) was added to the two types of gloves used in experiment 1. The meat packing and EVA gloves are totally different in material, construction, and design. The meat packing glove has a much more slippery surface than the rubber-coated surface of the EVA gloves, and therefore may require more force from the hand. The effects of handle size was also an added independent variable. The dynamometer having a handle size identical to the shuttle EVA handrail was kept, and the larger bar (as shown in figure 1) was added.

In summary, the independent factors of the experiment were four levels of gloves as shown in figure 5 (advanced, shuttle, meat packing and bare hand), three levels of load (5, 10, and 15 lb), two levels of orientation (transverse and lateral), and two levels of size (small, being identical to the EVA bar, and large, having one inch added to the long axis of the cross-section). There were 48 conditions in all, and 10 subjects (5 males and 5 females) participated in this experiment. The order of presentation was randomized across each subject.

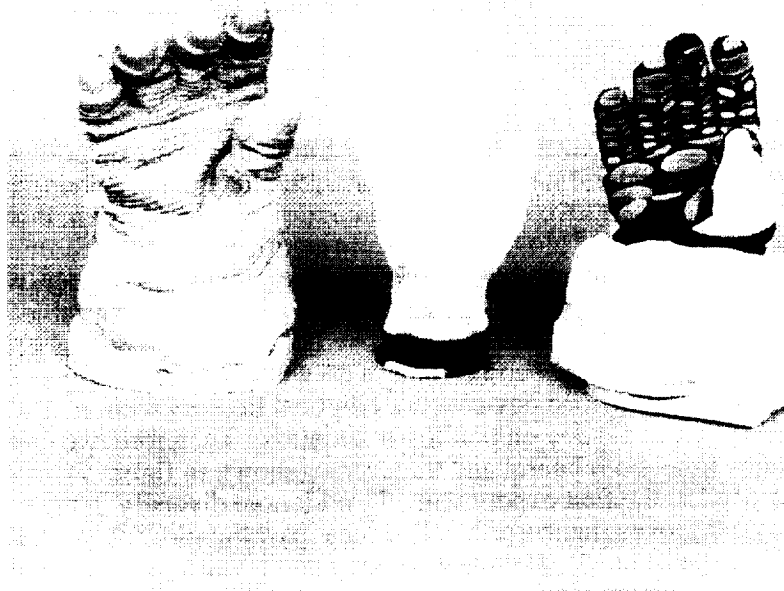


Figure 5. Gloves used in this experiment.

The trials were performed on two separate days. On day one 24 trials were performed with three minutes of rest between trials. These trials started with the placement of the grip device and adjustment of the arm support so that the subject felt comfortable. The treatment condition was determined from the randomized order. The subject donned the glove for that condition, and grasped and held the load for 20 seconds per that condition. The device was released as gradually as possible, so that it would slowly slip through the subject's hands. The grasp force was recorded continuously recorded through the ARIEL data recording system. From this data the stable force, peak force, and the ratio of peak to stable force were calculated and used as dependent measures in analyses.

RESULTS

Peak force, stable force, and the ratio of peak to stable force were the main dependent variables. An ANOVA was performed on the data and a summary follows in table 3.

Table 3. ANOVA Summary of Stable Grasp Data From Experiment 2

Independent Variables	Dependent Variables		
	Peak	Stable	Peak/Stable
Glove	***	***	*
Handle	*	*	NS
Orientation	***	***	NS
Load	***	***	***
Gender	***	NS	**
Glove*Handle	NS	NS	NS
Glove*Orientation	NS	*	NS
Glove*Load	*	***	NS
Handle*Orientation	NS	NS	NS
Handle*Load	NS	NS	NS
Orientation*Load	NS	NS	NS
Glove*Gender	NS	NS	NS
Handle*Gender	*	NS	NS
Orientation*Gender	NS	NS	NS
Load*Gender	NS	*	**

*** = $p < 0.0001$, ** = $p < 0.001$, * = $p < 0.01$, NS = not significant

All the main factors, namely glove, handle size, handle orientation, load, and gender were significant. Figure 6 shows the plot of the glove effect on the dependent measures. The meat packing glove appears to need large amounts of peak and stable grasp force. This could possibly be due to its low coefficient of friction. Range tests indicate that meat packing gloves are different from bare-handed and advanced gloves, which in turn are different from the shuttle glove for peak grasp force. Similar results were obtained on the range test for mean stable force. Figure 7 shows that the smaller of the two handles required slightly less peak and stable forces than the larger of the two, while the difference in ratios was insignificant. However, the orientation effect shown in figure 8 is surprising, with the lateral orientation of the handle requiring a significantly larger amount of force than the transverse orientation. The load effect seen in this experiment (figure 9) is similar to that of experiment 1 (see figure 4), with increasing grasp force for increasing loads. Again, the ratio of peak to stable grasp force decreases with increasing loads. Figure 10 shows a plot of the gender effect. The gender effects of the two experiments were also very similar (see figure 3).

