ARMY RESEARCH LABORATORY

Gloved Operator Performance Study
The Effects of Hand Wear and Elastic Resistance of a Control During Tracking Performance

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This study was to test the effects of wearing gloves during tracking performance at different levels of elastic resistance in a control. Forty-eight undergraduate students served as subjects. Each group contained 16 subjects, one group for each level of control resistance. The control was a spring-centered displacement joystick with resistance settings of 0, 12 and 17 oz. All subjects performed a compensatory tracking task both bare-handed and while wearing a leather and wool glove assembly. Results indicated that (a) wearing gloves is detrimental to tracking performance for female subjects, (b) female subjects do not benefit from additional exposure to the task before performing the task with gloves as do male subjects, (c) high control resistance may have been beneficial for female subjects during the gloved condition, and (d) small handed female subjects do not perform as well as medium and large handed female subjects, nor as well as male subjects.

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U.S. Army Research Laboratory
Human Research and Engineering Directorate
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CONTENTS

TABLES

FIGURES

The Effects of Hand Wear and Elastic Resistance of a Control During Tracking Performance

INTRODUCTION

The effect of wearing gloves during control operation is complex because the effect varies by (a) the control type, (b) the glove characteristics, and (c) the control operating characteristics; other authors agree with this assertion (Bradley, 1969a; McGinnis, Bensel, & Lockhart, 1973; Boff & Lincoln, 1988). Even though previous research in this area offers little information specifically about tracking, some effects of gloves during control operation have been determined (Berkhout, Anderson, McCleerey, & Granaas, 1992).

Tracking

People use tracking in various ways. Moving one's eyes or head to follow a flying insect across a room is a tracking task; a pilot who struggles to retain control of an airplane flying through turbulence is engaged in tracking; and a driver on a relaxing ride down a curving or straight road is engaged in tracking. Poulton (1974) asserts that people track when they speak in an unfamiliar foreign language. They must listen to their own voice while speaking, and use auditory feedback to make corrections.

Since tracking includes such a wide range of behaviors, a short, yet inclusive definition is difficult. Although Adams (1961) provides a definition for tracking that is several hundred words in length, Sanders and McCormick (1987) assert that the basic requirement for a tracking task is to execute correct movements at correct times. While this definition may have problems, it will suffice. Keep in mind that people must use feedback to execute the correct movements at the correct times.

Control Order

Control order specifies the way a system responds to inputs provided through the control. Generally, the higher the order of control, the more adjustments the operator must make to achieve the desired response. Zero-order control is position control. In the case of a cursor being moved with inputs from a joystick, the cursor moves while the joystick does and stops moving when the joystick stops. The cursor remains in that position as long as the joystick remains in its corresponding position. A direct relationship exists between the control movement and the display movement (Poulton, 1974). If the joystick centers when it is released, the cursor moves to the center of the display.

First order control is velocity control. When a joystick is deflected in a given direction, the cursor moves in the corresponding direction at a rate which is determined by the degree of joystick deflection. If the joystick is deflected a certain degree and held there, the cursor will continue to move at a constant velocity determined by the joystick position (as far as the display allows). If the joystick is recentered, the cursor will remain at the position of the last control input.

Second order control is acceleration control. When the joystick is deflected a certain degree and held there, the cursor accelerates at a constant acceleration. If the joystick is recentered, the cursor continues to move at the velocity it had achieved before the control input was neutralized.

Higher order control exists when control inputs are further removed from the actual system responses. In steering a large ship, there are linkages and time delays from the actual control movement until the system responds. The exact order of a higher order system is often debatable. Depending on what is included in the determination and definitions used, steering a ship could be considered a third, fourth, or even higher order control.

Control Gain

Control gain refers to the relationship between the magnitude of the control input and the magnitude of the cursor movement. It is usually expressed in the control/display (C/D) ratio, the ratio of the movement of the control to the movement of the cursor on the display. For example, if a joystick deflection of 10^{o} moving a cursor 100 mm were considered to be a C/D ratio of 1, then a deflection of 10^{o} moving the cursor 200 mm would be considered a C/D ratio of .50. It might also be a ratio of 2 if it were thought of as the ratio of the amount of cursor movement to the amount of control movement, which is often the case.

Control gain is also referred to as the sensitivity of the control. If a large amount of display movement resulted from a small control movement, the system would be very sensitive. A system is too sensitive when the slightest movements from a hand disrupt the task because limbs are not totally controlled by the operator. If the operator becomes fatigued by applying great control inputs to create small display movements, then the system is not sensitive enough.

Tracking Tasks

A forcing function is the track that an operator must follow during tracking. For a joystick and cursor application, the forcing function moves the cursor. The response function is the actual input that is delivered from the control, and the response function corresponds to what the operator intends to have the control do. The user may intend to make minute adjustments with the control, but if there is considerable dead space in the control, these minute responses will not be part of the response function. Dead space is area that may exist around the neutral position of the control which must be passed before the control sends actual signals to the system. Dead space occurs when there is a lot of "play" in an automotive steering wheel. The difference between the forcing function and the response function is the error function; therefore, the error function is the difference between the ideal response and how the operator actually responds.

There are different types of forcing functions. Three typical ones are step, ramp, and sine wave functions. Sanders and McCormick (1987) describe a step track as a discrete change in value. If a target appears on the screen and the operator responds by applying control movements to move the cursor to the target, the operator will be responding to a step track. The track can continue with another target appearing in a different part of the screen. The operator can make another discrete control movement to move the cursor to the target again. Stedman (1984) provides an example of a real world step function track. On radar displays, locations of tracked objects are periodically updated. At one moment, the object will be in one spot, and when the screen is updated, the object will suddenly reappear at a different position. If the operator responds by reacquiring the "blip" that represents the object (moving a response marker to cover it), the operator follows a step track.

A ramp function challenges the operator to match a constant rate of change, such as velocity (Sanders and McCormick, 1987). If a stationary target begins moving across the screen at a constant rate and the operator is required to match the velocity of the target with the cursor, the operator will be responding to a ramp track. When a patrol officer leaves a hiding place to catch a speeder, the officer responds to a ramp track in catching the speeder and matching velocity.

Combining sinusoidal waves can allow modeling of many real world tracking situations. Sine waves can represent repetitive occurrences. An automobile zigzagging around a row of pylons can be represented on a computer screen with a target moving back and forth horizontally at a certain rate. The amplitude at which the target moves back and forth can represent how wide a turn the car makes as it goes around the pylons. The frequency with which the cursor moves back and forth can represent the speed of the car. The sine wave track on the screen will be very predictable. To represent more complex and less predictable events, such as the buffeting that air pockets might cause in the flight path of an airplane, two or more sine waves can be combined to create the target disturbance on the screen.

Responses to the step task would be an example of a discrete tracking task. The operator moves the cursor to the target and the task stops until another target appears. Continuous tracking involves constant input by the operator. Continuous tracking tasks are typically either pursuit or compensatory. In a pursuit task, the operator views two objects: One is a continually moving target, and the other is the object that the operator controls or a representation of that object. When operating a joystick with feedback on a screen, the operator attempts to keep the cursor superimposed over the target. The operator "pursues" the target. Keeping a spotlight on an actor on stage is an example of pursuit tracking (Poulton, 1974).

In a compensatory tracking task, a target cursor moves continuously as directed by the forcing function. The operator can also exert influence over the target and direct it to some location, usually in the middle of the screen in the paradigm of interest for this study. The movement of the target is, therefore, a result of both the forcing function and the response function. The operator "compensates" for the distance between the target and the area in which the operator would like to keep the target. Keeping a stationary sensory array or gun sites aimed at a moving vehicle is an example of a compensatory tracking task.

Control Resistance

Forces within the control that oppose forces applied by a human are known together as control resistance. There can be four different types of resistance in a control: friction, elastic resistance, viscous damping, and inertial resistance. Friction is resistance caused by two surfaces rubbing against each other. Friction can be useful in keeping a control in the same position when the operator releases it; however, friction itself generally offers the operator no feedback about control movement except that the operator is, in fact, applying force. Friction is often difficult to measure when other types of resistance are at work, and attempts are usually made to decrease frictional resistance in a control. Lower friction allows smoother movement so that other types of resistance can be sensed by the user.

Elastic resistance (elasticity) or spring-loading is the conspicuous resistance in a spring-centered control. The resistance increases as the control actuation increases. A constant force applied by an operator will move the control to a specific position at which the resistance of the spring will equal the force being applied by the operator. The operator receives proprioceptive feedback which results from activation of neural receptors within the muscles and joints of the hand, wrist, and arm. This allows the operator to associate the control position with the degree of force. Cutaneous feedback from the skin being compressed against the control can also be associated with control position.

Viscous damping is when a person must apply more force to move a control at a high velocity than at a low velocity. This allows the person to associate the application of a specific force with a specific rate of movement. A good example of viscous damping is the increased force needed for a person to run in water as opposed to running the same speed on land. The water offers more resistance to the leg's movement than does the air. The water also offers more resistance to a leg moving quickly than to a leg moving slowly. There are other forms of resistance at work, but the increased difficulty of running in water is primarily because of viscous damping.

Inertial resistance is caused by objects at rest staying at rest and objects in motion staying in motion. As the mass of an object increases, inertial resistance increases. For example, a heavy joystick will require a certain force from the operator to get it moving. The acceleration of the movement will depend on the force applied by the operator and on the mass of the control. This resistance allows operators to associate particular forces that they apply with particular changes in rate of movement (acceleration) of the control.

The various types of resistance often interact with each other, so it may be difficult to identify which type of resistance is causing the performance effects. For example, increasing inertia by increasing the mass of a control will usually increase friction between various moving components within a control. This study will focus on elastic resistance.

The unit of measure for elastic resistance is often torque. To determine torque, the amount of force needed to move the control is multiplied by the distance from the axis of rotation at which the force measure was taken. Torque is expressed in terms such as meter-kilograms, inch-ounces, and foot-pounds. Sometimes, torque is expressed as the amount of torque required to move a control 1° (foot-pounds/degree). Some authors only report the force required to move the control to the maximum deflection, and express the force in pounds or kilograms. Others report the force needed per degree (e.g., pounds/degree) as opposed to a unit of torque per degree.

Bahrick, Fitts, and Schneider (1955) used an apparatus that illustrates how elasticity, viscosity, and inertia were varied in a joystick. The authors used springs of varying tension to adjust elasticity. Viscous damping was produced by attaching a drum to the opposite end of the joystick away from the subject and submerging the drum in water. The larger the diameter of the attached drum, the greater the damping effect. Inertia was varied by attaching different weights to the lower part of the joystick above the drum.

Howland and Noble (1953) required subjects to perform a one-dimensional tracking task. Subjects received visual feedback from a screen, but they could not see their hands on the rotary control. Subjects had to rely on proprioceptive feedback (and feedback from the screen) to determine control amplitude. During these conditions, spring-loading of 0.34 in-oz/degree allowed better performance than no spring-loading.