Among the interactions, glove*orientation, glove*load, handle*gender, and load*gender showed significance for at least one of the dependent variables. Figure 11 shows the glove*orientation interaction for the peak grasp force. It is seen that the difference between lateral and transverse orientations is less pronounced for bare-handed and advanced glove conditions, compared to the other two conditions. Figure 12, which shows the glove*orientation interaction for stable grasp force, is very similar to figure 11. Figures 13 and 14 show the glove*load interaction on peak and stable grasp force, respectively. It appears that the glove effects are more pronounced at larger loads. The handle*gender interaction, as seen in figure 15, shows that handle size did not seem to affect the female subjects' peak force, while the male subjects exhibited a higher peak force on the large handle than on the small handle. Figure 16 shows the load*gender interaction. It is apparent that the females tended to use less grip force to hold the same amount of weight than the males.

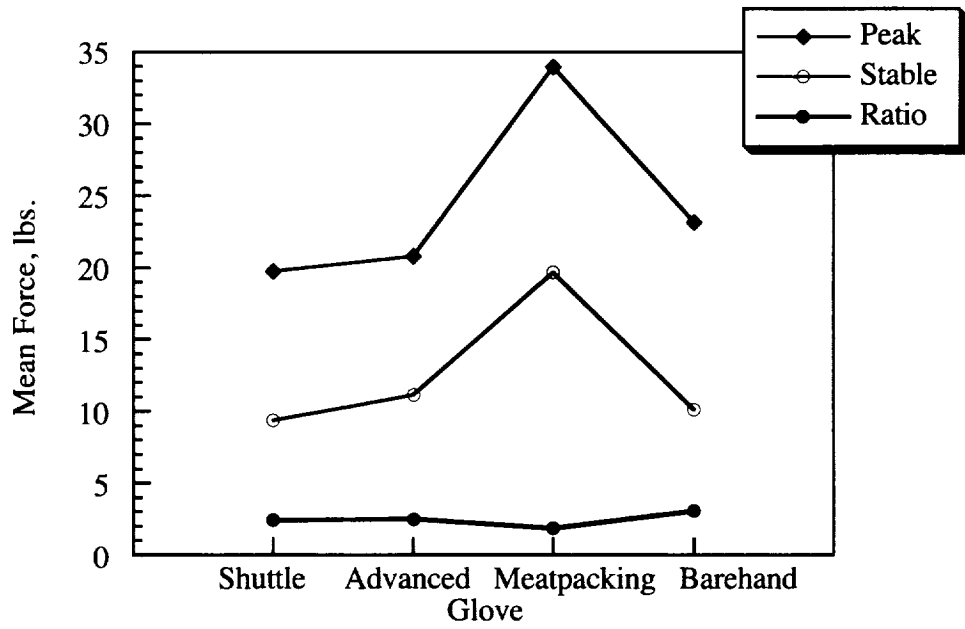


Figure 6. Glove effect on mean grasp force.

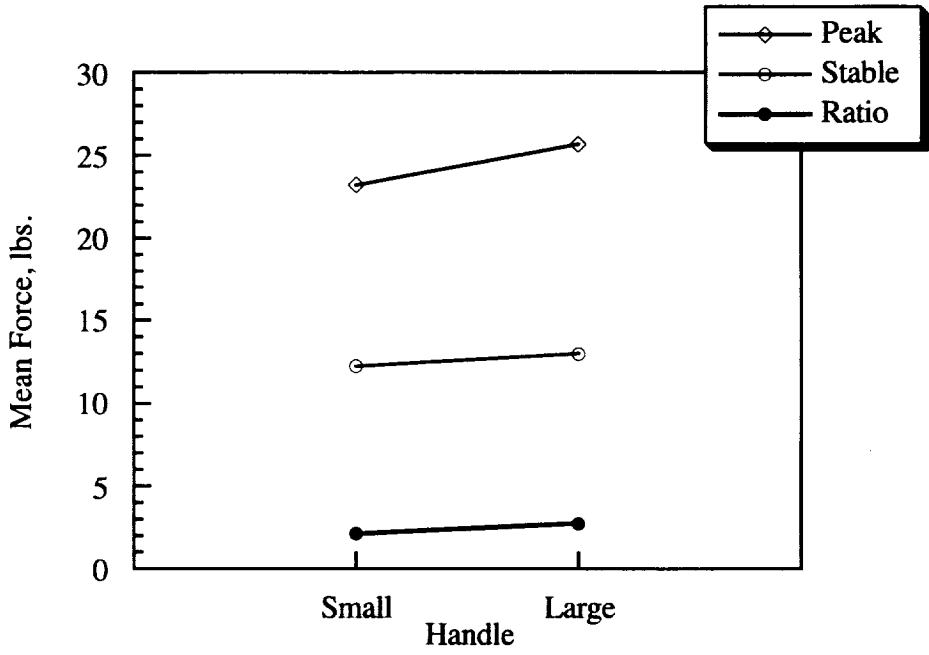


Figure 7. Handle size effect on mean grasp force.