After practicing with visual feedback, Bahrick, Fitts, and Schneider (1955) required subjects to reproduce triangular and circular patterns with a joystick with no visual feedback. Subjects were instructed to reproduce the patterns with the same timing and spacial accuracy as was performed in practice. The largest spring-loading constant allowed the smallest spacial error in reproduction of the triangle and the circle, but the overall results for spring-loading were inconclusive. Greater spring-loading also caused more temporal variability. The values for elastic resistance were 40, 80, and 160 in-oz/degree.

Bahrick, Bennett, and Fitts (1955) required subjects to move a lever a specified number of degrees without visual feedback. The elbow was fixed at the point of rotation of the lever with the hand at the movable end. With extended practice and knowledge of results, spring-loading improved tracking performance. If subjects had received continuous, instantaneous visual feedback, control resistance feedback may not have improved tasking performance.

Bahrick, Bennett, and Fitts (1955) found that elastic resistance performance improved as the ratio of change in resistance to change in distance of control deflection increased. The ratio is expressed in the following equation.

delta-F / F (delta-D)

F is the force needed to achieve a particular displacement. Delta-F is the force change associated with a given displacement, delta-D. In other words, for a given degree of deflection, a large change in elastic resistance across the deflection is best. The authors concluded that besides the ratio for relative torque change per unit of distance, the absolute force required to move a spring-loaded control to a given position affected performance, with higher absolute force, allowing better performance. Bahrick, Bennett, and Fitts (1955) also stated that a high ratio was more helpful for smaller deflections than for larger amplitude deflections. In this study, subjects moved the control 17.5°, 35°, and 70°. Some of the torque (elastic resistance) changes across movements were 0-50, 0-100, 0-200, 25-50, 50-100, and 100-200 in-lb. The lowest torque per degree was 5.7 in-oz/degree.

The generalization of the task performed in Bahrick, Bennett, and Fitts (1955) to other tasks in which subjects can observe visual feedback is by no means complete. The results only show that subjects can, in fact, make use of resistance feedback. With good visual feedback, proprioceptive feedback may not be as important. For circumstances in which visual feedback is disrupted or delayed, the study is more pertinent. During those circumstances, subjects would have had to rely more on proprioceptive and cutaneous feedback to help them apply forces that would achieve the desired responses.

Jenkins (1947) found that subjects were able to apply higher forces more consistently than lower forces in a range from 1 to 10 lb on a joystick. Once again, the task was performed with a blind fold. The author concluded that inconsistency in the lower pressure ranges was because of interference of the weight of the subject's arm.

Briggs, Fitts, and Bahrick (1957) required subjects to perform a compensatory tracking task during which the subjects had visual feedback and resistance feedback. Spring-loaded resistance and amplitude were investigated. The best performance was with high force and high amplitude.

Decreased elastic resistance hurt performance mildly, and decreased amplitude hurt performance more. A significant Force x Amplitude interaction again showed that the ratio for relative torque change per unit of distance was predictive of performance, but only within the same levels of delta-D (i.e., the ratio did not work across displacement values). The absolute resistance values in this study ranged from 3 to 10 lb.

Bahrick (1957) made some overall statements about the line of research on resistance of tracking controls. First, this line of research not only offered guidelines to control design but also provided information for the development of prosthetic devices. Second, this research provided information about the control of the physical properties of limbs by studying analogous characteristic of controls in which the properties can be adjusted.

Bahrick (1957) also made some conclusions about spring-loaded resistance in controls. He stated that positioning errors are smallest when the ratio of relative torque change to displacement is largest. During optimum conditions of spring-loading, average positioning errors can be reduced by 50% for a control which is not spring-loaded. Bahrick said that optimum results were obtained when a control provided geometric increases in force as a function of arithmetic changes in amplitude. (This gives the highest number of discriminable positions of displacement level.) He also said cutaneous feedback was probably unimportant for the range of forces and amplitudes of movements with which these studies dealt. Resistance values used in the current study were much smaller so cutaneous feedback may have been a factor. From a review of the literature, Glencross (1977) also concluded that increasing elastic resistance helps tracking performance.

Adams and Creamer (1962) explored the effects of proprioceptive feedback on anticipatory timing behavior in tracking. The authors used a repetitive step track which allowed subjects to learn patterns that could be anticipated. One of the variables manipulated was spring-loaded resistance. Three levels were employed: Zero loading, 1 lb of elastic resistance for small amplitude, and 4 lb of elastic resistance for large amplitude. The authors hypothesized that responses to stimuli which give regulatory proprioceptive stimulation (proprioceptive feedback which allows better performance) also leave a "timing-trace" in short term memory. This is used by the subject to anticipate motor movements that will be necessary. Results showed that subjects who operated with spring-loading showed better anticipatory timing.

Schmidt and Christina (1969) found more support for the hypothesis that proprioceptive feedback improves anticipatory responses, though they did not vary elastic resistance. The authors stated, however, that anticipatory improvement may not have actually occurred. Subjects may simply have been responding to a more beneficial input situation. Regardless, Adams and Creamer (1962) still showed improved performance with spring-loaded resistance.

Weiss (1954, 1955) did not find any significant or consistent effects for varying control resistance in his experiments. In these studies, subjects performed a task in which they compensated for the displacement of a spot of light from the center of an oscilloscope screen. The spot of light flashed for a brief period of time, then disappeared. Subjects would then use a joystick to make a movement that they thought would bring the spot of light to the center of the screen. The spot would then reappear and remain visible for 2 s to give the subjects an opportunity to correct any position error. This task allowed the importance of proprioceptive feedback during a delayed visual feedback condition to be examined. Pressure ranges used in these experiments were from 0 lb to 6, 12, 18, 24, 30, 7.5, 15, and 30 lb. The lowest force-per-degree was 3.2 oz/degree.

Bahrick, Bennett, and Fitts (1955) suggested that the reason Weiss (1954) found no evidence of a resistance effect was that relative pressure change (relative to the degree of displacement) was not examined. Also, visual feedback regarding the extent of control movement was not present.

Most of the values for resistance cited above are greater than those that were examined in the current study. Howland and Noble (1953) examined a fairly light spring resistance, but they used a rotary handle, not a joystick. Most of the studies also used controls that required forces from the arm. The current study used a hand-operated joystick.

In the 1950's and 1960's, controls used in real world applications were usually mechanically connected directly to the devices that they controlled. Physical principles often demanded high actuation forces be applied through controls. Today, controls are often interfaced through computers which in turn send signals to mechanical devices which are powered by hydraulic systems. Often, energy to enable the system no longer comes from the operator. Any resistance to inputs by a person is artificial and is put there only to help the human control the mechanical devices better. Also, visual feedback to a person may be through a video screen with small dimensions. Large controls with high amplitudes of movement are often not necessary. It now makes sense to examine smaller forces and to see the effects of smaller values of resistance. Findings from previous studies may or may not apply.

Fellows and Freivalds (1991) found that rubber grips on tool handles caused subjects to apply greater grip forces. The same effect might apply to tracking while wearing gloves since the glove material between the hand and the control could act in the same way as a rubber grip. In that study, the rubber grips acted as cushions, distributing the applied force more evenly over the handle.

If wearing gloves while tracking caused a distribution of the force applied to a joystick, there might be a tendency for the glove to absorb some higher frequency responses applied by the operator. Also, if subjects applied a stronger grip to the joystick as they did to the tool handles, adjustments of the control, particularly fine adjustments, might be affected.

Chase, Rapin, Gilden, Sutton, and Guilfoyle (1961) showed that decreased auditory feedback, decreased proprioceptive feedback (induced by applying vibration to the forearm), and a combination of these with decreased visual feedback, each caused impairment in a key-tapping task. The dependent variables were the degree to which subjects could tap at a specific rate, and tap with a specific amount of force. The task does not relate directly to tracking, but it shows the importance of proprioceptive feedback in a manual task.

Gloves and Tracking

In published literature, very little research exists that evaluates the effects of wearing gloves during tracking performance. No published studies have examined the possible interaction between wearing gloves and the level of elastic resistance of a control.

Taylor and Berman (1982a, 1982b) use a single axis compensatory tracking task as a secondary task to examine the effects of wearing gloves during keying performance. Wearing gloves did not affect the keying task; however, impairment of the tracking task, measured in the proportion of root mean squared error (RMS) during the dual task to RMS during the tracking task alone, was higher for several gloved conditions than for bare hands. Wearing cape leather gloves, winter leather gloves, and either of these gloves over neoprene gloves hindered performance. The neoprene inner glove worn alone did not impair performance. These results suggest that tenacity is more important than bulk and loss of dexterity during these conditions since the leather gloves alone caused as much impairment as the leather gloves over the neoprene gloves.

Berkhout, Anderson, McCleerey, and Granaas (1993) recently conducted a study to determine whether wearing gloves affected performance of a compensatory tracking task. Performance differences among four hand-wear conditions were small and nonsignificant. Means across hand-wear conditions for root mean squared error on the vertical axis (RMSV), horizontal axis (RMSH), and percent time-on-target (TOT), however, did vary in the predicted direction (see Table 1). The highest TOT and lowest RMS occurred during the bare-handed condition, indicating best performance. TOT decreased and RMS increased as thickness of the three glove types increased. The authors conclude that the degree of elastic resistance of the control may have been adequate to prevent any significant detriments to tracking performance while wearing gloves.

Table 1

Means (and Standard Deviations) for Percent TOT,
RMSV, and RMSH for Each Hand-Wear Condition

Hand wear	TOT (%)	RMSV	RMSH
Bare hand	35.7(10.6)	0.185(.038)	0.178(.040)
Butyl and cotton	35.2(9.4)	0.189(.039)	0.182(.038)
Butyl and nomex	34.2(10.4)	0.190(.039)	0.185(.044)
Leather and wool	33.7(9.1)	0.198(.062)	0.186(.055)

The joystick used in that study met all the requirements stated in the military standard (MIL-STD) 1472D. Simply meeting these standards for size, force, and movement dynamics may have been enough to prevent the occurrence of glove effects.

It is possible that the resistance of the joystick allowed enough proprioceptive and cutaneous feedback to prevent any serious detriment to performance that gloves might cause during those conditions. Performance with a joystick of lower resistance could be considerably worse if the lessened feedback associated with low resistance were coupled with lessened feedback associated with hand wear.

The full deflection resistance of the joystick used in the study (17 ounces) was greater than the minimum required by the MIL-STD-1472D (12 ounces). The authors suggest that a useful follow-up study could examine whether the MIL-STD minimum resistance is adequate for operators wearing heavy gloves.

This study was to test the effects of wearing gloves during tracking performance at different levels of elastic resistance of a joystick. It was hypothesized that (a) wearing gloves would be detrimental to tracking performance and (b) the detrimental glove effect would be greater for conditions of lower control resistance.

METHOD

Subjects

Forty-eight right-handed undergraduate psychology students (24 male and 24 female) from the University of South Dakota participated as subjects for extra credit points. Subjects were randomly assigned to one of three conditions of a between-subjects independent variable. All subjects were tested to ensure that they had 20/30 or better vision, corrected or uncorrected. That level of visual acuity was more than adequate to perceive the visual stimuli.

Three hand measurements were taken: hand girth, hand length (wrist to second digit), and third digit length using a procedure developed in a previous study (Berkhout, Anderson, McCleery, and Granaas, 1992). The three measures were used to assign subjects to the correct glove size as described in Berkhout, Anderson, McCleery, and Granaas.

A comparison between hand-girth measures of subjects in this study and hand-girth measures of Army soldiers in Gordon et al. (1989) is of interest for generalization of the results from this study. Table 2 presents percentile information and means for hand-girth measures from subjects in both studies. As shown in Table 2, subjects from the two studies match rather closely in hand-girth measures.

Female subjects were divided into three hand-size groups based on the girth measure taken to fit gloves: 180 mm and below were small, from 181 to 190 mm were medium, and 191 mm and above were large. There were 8 subjects in each group, and each group was balanced for hand-wear condition order.

Male subjects were also divided into three hand-size groups based on the girth measure taken to fit gloves: 209 mm or less was small, from 210 mm to 218 mm was medium, and 219 mm or more was large (1 subject with a girth of 210 mm was placed in the small group, and 1 subject with girth of 219 was placed in the medium group to allow equal group sizes). There were 8 subjects in each group, and each group was nearly balanced for order. The small group had one extra subject for the bare-glove (B-G) order condition, and the large group had one extra subject for the glove-bare (G-B) order condition.

Apparatus

Joystick

The control that was used to deliver zero-order control was an Advanced Gravis™ joystick, manufactured by Computer Tech. LTD., Burnaby, British Columbia, Canada. Poulton (1974) stated that a position control system (zero-order) is the most compatible with a sine wave track.

Table 2

Hand-Girth Measure Percentile Information and Means for Army Soldiers and for Subjects in This Study

Group	Mean (mm)	Percentile 25th (mm)	 50th (mm)	 75th (mm)
Army soldiers				
Male subjects	213.8	207.2	213.4	220.1
Female subjects	186.2	180.4	186.0	191.6
Students				
Male subjects	214.6	209.0	215.0	219.5
Female subjects	187.9	180.0	187.5	197.0

The displacement (isotonic) joystick was spring-centered, and its full deflection in each direction was 30°. MIL-STD-1472D allows a maximum deflection of 45°. There was more than adequate room around the stick for maximum deflection, and control gain was set at 40 mm for a full deflection of the joystick. This setting required subjects to deflect the joystick to nearly its full range.

Elastic resistance in the joystick increased as angular deflection increased. The joystick allowed three different levels of resistance to be set. Table 3 shows the values for elastic resistance at 10°, 20°, and 30° for each of the three different settings. Force required to reach the three deflection values varied slightly depending upon the direction of deflection; however, the values given in Table 3 are correct for all directions within 1 oz. The highest torque per degree was 3.9 in-oz/degree, and the highest absolute force was 18 oz. The joystick resistance values examined in this study were much smaller than those in any of the studies previously reviewed.

MIL-STD-1472D allows a range of joystick resistance from 12 oz to 32 oz. The zero resistance at the lowest level for this study did not satisfy these specifications, but the middle level satisfied the minimum requirement. The high setting was used in a previous study in which no glove effects were found (Berkhout, Anderson, McCleerey, & Granaas, 1993). This setting was used again in the current study because the track that subjects followed and the control order were different from the previous study.

The measures of elastic resistance included a small amount of friction which was not measured separately. Since the control was lightweight plastic, there was negligible inertial resistance and negligible viscous damping in the control.

Table 3

Force and Torque Required for Joystick Deflections of 10°, 20°, and 30°

Traditional U.S. Units

Resistance setting	Force (oz) degrees			Torque (in-oz) degrees			In-oz/degree degrees		
	10	20	30	10	20	30	10	20	30
Low	0	0	0	0	0	0	0	0	0
Medium	6	9	12	21	31	42	2.1	1.5	1.4
High	11	14	17	39	49	59	3.9	2.5	2.0

Metric Units

Resistance setting	Force (kg) radians			Torque (cm-kg) radians			Cm-kg/radian radians		
	.17	.35	.52	.17	.35	.52	.17	.35	.52
Low	0	0	0	0	0	0	0	0	0
Medium	0.17	0.25	.34	1.5	2.3	3.1	9.0	6.6	5.9
High	0.31	0.40	.48	2.8	3.6	4.3	16.5	10.2	8.3

The joystick control (base and stick) rested on a workstation surface that was 70 cm from the floor. The control was approximately 25 cm in front and 35 cm below the screen on which the stimulus was presented.

The stick itself was 110 mm high, the minimum length required by MIL-STD-1472D. The maximum diameter of the stick was 30 mm, which satisfied the MIL-STD-1472D requirement to be under 50 mm. The circumference of the stick was 78 mm at the base. At 40 mm from the base of the stick, the stick angled forward approximately 15°, and the circumference gradually increases to 85 mm at the top. The stick sat on a 32-mm-high base that was 165 mm wide by 125 mm deep.

Tracking Task

A compensatory tracking task was created using the "Manual Control Laboratory" from Engineering Solutions Incorporated. The computer that was used was a CSS 286 PC-AT™ compatible computer with a processing speed of 10 megahertz.

A constant target size of 30 mm by 20 mm was used for all conditions. The subject's task was to move the joystick to keep a constantly moving cursor in the target box. The movement of the cursor was a result of a forcing function plus the control inputs by the subject.

The forcing function that disturbed the cursor was composed of three sine waves of varying frequency and amplitude. Using three sine waves allowed a stimulus that elicited a wide range of frequency in the response movements from subjects. Table 4 presents the frequency and amplitude of each of the sine waves that composed the disturbance.

The higher frequency sine waves were assigned lower amplitudes because this reflects real world tracking situations. For example, targets in a military scenario may make movements to avoid being acquired in the sites of an opponent. If the target is a ground vehicle, physical limitations (such as the danger of tipping over) usually apply that prevent the vehicle from making many high degree turns in a short period of time. Likewise, higher amplitude movements are associated with low frequencies in the real world, as were the high amplitude sine waves composing the disturbance.

The forcing function that was used in this study was simplified from earlier work (Berkhout, Anderson, McCleerey, & Granaas, 1993). In that study and in pilot subject testing for the present study, the more difficult track resulted in some irregularity in the learning curve. The track that was used in the present study allowed a more regular learning curve while still making the task challenging.

A maximum amplitude of 40 mm was imposed on the disturbance function to prevent the task from being too difficult for subjects.

Table 4

Frequency and Amplitude of Each Sine Wave Composing the Disturbance Function

	Frequency (radians/sec)	Amplitude (mm)
Wave 1	5	10
Wave 2	3	20
Wave 3	2	40

Gloves

Subjects performed the task both bare-handed and while wearing a leather and wool glove assembly on their right hands. This assembly is used commonly in the armed forces, and it is a good representation of a thick, somewhat cumbersome glove. The assembly was approximately 2 mm thick and was made of a leather shell worn over a wool liner. The surface of the leather shell was smooth and pliable, and the assembly covered the hand and wrist. The wool and leather gloves can be worn separately, but they were worn only as an assembly in this study.

The leather and wool gloves were size 2 through 5, and a size 3 wool glove was worn with a size 3 leather glove (likewise for the other sizes). Size 2 of the leather and wool glove assembly was not available for this study, so size 3 was substituted for the low end of the hand size range.

A glove-fitting protocol used previously (Berkhout, Anderson, McCleerey, and Granaas, 1992) allowed subjects to be assigned appropriate glove sizes. Subjects were fit with a wool glove and wore the corresponding leather shell.

Procedure

When subjects arrived for the experiment, they read and signed a consent form (see Appendix A), their vision was tested, and the three hand measures were taken (see Appendix B). After reading instructions (see Appendix C), subjects began the first trial. The rectangle in which the subject was trying to keep the cursor and the cursor itself appeared with the cursor immediately in motion. Subjects operated the joystick for 90 s.

After 90 s, the program stopped and began giving a variety of graphical feedback about performance. To prevent the subjects from being distracted by the graphics, the subject's monitor was shut off between trials. Subjects were told their percent time-on-target which helped them to maintain their best performance. The computer took approximately 2 minutes to process the information from each trial. The subjects waited and rested their arms until the monitor was turned back on to begin the next trial.

Subjects performed eight 90-s trials of the first hand-wear condition and four 90-s trials of the second hand-wear condition. Half of the subjects performed bare-handed first, with the leather and wool glove assembly second. The other half of the group performed with the glove first, with bare-handed second.

Subjects were told that the first seven trials were practice and the eighth trial was a test trial, and that the following three trials were again practice and the fourth was a test. Data from pilot subjects showed that seven trials were enough to reach asymptote on the learning curve for the first condition. Pilot data also showed that three more trials were enough to reach asymptote after changing hand-wear conditions.

Design

A 2 (hand-wear) by 3 (resistance) by 2 (hand-wear order) by 2 (gender) mixed measures design was used to examine the effects of wearing gloves and joystick resistance on tracking performance. Each subject performed during the two hand-wear conditions, and 16 subjects performed during each of three levels of control resistance. Half of the subjects in each resistance group (4 males and 4 females) performed bare-handed first, and half performed with the glove assembly first.

Repeating measures on the hand-wear conditions allowed high statistical power for the main effect of hand wear. This approach, as opposed to having each subject operate during three levels of resistance, also allowed subjects to complete the task within 1 hour. Keeping the time to 1 hour avoided possible difficulties in scheduling and running subjects. The differences attributable to control resistance were expected to be greater than those attributable to hand wear, so this and hand-wear order (hereafter referred to as order) were between-subjects independent variables. Gender was a blocking variable.

Data Collection

The "Manual Control Laboratory" program recorded percent TOT. It also recorded root mean square error on both the horizontal (RMSH) and vertical (RMSV) axes.

Poulton (1974) stated that RMS error is the best measure of overall tracking performance. TOT was included for three reasons. First, it is an easily interpreted variable. It is much easier to understand what a difference of five TOT means than what a difference of .01 RMS error means. RMSV and RMSH, in this case, are even more difficult to interpret. The software package purchased for this evaluation uses a unit of measure of a decimal percentage of 1/2 the screen height (90 mm). For example, A 0.2 RMSV translates into an error of 18 mm of error. Second, the measure has a great deal of face validity for the types of tasks in which tracking is performed. Third, this measure is what subjects used to evaluate their own performance, both during and after each trial.

RESULTS

Each subject produced two scores for RMSH, RMSV, and TOT, one for each hand-wear condition. This resulted in 96 data points for each of the three dependent variables. Table 5 presents the correlations among RMSH, RMSV, and TOT across both hand-wear conditions.

Primary Analysis

A 2 (hand wear) by 3 (resistance) by 2 (order) by 2 (gender) mixed measures multivariate analysis of variance (MANOVA) was performed on the three measures, RMSH, RMSV, and TOT. The Hand Wear x Gender x Order interaction was significant ($F(3,34) = 4.50$, $p < .01$), the Hand Wear x Gender interaction was significant ($F(3,34) = 4.33$, $p < .01$), and the Hand Wear x Order interaction was significant ($F(3,34) = 27.06$, $p < .0001$). The Hand Wear x Resistance x Gender interaction approached significance ($F(6,68) = 1.91$, $p < .10$). Appendix D contains the terms used in the appendices, and Appendix E contains the source table for the MANOVA.