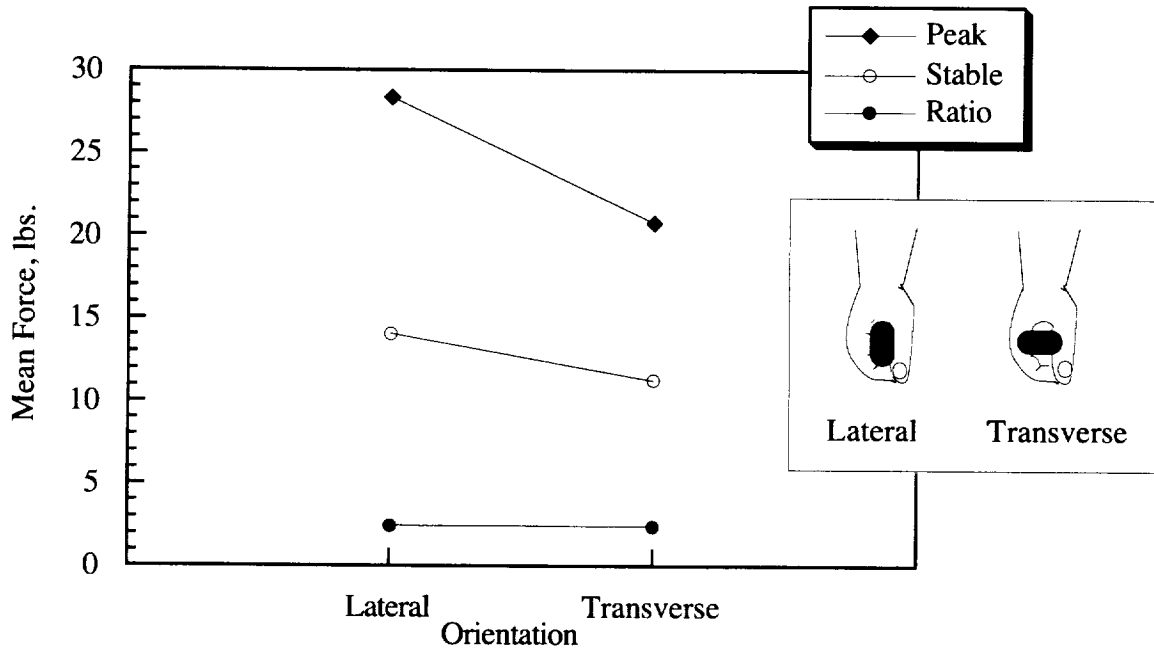


Figure 8. Handle orientation effect on mean grasp force.

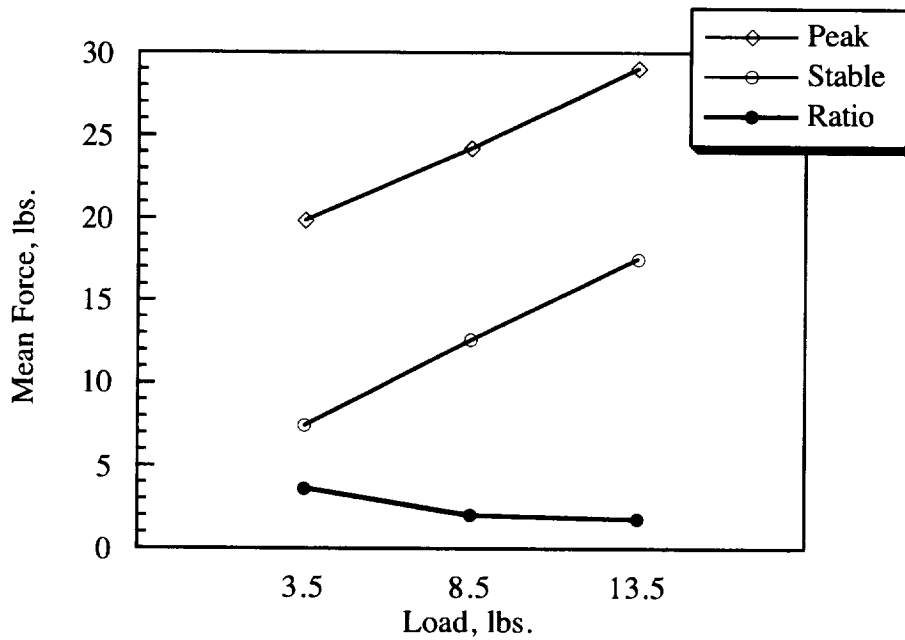


Figure 9. Load effect on mean grasp force.

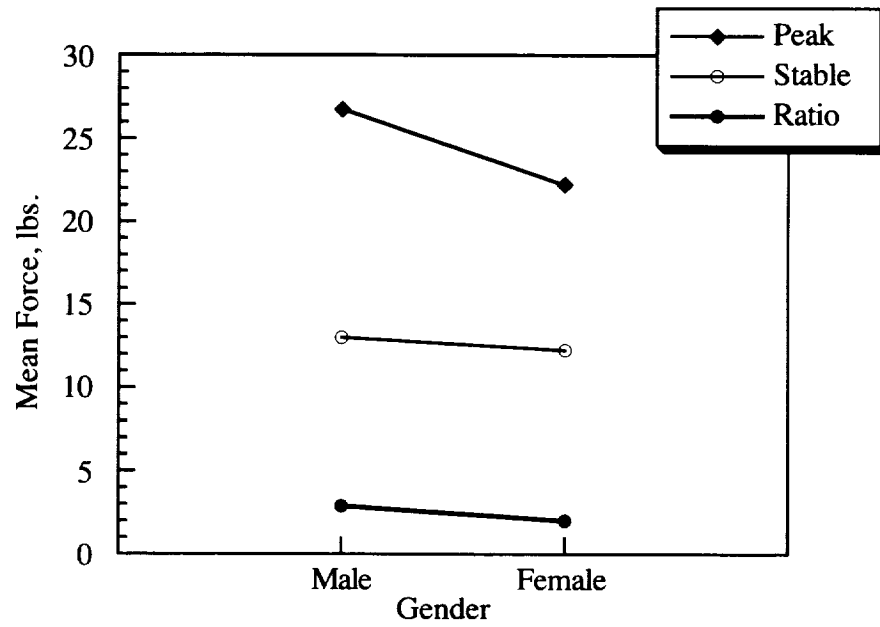


Figure 10. Gender effect on mean grasp force.

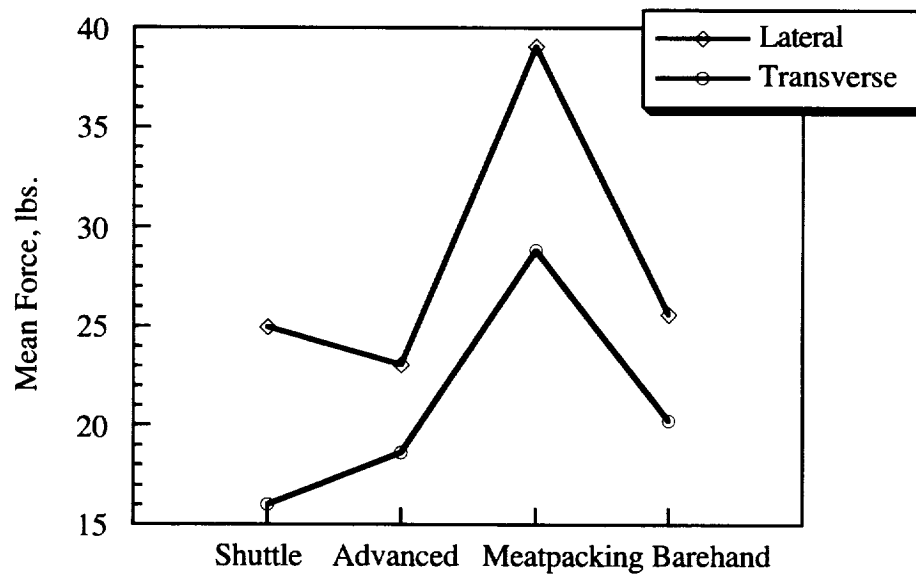


Figure 11. Glove*orientation interaction for the peak force.

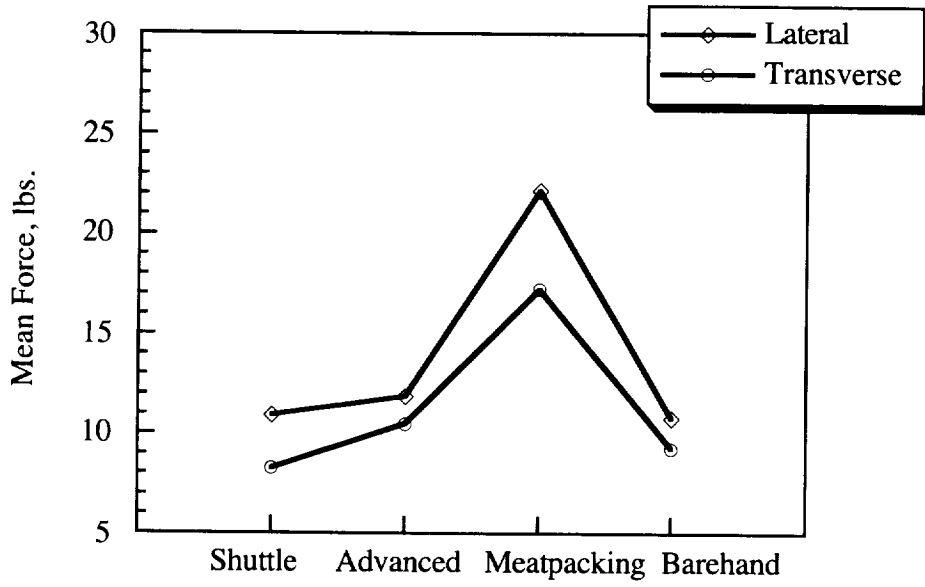


Figure 12. Glove*orientation interaction for the stable force.