Table 5

Correlations Among RMSH, RMSV, and TOT Across Hand-Wear Conditions

	RMSH	RMSV	TOT
RMSH	------	.91*	-.95*
RMSV		-----	-.94*
TOT			-----

*p<.001

Univariate Analysis

A 2 (hand wear) by 3 (resistance) by 2 (order) by 2 (gender) mixed measures analysis of variance (ANOVA) was performed on three dependent variables. For RMSH, the same three effects were significant as in the MANOVA. The Hand Wear x Gender x Order interaction was significant ($F(1,36) = 4.90$, $p < .05$), the Hand Wear x Gender interaction was significant ($F(1,36) = 10.30$, $p < .005$), and the Hand Wear x Order interaction was significant ($F(1,36) = 15.32$, $p < .0005$). Appendix F contains the ANOVA source table for RMSH.

In the RMSV ANOVA, the Hand Wear x Gender x Order interaction was significant (F (1,36) = 5.08, p < .05), and the Hand Wear x Gender interaction was significant (F (1,36) = 8.13, p < .01). The Hand Wear x Order interaction was not significant. Appendix G contains the ANOVA source table for RMSV.

In the TOT ANOVA, the Hand Wear x Gender interaction was significant (F (1,36) = 11.05, p < .005), and the Hand Wear x Order interaction was significant (F (1,36) = 33.22, p < .0001). The Hand Wear x Gender x Order interaction was not significant. Appendix H contains the ANOVA source table for TOT.

Comparisons of the Means

Hand Wear x Gender x Order

Means from the effects that were significant in the ANOVA's were submitted to post hoc analyses using Tukey's Honestly Significant Difference (HSD) Test. Table 6 presents pairwise comparisons among the means for the three-way interaction (Hand Wear x Gender x Order) for both RMSH and RMSV (this effect was nonsignificant for TOT). The critical differences for RMSH and RMSV were 0.0111 and 0.0136, respectively.

Figure 1 shows the three-way interaction for RMSH. For the B-G order, male subjects performed significantly better with gloves than without gloves. During the G-B condition, male subjects performed better bare-handed, though not significantly better. Female subjects performed better bare-handed regardless of order, though not significantly better during the B-G condition. Female subjects performed equally with gloves regardless of the order. Figure 2 presents the same interaction for TOT. Although the effect was not significant for this measure, the pattern of means is similar.

Figure 3 shows the three-way interaction for RMSV. Once again, female subject performance during the gloved condition did not surpass their bare-handed performance for either order condition. During bare-handed performance, both order conditions were significantly better than the gloved performance during the B-G condition. Mean RMSV for male subjects did not differ significantly among any of the conditions. During the B-G condition, bare-handed male subjects did not perform significantly better than bare-handed female subjects during either order condition; however, during the G-B condition, male subjects performed better than female subjects during any condition.

Hand Wear x Gender

Table 7 presents pairwise comparisons among the means using Tukey's HSD for the Hand Wear x Gender interaction for RMSH, RMSV, and TOT. The critical differences for RMSH, RMSV, and TOT were 0.0065, 0.0080, and 5.0, respectively.

Figure 4 shows the interaction for all three measures. For RMSV and TOT, it is clear that (a) male subjects consistently performed better than female subjects, (b) female subjects performed better bare-handed than gloved, and (c) male subjects performed about the same bare-handed and gloved. For RMSH it was the same, except that during the bare-handed condition, female subject performance was not significantly different from male subject performance (gloved or bare-handed). For all three measures, it is clear that wearing gloves is detrimental to tracking performance for female subjects. In light of the three-way interaction, it should be kept in mind that part of the difference in performance by hand wear and gender is because of differences between order conditions.

Table 6

Results of Tukey's HSD Post Hoc Tests of the Means for the Hand Wear x Gender x Order Interaction for RMSH and RMSV

			Differences among means							
Hand/Gender/Order	Mean RMSH	N	B/F/B	B/F/G	B/M/B	B/M/G	G/F/B	G/F/G	G/M/B	G/M/G
Bare/Female/B-G	.126	12	----	.005	.008	.021*	.004	.005	.023*	.015*
Bare/Female/G-B	.120	12		----	.003	.016*	.010	.010	.017*	.009
Bare/Male/B-G	.117	12			-----	.013*	.013*	.013*	.014*	.006
Bare/Male/G-B	.104	12				-----	.026*	.026*	.001	.007
Glove/Female/B-G	.130	12					-----	.000	.027*	.019*
Glove/Female/G-B	.130	12						-----	.027*	.019*
Glove/Male/B-G	.103	12							-----	.008
Glove/Male/G-B	.111	12								-----

*p<.05 HSD=.0111

Hand/Gender/Order	Mean RMSV	N	B/F/B	B/F/G	B/M/B	B/M/G	G/F/B	G/F/G	G/M/B	G/M/G
Bare/Female/B-G	.125	12	-----	.003	.011	.023*	.013	.007	.019*	.021*
Bare/Female/G-B	.128	12		----	.013	.025*	.011	.004	.021*	.024*
Bare/Male/B-G	.115	12			-----	.012	.023*	.017*	.008	.011
Bare/Male/G-B	.103	12				-----	.036*	.029*	.004	.001
Glove/Female/B-G	.138	12					------	.007	.032*	.034*
Glove/Female/G-B	.132	12						-----	.025*	.028*
Glove/Male/B-G	.107	12							------	.033
Glove/Male/G-B	.104	12								-----

*p<.05 HSD=.0136

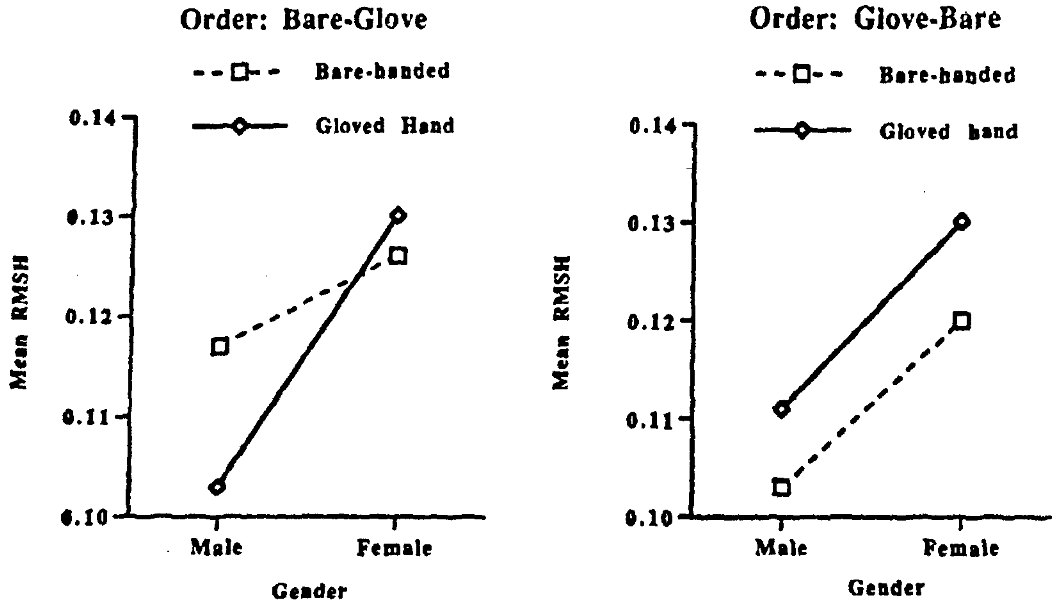

Figure 1. Mean RMSH for each Hand Wear x Gender for both the B-G and G-B hand-wear condition orders

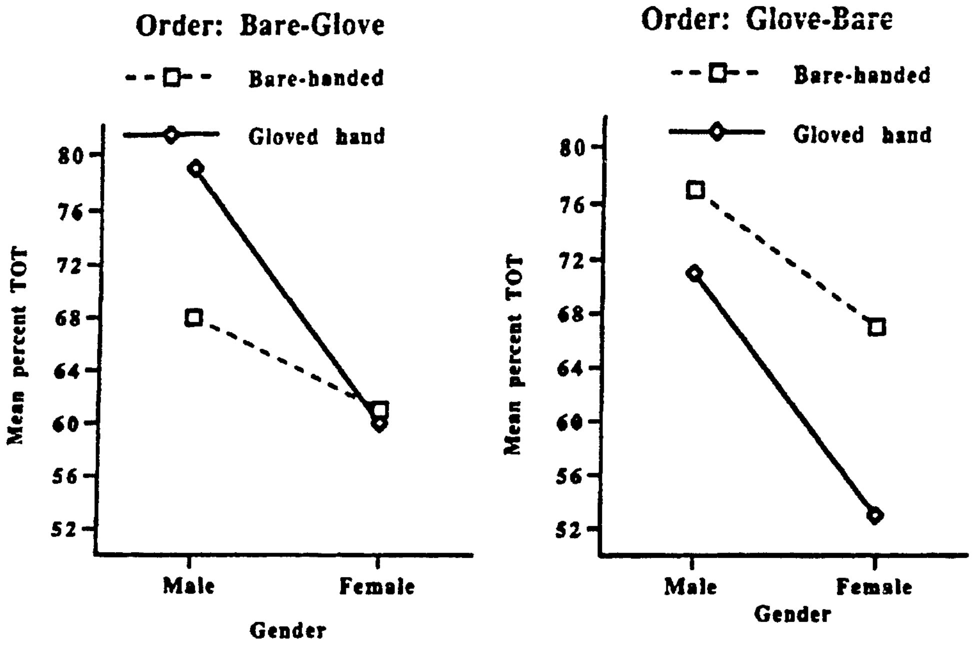

Figure 2. Mean percent TOT for each Hand Wear x Gender for both the B-G and G-B hand-wear condition orders.