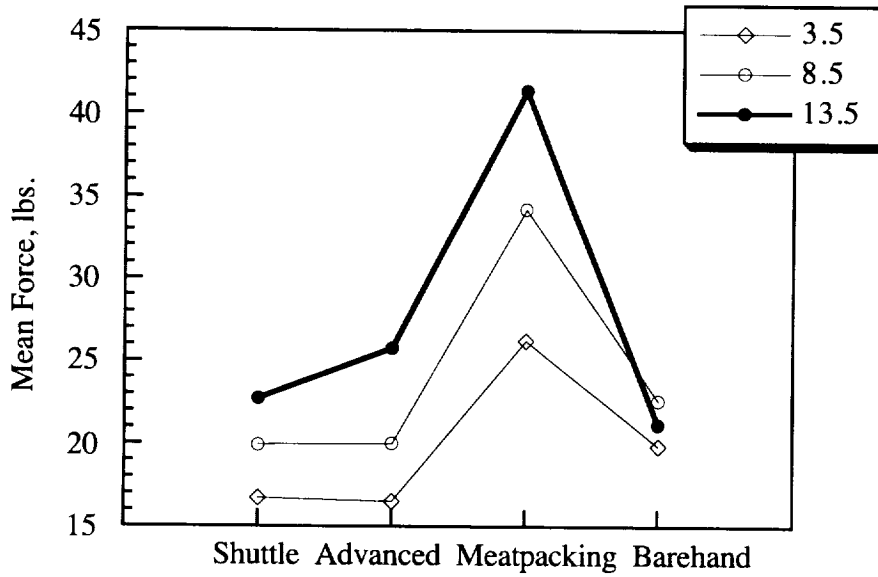


Figure 13. Glove*load interaction for the peak force.

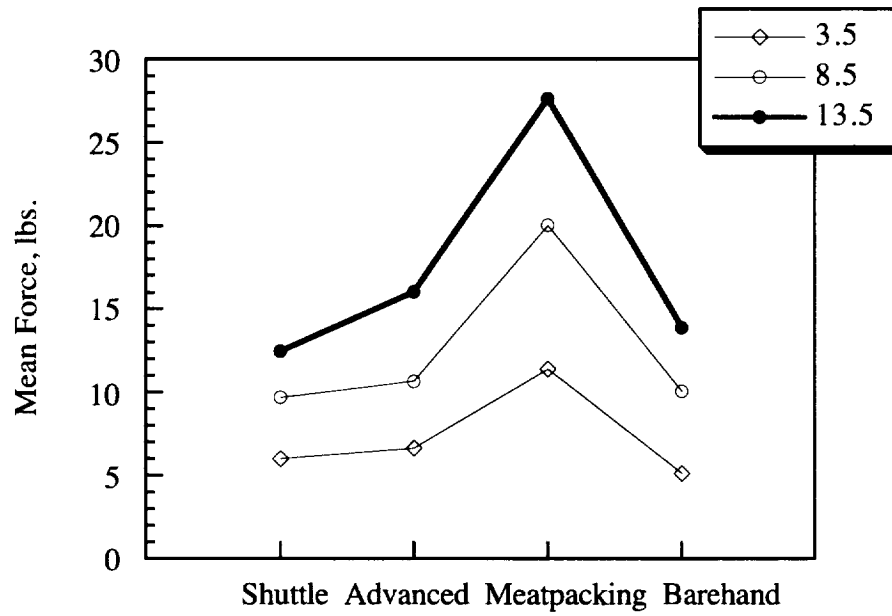


Figure 14. Glove*load interaction for the stable force.

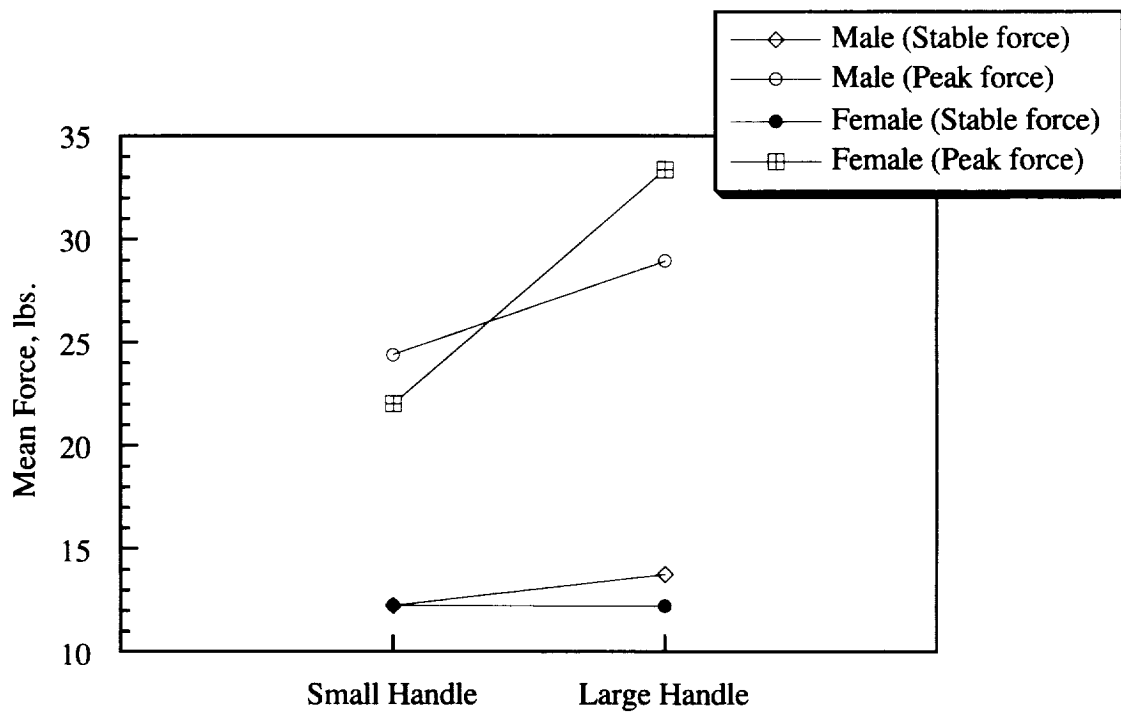


Figure 15. Handle*gender interaction.

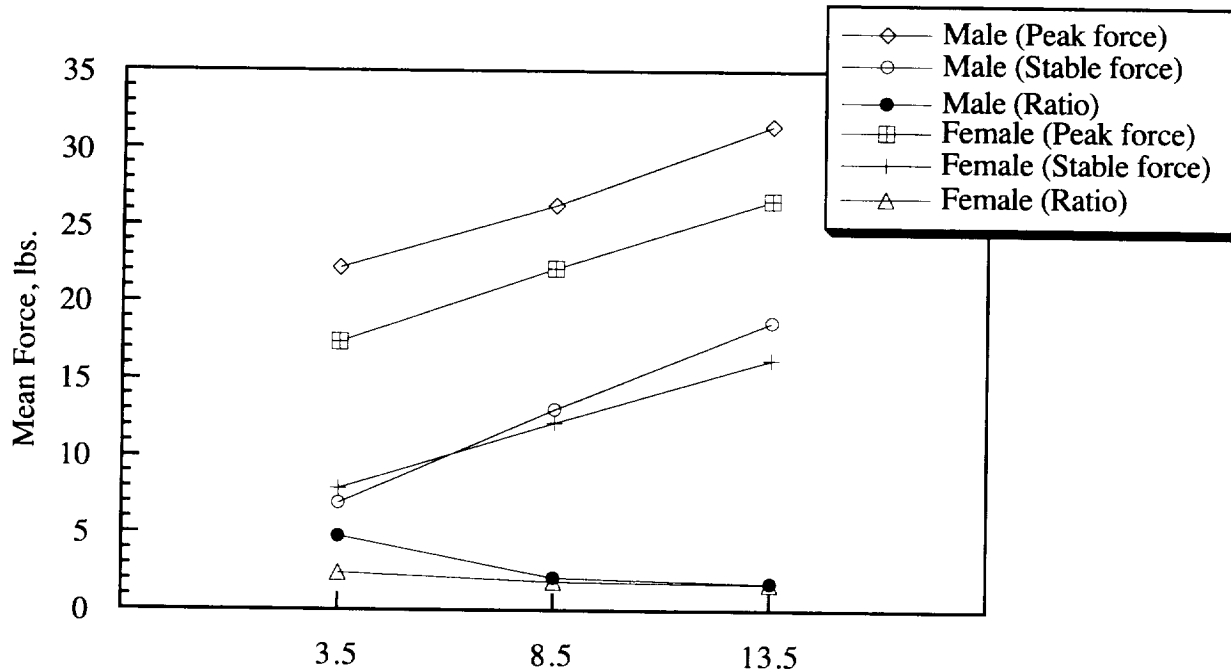


Figure 16. Load*gender interaction.

DISCUSSION

Generally speaking, the results of this experiment were consistent with that of experiment 1. Meat packing gloves stood out to be different from the rest of the glove conditions, which were similar. The difference among the gloves were consistent in both stable grasp as well as in peak grasp force. The load effect on peak and stable force seen in this experiment is similar to that seen in the first experiment, and is consistent with what was expected before the experiment. The decreasing ratio of peak to stable force with an increasing load found by both tests is an interesting effect and, as mentioned earlier in this report, can have far-reaching implications. The gender effect observed in this experiment is also similar to the effect found in experiment one, with the females exerting lower peak and stable grasp forces.

This experiment did find a glove effect, however, while the previous study did not. As expected, the addition of the meat packing glove in this study showed that the coefficient of friction of a glove can greatly affect holding an object. Handle size effect was not noticeable while lateral orientation registered lower grasp forces. Handle size and handle orientation alter the biomechanics of hand-handle coupling, and hence were expected to influence grasp forces. It is possible that the change in biomechanics of such a coupling was inadequate for handle size. In summary this experiment has shown that:

- Presence or absence of visual cue did not matter in the force exertions.
- The magnitude of force exertions in the advanced glove and bare handed conditions were similar.
- The magnitude of force exertion was the highest with meat packing gloves.
- The ratio of peak to stable grasp force increased with increasing loads.