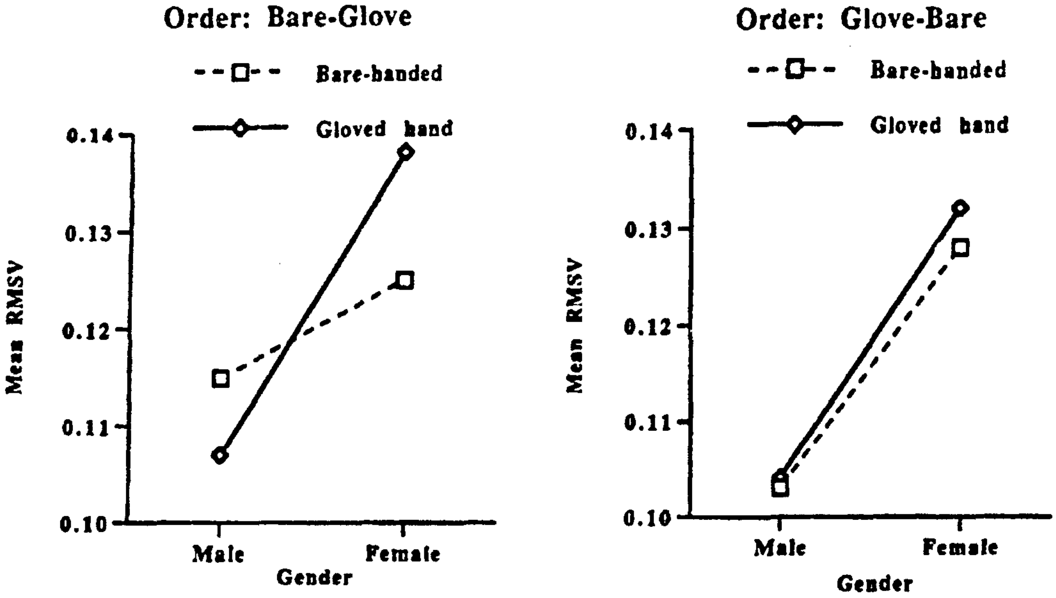

Figure 3. Mean RMSV for each Hand Wear x Gender for both the B-G and G-B hand-wear condition orders.

Table 7

Results of Tukey's HSD Post Hoc Tests of the Means for the Hand Wear x Gender Interaction for RMSH, RMSV, and TOT

			Differences among means			
Condition	Mean RMSH	N	Bare/F	Bare/M	Glove/F	Glove/M
Bare/female	.113	24	-----	.002	.017*	.006
Bare/male	.111	24		-----	.019*	.004
Glove/female	.130	24			-----	.023*
Glove/male	.107	24				-----

*p<.05 HSD=.0065

Condition	Mean RMSV	N	Bare/F	Bare/M	Glove/F	Glove/M
Bare/female	.127	24	-----	.018*	.009*	.021*
Bare/male	.109	24		-----	.027*	.003
Glove/female	.135	24			-----	.030*
Glove/male	.105	24				-----

*p<.05 HSD=.0080

Condition	Mean TOT	N	Bare/F	Bare/M	Glove/F	Glove/M
Bare/female	62.9	24	-----	9.6*	6.8*	11.4*
Bare/male	72.5	24		------	16.5*	1.8
Glove/female	56.0	24			-----	18.3
Glove/male	74.3	24				-----

*p<.05 HSD=.50

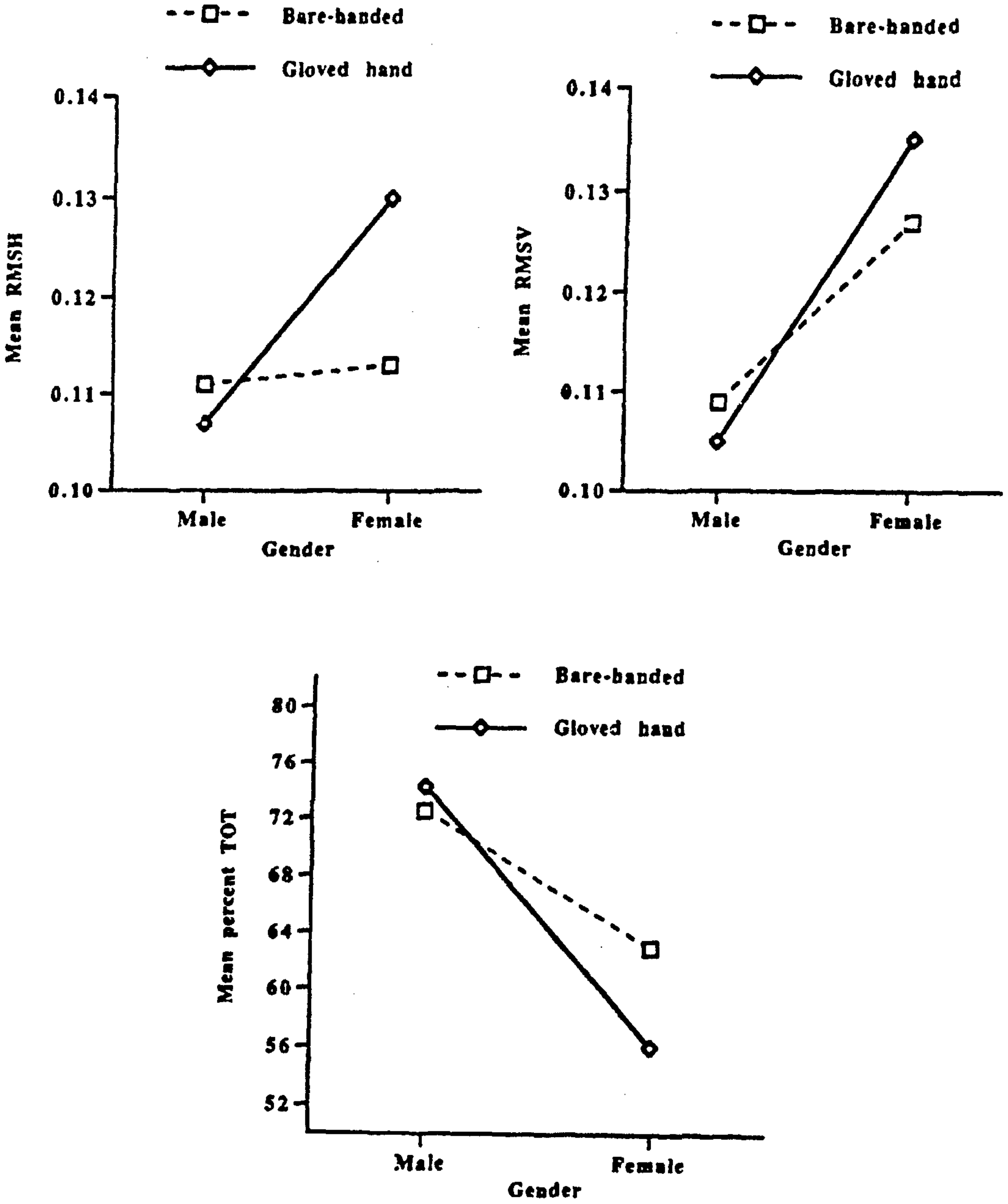

Figure 4. Mean RMSH, RMSV, and TOT for each Hand Wear x Gender

Hand Wear x Order

Table 8 presents pairwise comparisons among the means using Tukey's HSD for the Hand Wear x Order interaction for RMSH and TOT (this effect was nonsignificant for RMSV). The critical differences for RMSH and TOT were 0.0065 and 5.03, respectively.

Figure 5 presents the Hand Wear x Order interaction. The graphs for both RMSH and TOT indicate that performance was better with gloves when the gloved condition was second (B-G order) and better with bare-hands when the bare-handed condition was second (G-B order). The graph for RMSV does not show the same trend, but the effect was nonsignificant for this measure.

The Hand Wear x Order interaction must be interpreted in light of the three-way interaction (Hand Wear x Gender x Order). Figures 1 and 3 for the three-way interaction show that during the B-G order, the larger difference in performance between hand-wear conditions was for male subjects. During the G-B order, the larger difference in performance between hand-wear conditions was for female subjects. Therefore, in the two-way interaction, better performance with gloves during the B-G order condition was because of male subjects, and better performance bare-handed during the G-B order condition was mostly because of female subjects.

Hand Wear x Resistance x Gender

Figures 6, 7, and 8 present the Hand Wear x Resistance x Gender interaction (which approached significance) for RMSH, RMSV, and TOT, respectively. During the gloved condition for the three measures, female subjects consistently performed best with high resistance, and male subjects performed about the same across resistances while wearing gloves. For RMSV, female subjects also performed best with high resistance while bare-handed, but there were no clear trends across the measures for bare-handed performance for either gender.

Exploratory Analysis

The gloves used in this study did not fit small handed female subjects as well as other subjects. To determine whether smaller handed female subjects had greater performance decrements with gloves because of sizing, a post hoc test using Tukey's HSD was performed on the means for Hand Wear x Hand Size for female subjects only.

Female subjects were divided into three hand-size groups based on the girth measure taken to fit gloves: 180 mm or less was small, from 181 mm to 190 mm was medium, and 191 mm or more was large. There were 8 subjects in each group, and each group was balanced for hand-wear condition order. Table 9 presents pairwise comparisons among the means for Hand Wear x Hand Size for female subjects for RMSH, RMSV, and TOT. The critical differences for RMSH, RMSV, and TOT were 0.0169, 0.0187, and 11.8, respectively.

Figure 9 presents the means from the post hoc comparison for Hand Wear x Hand Size for female subjects for all three measures. While the hand wear effect shown in other analyses is apparent for all three variables, there is no evidence that small handed female subjects had a greater performance decrement, relative to their bare-handed performance, than medium and large handed female subjects.

Table 8

Results of Tukey's HSD Post Hoc Tests of the Means for the Hand Wear x Order Interaction for RMSH and TOT

			Differences among means			
Hand/order	Mean RMSH	N	Bare/B-G	Bare/G-B	Glove/B-G	Glove/G-B
Bare/B-G	.121	24	-----	.009*	.005	.001
Bare/G-B	.112	24		-----	.004	.008*
Glove/B-G	.116	24			-----	.004
Glove/G-B	.120	24				-----

*$p < .05$ HSD = .0065

Hand/order	Mean TOT	N	Bare/B-G	Bare/G-B	Glove/B-G	Glove/G-B
Bare/B-G	63.6	24	-----	8.0*	5.0	2.0
Bare/G-B	71.7	24		----	3.0	10.0
Glove/B-G	68.7	24			-----	7.0
Glove/G-B	61.7	24				-----

*$p < .05$ HSD = 5.03

Figure 9 shows that smaller handed female subjects performed worse than the other two groups during both gloved and bare-handed conditions. Table 9 shows that almost all differences between the small and medium and between the small and large handed groups are significant. Appendix I contains means and standard deviations for RMSH, RMSV, and TOT for each hand size group for female subjects. Appendix J contains the means and standard deviations for RMSH, RMSV, and TOT for main effects.

Male subjects were also divided into three hand-size groups based on the girth measure taken to fit gloves: 209 mm or less was small, 210 mm to 218 mm was medium, and 219 mm or more was large (one subject with a girth of 210 mm was placed in the small group, and one subject of girth 219 mm was placed in the medium group to allow equal group sizes). There were 8 subjects in each group, and each group was balanced for order. The small group had one extra subject during the B-G order condition, and the large group had one extra during the G-B order condition.

Table 10 presents pairwise comparisons among the means for Hand Wear x Hand Size for male subjects for RMSH, RMSV, and TOT. The critical differences for RMSH, RMSV, and TOT were 0.0121, 0.0147, and 9.0, respectively. There were no significant differences among the means for RMSV and TOT. For RMSH, the medium size group with gloves performed better than the large and small handed groups. With bare hands, the medium group performed better than the small group bare-handed.