What do all these mean for the practitioner? It is clear from both experiments that meat packing gloves are different from other gloves tested which are similar to bare handed-conditions. This observation, taken together with the fact that there exists overwhelming evidence on reduction of strength performance when gloves are donned (see, for example, Bishu and Klute 1993, O'Hara et al., 1988), can imply that glove effects are not uniform in the range of level of exertions. In other words it is possible that gloves reduce maximal exertions, while not influencing submaximal exertions. The last experiment in this series was performed to verify this construct.

EXPERIMENT 3: MAXIMAL EXERTION AS A FUNCTION OF GLOVE AND HANDLE SIZE

Earlier experiments raised more questions than answers on the issue of using grasp force as a measure of tactile sensitivity. Lack of glove effect could mean that either the gloves tested here were very similar, or some other issue, as yet undetermined, was causing the observed results. It is possible that gloves, while deterring maximal exertions, were facilitating grasping under submaximal conditions. To investigate this, a third experiment was run in which the subjects' maximal exertion was measured under various glove conditions of experiment 2.

METHOD

The same subjects who participated in experiment 2 (5 males and 5 females) performed maximum hand grasps on both dynamometers, laterally, in each of the gloved conditions, for a total of 8 exertions each. These exertions were performed according to the Caldwell regimen, and two minutes of rest time between each exertion was allowed (Caldwell et al., 1974).

RESULTS

An ANOVA was performed on the maximum exertion data, the results of which appear in table 4.

Table 4. ANOVA Summary of Maximum Grasp Data From Experiment 2

Dependent Variable	Gender	Glove	Handle	Gender * Glove	Gender * Handle	Glove * Handle
Maximum Force	***	***	NS	NS	NS	NS

*** = $p < 0.0001$, ** = $p < 0.001$, * = $p < 0.01$, NS = not significant

The significant main factors were gender and glove. Females on the average exerted approximately 59% that of males as shown in figure 17. Figure 18 shows the effect of gloves on the maximum grip strength. When compared to a bare-handed condition, the advanced glove reduced grip strength the most at 59.4%. The shuttle glove followed with a 66.3% reduction, and the meat packing glove showed the smallest reduction at 89.9% of bare-handed grip strength. A range test showed the meat packing and bare-handed conditions to be in one group, while the shuttle and advanced gloves were in another group. None of the interactions showed significance.

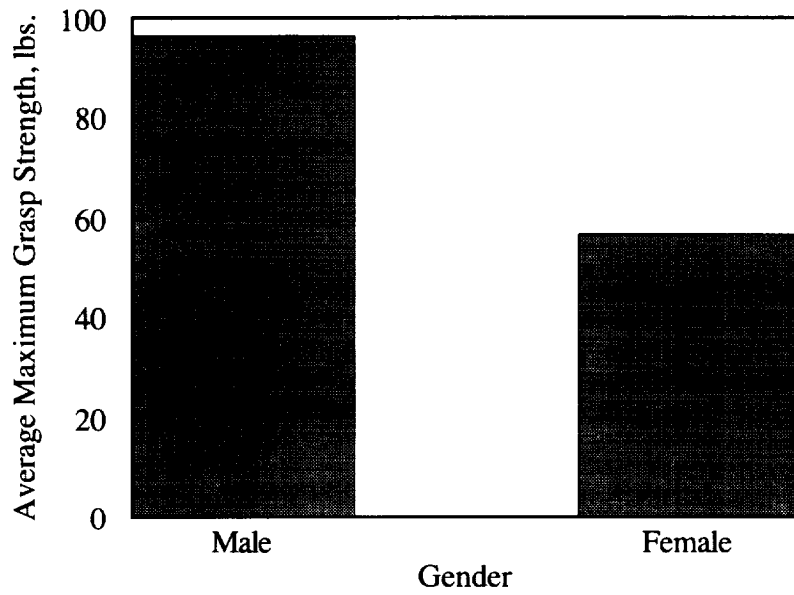


Figure 17. Gender effect on maximum grasp strength.

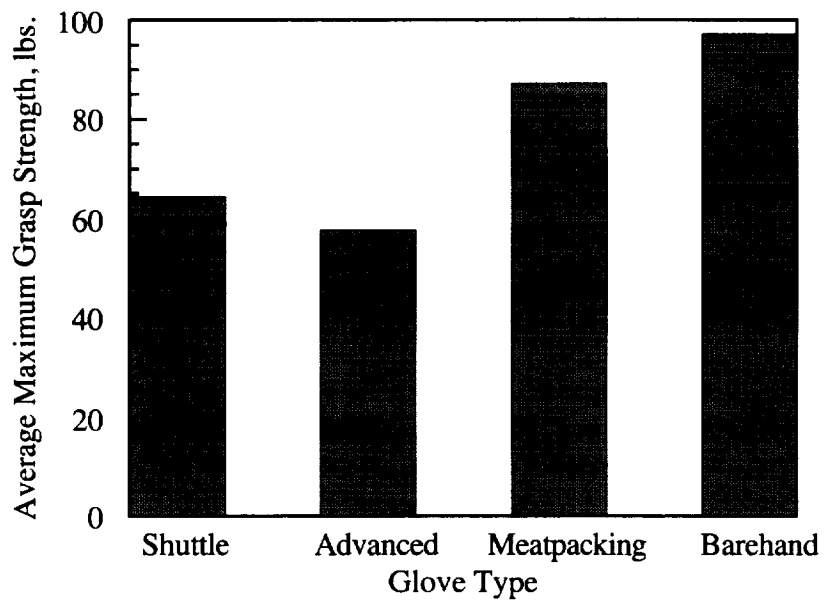


Figure 18. Glove effect on maximum grasp strength.