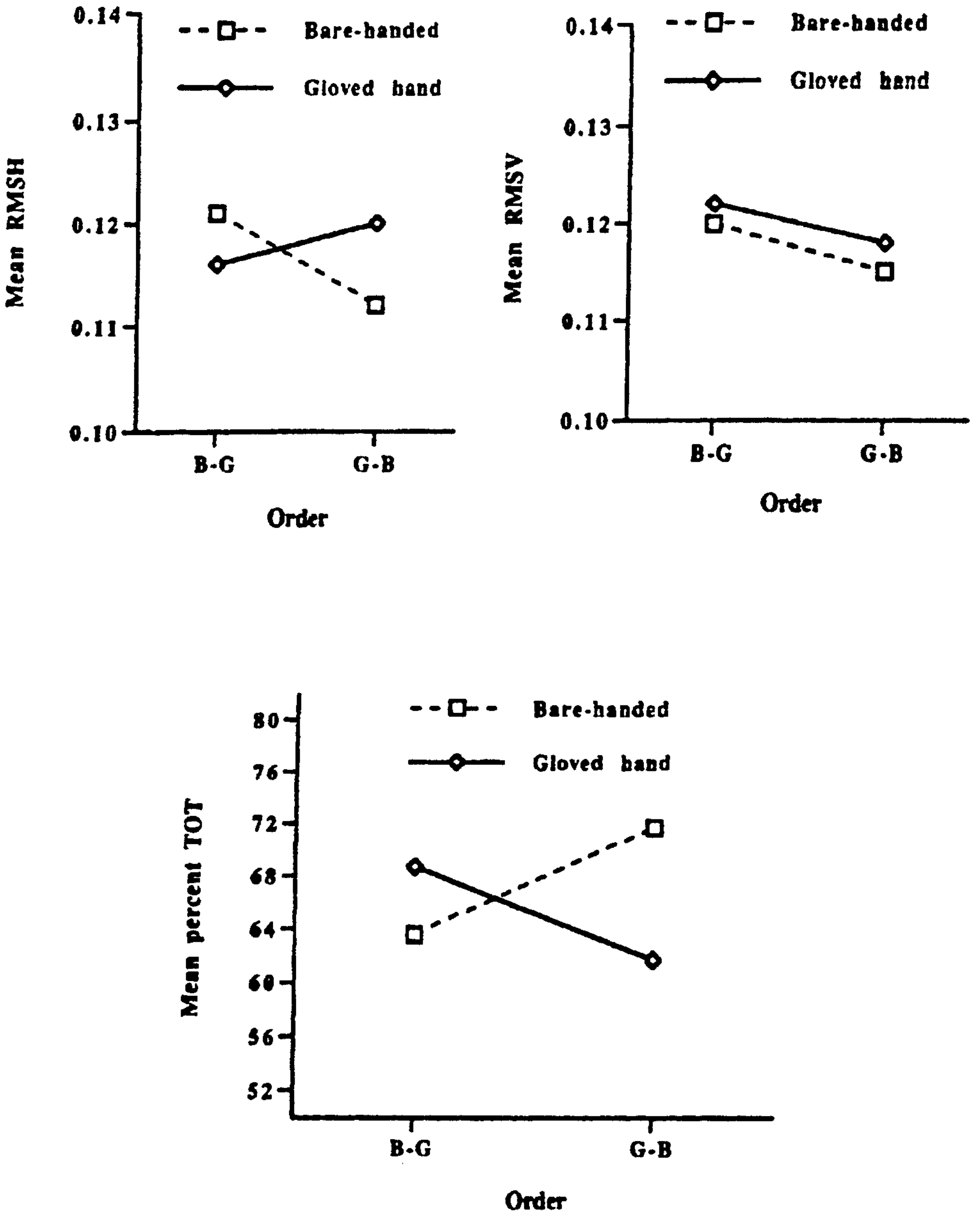

Figure 5. Mean RMSH, RMSV, and TOT for each Hand Wear x Order.

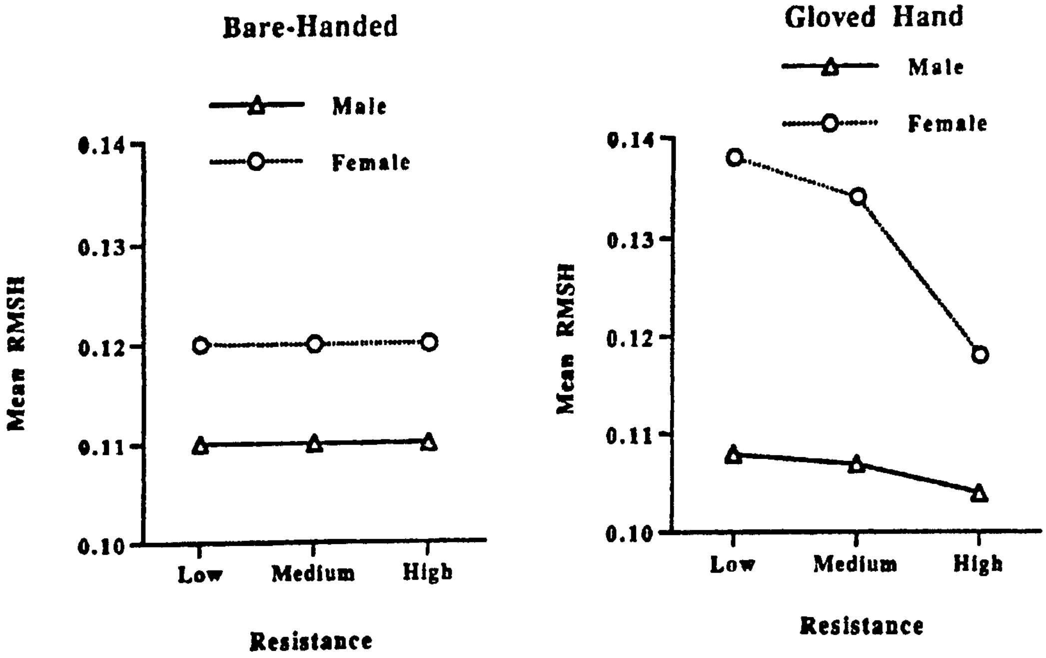

Figure 6. Mean RMSH for each Gender x Resistance for both the gloved hand and bare-handed hand-wear conditions.

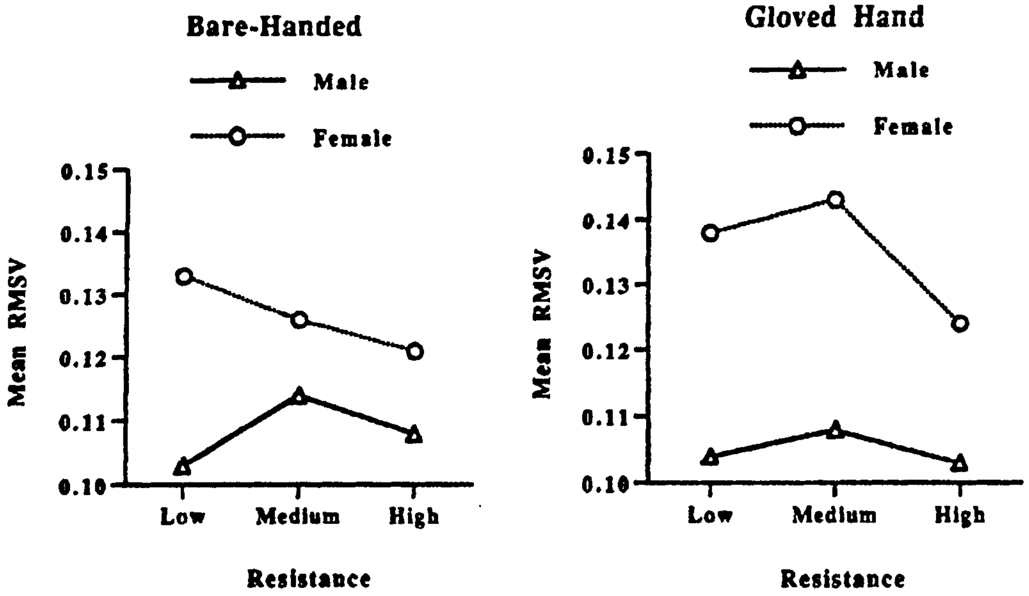

Figure 7. Mean RMSV for each Gender x Resistance for both the gloved hand and bare-handed hand-wear conditions.

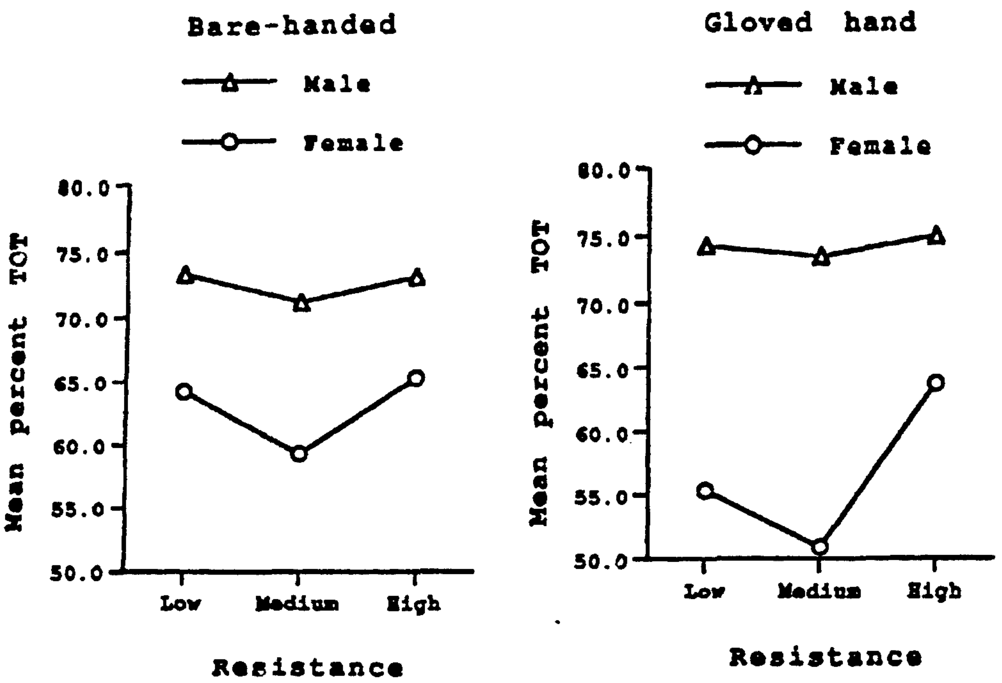

Figure 8. Mean percent TOT for each Gender x Resistance for both the gloved hand and bare-handed hand-wear conditions