OVERALL DISCUSSION

The objectives of this research were to ensure that a reduction in tactile sensitivity was in fact causing a reduction in gloved performance, and to measure this reduction in tactile sensitivity through grasp force at the hand-handle interface under a variety of performance conditions. It was hypothesized that grasp strength could represent a measure of tactile sensitivity. The logic behind this was that grasping force for a certain load will be a function of the weight to be lifted and the hand conditions. The differences in grasping force for various hand conditions will then be a correlate of the tactile sensitivity of the corresponding hand conditions. It was further reasoned that when a person grasps an object, a firm grasp is made initially followed by a slow release to reach an effort that would just hold the object. Humans, being natural optimizers, would always try to hold an object with as minimal effort an effort as possible. This minimal effort for each glove condition would be a correlate of the tactile feedback that the person receives while holding the object under that glove condition. Therefore the initial firm grasp force, the following minimal grasp force, and their ratio would represent the amount of tactile adjustment that is made when picking up an object, and this adjustment should vary with the use of gloves.

How do the results reflect the above-mentioned premises? The most consistent findings across the three experiments are:

- There is no pressure effect, and glove effect is marginal at submaximal exertions.
- Presence or absence of visual cue did not matter in the force exertions.
- The magnitude of force exertions in the advanced glove and bare-handed conditions were similar.
- The magnitude of force exertion was the highest with meat packing gloves.
- The ratio of peak to stable grasp force increased with increasing loads.
- The glove effect for maximal exertions as seen in experiment 3 is consistent with published evidence.

It seems that the glove effects are different at different levels of exertions. Under maximal exertion, the effects found in these experiments are consistent with published evidence. It is possible that the reasons provided in the literature for reduction in strength performance with gloves, namely reduction in inter-digit distances, reduction in range of motion, etc., are possibly accounting for results presented in figure 18. However, judging from figure 6 it is evident that friction at the glove-handle interface impacts the grasping force. This is seen by the reduced grasp force with the advanced and shuttle gloves, two gloves which have a large amount of friction. The indications are that the shuttle and advanced gloves have frictional characteristics similar to that of a bare hand, while the meat packing gloves appear to be different. When comparing the maximal exertion data and the stable grasp data for both males and females, the graphs look very similar. That is, males consistently grasp with more force than females, whether it be a maximal effort or just holding an object. However, when comparing a stable grasp with a maximal effort, the females' stable grasp was, on the average, 21.5% of their MVC, while the males' stable grasp was an average of 13.5% of their MVC. Therefore, while the female subjects used less force than the male subjects, they still used a larger percentage of their maximum capacity.

In conclusion, it is clear from these experiments that when people go through a grasping action, the neuro-muscular control mechanisms that go toward maximal exertions are different from those during sub-maximal or just holding type of exertions. An important question is when a person holds a 5-lb object with a number of different gloves, for example, are the exertion levels of the lower arm musculature the same? This issue was not investigated here and the answer to this question may hold the key to a better understanding of glove effects.

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13. ABSTRACT (<i>Maximum 200 words</i>) One of the reasons for reduction in performance when gloves are donned is the lack of tactile sensitivity. It was argued that grasping force for a weight to be grasped will be a function of the weight to be lifted and the hand conditions. It was further reasoned that the differences in grasping force for various hand conditions will be a correlate of the tactile sensitivity of the corresponding hand conditions. The objective of this experiment, therefore, was to determine the effects of glove type, pressure, and weight of load on the initial grasping force and stable grasping force. It was hypothesized that when a person grasps an object, he/she grasps very firmly initially and then releases the grasp slightly after realizing what force is needed to maintain a steady grasp. This would seem to be particularly true when a person is wearing a glove and has lost some tactile sensitivity and force feedback during the grasp. Therefore, the ratio of initial force and stable force and the stable force itself would represent the amount of tactile adjustment that is made when picking up an object, and this adjustment should vary with the use of gloves. A dynamometer was fabricated to measure the grasping force; the tests were performed inside a glove box. Four female and four male subjects participated in the study, which measured with four variables: load effect, gender effect, glove type, and pressure variance. The only significant effects on the peak and stable force were caused by gender and the weight of the load lifted. Neither gloves nor pressure altered these forces when compared to a bare-handed condition, as was suspected before the test. It is possible that gloves facilitate in holding due to coefficient of friction while they deter in peak grasp strength.				
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