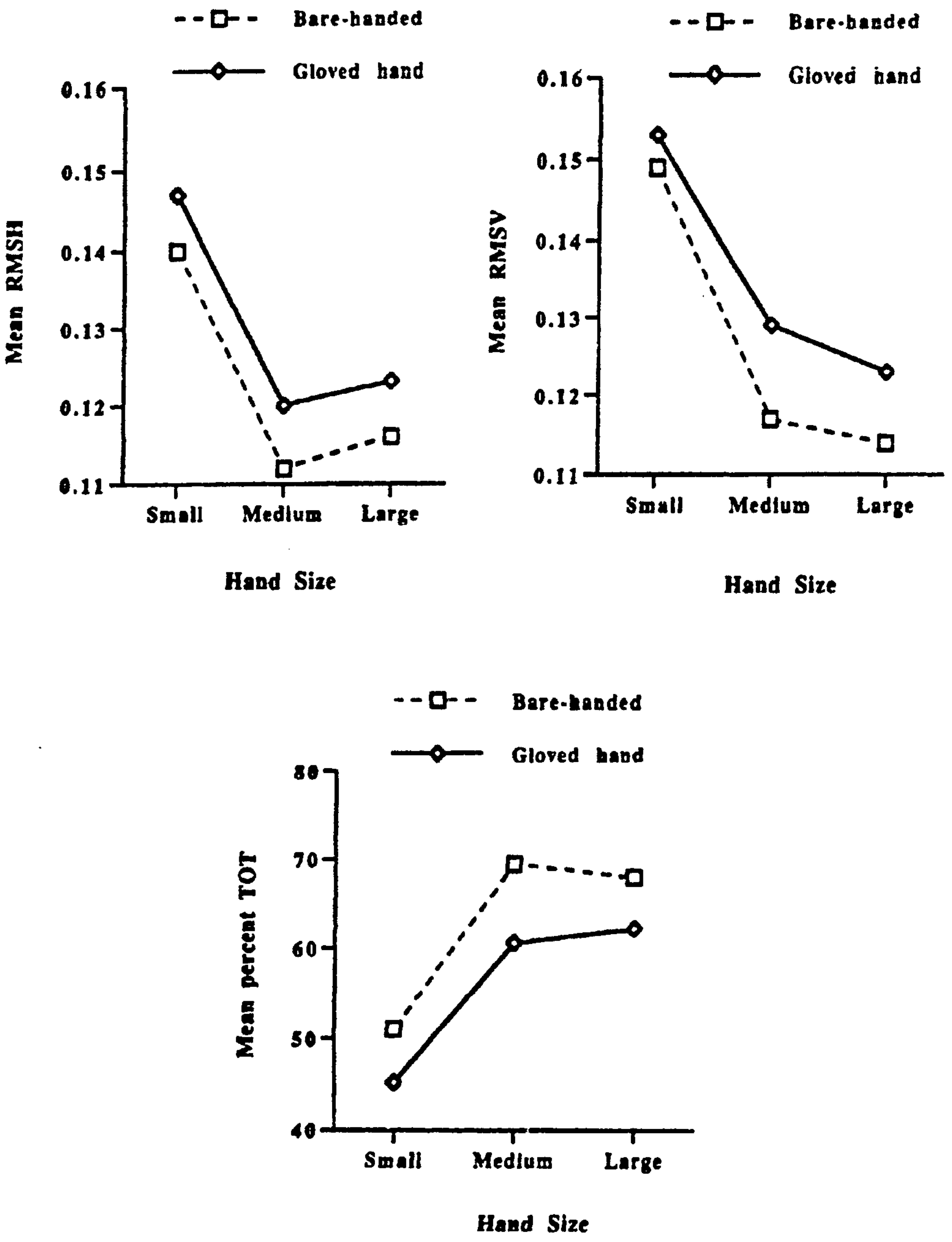

Figure 9. Mean RMSH, RMSV, and TOT for each Hand Wear x Hand Size for female subjects.

Table 9

Results of Tukey's HSD Post Hoc Test of the Means for Hand Wear x Hand Size for RMSH, RMSV, and TOT for Female Subjects

			Differences among means					
Hand wear/ size	Mean RMSH	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	.140	8	-----	.029*	.025*	.006	.020*	.017*
Bare/medium	.112	8		-----	.004	.035*	.008	.011
Bare/large	.116	8			-----	.031*	.004	.007
Glove/small	.147	8				-----	.026*	.023*
Glove/medium	.120	8					-----	.003
Glove/large	.123	8						-----

*p<.05 HSD=.0187

Hand/wear/ Size	Mean RSMV	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	.149	8	-----	.031*	.035*	.005	.020*	.026*
Bare/medium	.117	8		-----	.004	.036*	.012	.005
Bare/large	.114	8			-----	.040*	.015	.009
Glove/small	.153	8				-----	.025	.031*
Glove/medium	.129	8					-----	.006
Glove/large	.123	8						-----

*p<.05 HSD=.0169

Hand wear/ size	Mean TOT	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	51.0	8	-----	18.5*	16.9*	5.9	9.6	11.2
Bare/medium	69.5	8		-----	1.5	24.3*	8.9	7.3
Bare/large	68.0	8			-----	22.8*	7.4	5.8
Glove/small	45.2	8				-----	15.4*	17.0
Glove/medium	60.6	8					-----	1.6
Glove/large	62.2	8						-----

*p<.05 HSD=11.8

Table 10

Results of Tukey's HSD Post Hoc Tests of the Means for Hand Wear x Hand Size for RMSH, RMSV, and TOT for Male Subjects

			Differences among means					
Hand wear/ size	Mean RMSH	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	.116	8	-----	.014*	.003	.006	.019*	.004
Bare/medium	.102	8		-----	.011	.008	.005	.010
Bare/large	.113	8			-----	.003	.015*	.001
Glove/small	.111	8				-----	.013*	.001
Glove/medium	.098	8					-----	.014*
Glove/large	.112	8						-----

*p<.05 HSD=.0121

Hand wear/ size	Mean RMSV	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	.108	8	-----	.001	.004	.001	.008	.001
Bare/medium	.106	8		-----	.005	.001	.007	.003
Bare/large	.112	8			-----	.005	.012	.003
Glove/small	.107	8				-----	.007	.002
Glove/medium	.110	8					-----	.009
Glove/large	.109	8						-----

*p<.05 HSD=.0147

Hand wear/ size	Mean TOT	N	Bare/S	Bare/M	Bare/L	Glove/S	Glove/M	Glove/L
Bare/small	70.6	8	-----	5.6	.1	2.7	8.6	.3
Bare/medium	76.2	8		-----	5.7	2.8	3.0	5.9
Bare/large	70.5	8			-----	2.8	8.7	.3
Glove/small	73.4	8				-----	5.9	3.1
Glove/medium	79.2	8					-----	8.9
Glove/large	70.3	8						------

*p<.05 HSD=9.0

DISCUSSION

Hypothesis 1

The first hypothesis that wearing gloves is detrimental to tracking performance was supported for female subjects only. The significant three-way interaction (Hand Wear x Gender x Order) indicated that female subjects did not perform as well gloved as bare-handed. RMSH and RMSV ranged from 3% to 9% higher for female subjects with gloves during the two order conditions. When male subjects had the gloved condition after the bare-handed condition, they performed better gloved than bare-handed. The male subjects may have been able to perform better with gloves because of the extra practice during the bare-handed condition. Female subjects did not benefit from this previous exposure to the task before the gloved condition.

The Hand Wear x Gender interaction also supported the hypothesis that wearing gloves is detrimental to tracking performance for female subjects. RMSH, RMSV, and TOT were 6% to 13% better without gloves. The Hand Wear x Gender interaction also shows that overall, while wearing gloves, male subjects performed 18% to 25% better than female subjects across the three measures.

It is unlikely that the hand-wear effect for female subjects was because of a lack of previous experience compared to male subjects. Tracking with a joystick while wearing gloves is probably uncommon among both male and female subjects in the college student subject pool. It is true that male subjects have much more experience than female subjects in playing video games, which are largely tracking tasks, particularly in the age range represented by the subjects. However, if this was a source of the poorer female subject performance, it should have occurred in the bare-handed condition as well.

It is also unlikely that female subjects made less of an effort during the gloved condition. The feedback that subjects received during the practice trials encouraged them to do their best. Also, they were told when a test trial was about to occur, so they knew when good performance was most important. This gender difference is most likely because of anatomical differences in the hands of male and female subjects.

Hypothesis 2

Hypothesis 2 predicted that the detrimental glove effect would be greater for conditions of lower control resistance. The null hypothesis cannot be rejected since there were no effects involving resistance that were significant at the .05 alpha level. The Hand Wear x Resistance x Gender interaction was, however, nearly significant. When female subjects wore gloves, they performed 10% to 17% better across the three measures during high control resistance than during medium or low control resistance. During the bare-handed condition, there were no consistent trends for female subjects across the measures. Male subjects showed no consistent trends during any of the conditions.

If the higher resistance did help female subjects, it was because of increased cutaneous and proprioceptive feedback. Since female subjects generally have smaller hands, they may be more susceptible to interference with cutaneous feedback. Their hands have less surface area than male subjects' hands, so thick gloves could be more effective in insulating female subjects' skin from the surface of the control. Also, since female subjects' hands are generally smaller, they might be more susceptible to interference with proprioceptive feedback. The forces applied by the muscles in female subjects' hands and wrists are smaller in scale than male subjects (i.e., they cover a smaller area). Even when the total force applied is the same as male subjects, the force is distributed over a smaller area. Thick gloves could act as a cushion to absorb the forces and reduce feedback. Since male subjects have larger hands, they can distribute forces over a wider area of the control, providing stable feedback despite the cushioning from a glove.

The Hand Wear x Resistance x Gender interaction was not significant at the .05 alpha level, so it does not have the robustness of other results. It was, however, consistent across the three measures.

Hand Wear x Order

Performance during the gloved condition was better during the B-G order, and performance during the bare-handed condition was better during the G-B order. The three-way interaction (Hand Wear x Gender x Order) showed that the order effect differed by gender. Female subjects' performance with gloves was the same during both orders, so better gloved performance under the B-G condition in the two-way interaction was because of male subjects' performance. Male subjects performed slightly better bare-handed than gloved during the G-B order. Female subjects performed much better bare-handed than gloved during the G-B order, so the better performance bare-handed during the G-B order in the two-way interaction was because of female subjects' performance. In short, male subjects seemed to benefit more from practice when the gloved condition was second, and female subjects seemed to benefit more from practice when the bare-handed condition was second.

Since there was an order effect, it should be determined whether differential learning effects between gloves and bare hands influenced the results. The most important conclusion of this study (that gloves are detrimental to performance for female subjects) is not affected. Female subjects performed the same with gloves regardless of order. Figure 3 shows that for the RMSV measure, female subjects actually performed worse (though not significantly worse) with gloves during the B-G order than during the G-B order.

A differential learning effect for gloves and bare hands did not seem to occur for male subjects either. If there was a differential learning effect, it would be expected that gloved performance during the G-B order would have been worse than bare-handed performance during the B-G order. Again the opposite is true. The gloved performance during G-B order is slightly better (though not significantly) than the bare performance during B-G order.

Hand-Size Effect

The smallest size of glove used in this study was worn by 17 of the 24 female subjects. For some female subjects, this size was not ideal. The male subjects, however, were well suited with the 3 through 5 size range. This situation is fairly common in real life situations, so it is valid in an experimental setting. The most obvious explanation for a glove effect for female subjects would be that the gloves did not fit them as well; therefore, only female subjects suffered a performance deficit because of gloves.

If this explanation were true, smaller handed female subjects should have had greater performance deficits than larger handed female subjects during the gloved condition. This was not the case. Though small handed female subjects did not perform as well overall, the glove effect was constant for all three hand sizes. Male subjects did not show this size effect.

It is not clear why small handed female subjects performed worse than medium and large handed female subjects. It is possible that the dimensions of the joystick were too large for people with small hands, making it difficult for them to make adjustments.

In Berkhout, Anderson, McCleerey, & Granaas (1992), there was also evidence for a hand-size effect. Subjects of both genders with larger hand girths tended to perform faster and with more errors on a push-button task.

The differences in performance because of hand size in female subjects were high, from 16% to 25% worse across the three measures for small handed female subjects. This is especially great considering differences across genders are not involved. Mean overall RMSH, RMSV, and TOT for male subjects was 24% to 34% better than overall means for small handed female subjects. Remember that this is the result of a post hoc test with only half the total sample, but the results are very consistent across the three measures.

The hand-size effect for female subjects shows the importance of the anthropometric representativeness of the population to which the results should generalize. As Table 2 shows, this sample closely approximates the girth measures from a Army anthropometric survey (Gordon et al., 1989).

Regardless of the cause for any gender differences, from a human factors standpoint it is most important to design the controls, task, or gloves for optimum use by as many users as possible.

Control Design

There was some evidence that higher resistance in the joystick helped compensate for the performance decrement that the gloves caused for female subjects. When designing control panels, thought should be given to the different types of people who will use the control and to the different conditions during which the control will be used, such as gloved operation. Often designers only consider the task that will be performed and do not use the optimum design across users and circumstances.

In the absence of contradictory evidence, it would be advisable to have higher resistance in a control such as the one used in this study. The higher resistance did not hurt performance, and with the higher resistance, female subjects might be able to perform better while wearing gloves than they would during lower resistance. Higher resistance would allow additional feedback if visual feedback were interrupted or delayed. Also, higher resistance would help prevent accidental actuation of controls.

At some higher level of resistance, it would be expected that resistance would be detrimental to female subject performance, a lower value than at which it would affect male subject performance. Again, this would be because of the size and strength differences between male and female subjects. This study did not examine higher values, so it does not follow from this study that in general, female subjects will benefit with high resistance. The magnitude of the resistance and the type of control used in this study must remember when generalizing results.

For female subjects during the bare-handed condition and for male subjects during both bare-handed and gloved conditions, resistance level did not cause any differences in performance. One of the reasons for limited effects of resistance, which was more important in the studies previously reviewed, may be that the task used in this study involved good visual feedback. Results of the current study do not generalize tracking situations in which there is a delay in visual feedback or no visual feedback (e.g., Bahrick, Bennett, & Fitts, 1955; Bahrick, Fitts, & Schneider, 1955). Proprioceptive and cutaneous feedback are probably more important in these situations. A control operator might rely on other types of feedback when their visual feedback is disrupted.

Another reason for the limited resistance effect may be the control that was used. Bahrick (1957) concluded that during optimum conditions of spring-loading, average positioning errors can be reduced by 50% for a control which is not spring-loaded. The error is least when the ratio of relative torque change to displacement is highest. Most of the studies from which Bahrick drew this conclusion involved larger controls with much greater levels of resistance than the control used in this study. The larger controls usually required forces delivered at least partially by the arm. For small, low resistance controls, the change in torque relative to the change in displacement may not be as important. Since the resistance allowed for hand controls is limited to relatively low levels, the range of resistance is restricted. A smaller range of resistance in a control means that operators would not be able to discern control positions as well, especially when the control is operated with quick movements that allow less opportunity for feedback to be processed.

Hand-Wear Characteristics

Because only one type of glove was used in this study, it limits the generalizability of the results. This does not mean that the knowledge gained from this study applies only to leather and wool glove assemblies. This study offers a point of reference for tracking tasks in which operators wear gloves. If the hand wear is even more bulky and less supple than the leather and wool assembly, even greater performance decrements can be expected, at least for female subjects. Performance with gloves that are similar in bulk, but that are more or less pliable, may be similar. For a joystick with a smooth surface and high resistance, however, a less pliable glove could cause greater performance problems. As previously stated, this type of situation is avoidable with a control that is designated for circumstances during which the control will be used.

For gloves that are less thick, female subjects would probably have fewer substantial decrements. In many situations, however, different types of gloves may be worn during a particular task, so the designer must consider some of the more extreme circumstances (e.g., some of the thickest gloves).

In the task performed for this study, glove snugness was not important. The smallest glove fit the smallest handed female subjects loosely, and yet small handed female subjects performed the same as medium and large handed female subjects. During other circumstances, glove snugness can be more important.

Even though a glove fits a small handed person as snugly as a large handed person, the ratio of the material's thickness to hand size is greater for the smaller handed person. Therefore, thinner material should be used for gloves when it can supply the needed protection, especially for smaller sizes.

Indications for Further Study

Hand Size

It is interesting that small handed female subjects performed much worse than any other group. Performance as a function of hand size was not the primary focus of this evaluation; however, this is perhaps the most important area for future research. It is important because of the large performance differences and because of the large number of female subjects with small hands. The joystick used in this study was small relative to what is required by MIL-STD-1472D. It equals the minimum length required, and it is much smaller than the maximum diameter allowed. If the control was too large for the small handed subjects, the hand size effect would have important implications for control design.

It is possible that performance for female subjects with small hands would not improve with a more customized control. The poor performance may have been because of other characteristics of female subjects with small hands, not the size of their hands relative to the control.

An interesting line of research would begin with a verification that small handed female subjects perform worse than medium and large handed female subjects on tracking tasks during the present conditions. If this were verified, then other tasks and conditions should be examined with people of various hand sizes. Finally, alternative controls and training methods should be examined to determine how they could compensate for the hand size effect.

Control Design and Hand Wear

Since the evidence for higher resistance improving female subject performance with gloves is not conclusive, a future experiment could examine this possible effect more closely. This present study could be repeated using only female subjects, and higher levels of resistance could be added to determine at what point higher resistance ceases to improve performance.

CONCLUSIONS

1. Wearing gloves is detrimental to tracking performance for female subjects.

2. Female subjects do not benefit from additional exposure to the task before performing the task with gloves, as do male subjects.

3. There is some evidence that high control resistance in the joystick is beneficial for female subjects during the gloved condition.

4. Smaller handed female subjects did not perform as well as medium and large handed female subjects or as well as male subjects. An exploratory analysis could not determine the cause for the reduced performance. Future studies would have to be designed to specifically examine whether the relative size of hands (regardless of gender) to joystick size is the dominant factor or if there is some other characteristic (such as experience of glove fit) that caused their reduced performance.

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APPENDIX A

INFORMED CONSENT FORM

INFORMED CONSENT FORM

You are invited to participate in the Gloved Operator Performance Study at the USD Human Factors Laboratory. Your participation is voluntary. You must be at least 18 years old to participate. The purpose of the study is to determine how best to design control panels for gloved operators.

Your participation in this study is voluntary. If you agree to participate, you will be asked to perform control operations bare-handed and while wearing a glove. You will go through several training periods, a test period, some more practice, and then a final test.

The study will require about one hour of your time. You will be awarded extra credit in your psychology class for participating. The number of points will be determined by the class instructor. You may choose not to participate or may withdraw at any time without penalty.

There is no risk involved, and you will not be asked to work at full strength or in a fatigued condition. Any information relating to participants in the study will be kept confidential. Your name will not be associated with any results.

If you have any questions or concerns now or later about the study, you may contact Dr. Jan Berkhout at 677-5295. If you agree to take part in the study, please sign this form. You will be given a copy for your own records.

____

Signature of Participant   Date

____

Signature of Investigator   Date

APPENDIX B

HAND MEASUREMENT RANGES FOR FITTING GLOVES

Table B-1

Hand Measurement Ranges for Fitting Gloves

Size	Hand Circumference	Third Digit Length	Wrist to Second Digit
3	-200	-84	-173
4	192-212	81-89	163-181
5	209-	83-	177-

APPENDIX C

INSTRUCTIONS TO THE SUBJECT

INSTRUCTIONS TO THE SUBJECT

When the experiment begins, a square will appear in the center of the screen. Also on the screen you will see a cursor. Your task will be to use the joystick to move the cursor so it will remain inside the square, as close to the center of the square as possible. Moving the joystick away from you will move the cursor up the screen. Moving the joystick toward you will move the cursor down the screen. Moving the joystick to the right or left will move the cursor to the right or left, respectively.

The cursor has been programmed to continually leave the square. Consequently, you will need to make continuous adjustments with the joystick to keep the cursor inside the square as often as possible.

You will perform this task with your bare hand and while wearing a glove. The experimenter will notify you when you need to take off or put on the glove. You will repeat the task 12 times. Some of these 12 trials will be practice and some test. The experimenter will tell you before the trial each time whether it is practice or test. After each trial the experimenter will give you feedback on your performance. Please try your best at all times.

Do you have any questions before you begin the experiment?

APPENDIX D

TERMS USED IN THE APPENDICES

TERMS USED IN THE APPENDICES

EFFECT	ERROR TERM
RESISTANCE	SUBJECT(RESISTANCE*GENDER*ORDER)
GENDER	SUBJECT(RESISTANCE*GENDER*ORDER)
ORDER	SUBJECT(RESISTANCE*GENDER*ORDER)
RESISTANCE*GENDER	SUBJECT(RESISTANCE*GENDER*ORDER)
RESISTANCE*ORDER	SUBJECT(RESISTANCE*GENDER*ORDER)
GENDER*ORDER	SUBJECT(RESISTANCE*GENDER*ORDER)
RESISTANCE*ORDER*GENDER	SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*RESISTANCE	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*GENDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*ORDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*RESISTANCE*GENDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*RESISTANCE*ORDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*GENDER*ORDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)
GLOVE*RESISTANCE*ORDER*GENDER	GLOVE*SUBJECT(RESISTANCE*GENDER*ORDER)

APPENDIX E

MANOVA SOURCE TABLE

Table E-1

MANOVA Source Table, Wilk's Criterion

Source	DF	F	Prob>F
RESISTANCE	6,68	1.08	0.3840
GENDER	3,34	2.84	0.0523
ORDER	3,34	1.36	0.2722
RESISTANCE*GENDER	6,68	1.09	0.3750
RESISTANCE*ORDER	6,68	0.43	0.8556
GENDER*ORDER	3,34	0.43	0.7298
RESISTANCE*GENDER*ORDER	6,68	0.48	0.8226
GLOVE	3,34	1.23	0.3133
GLOVE*RESISTANCE	6,68	1.57	0.1679
GLOVE*GENDER	3,34	4.33	0.0109
GLOVE*ORDER	3,34	27.06	0.0001
GLOVE*RESISTACE*GENDER	6,68	1.91	0.0915
GLOVE*RESISTANCE*ORDER	6,68	0.74	0.6164
GLOVE*GENDER*ORDER	3,34	4.50	0.0092
GLOVE*RESISTANCE*GENDER*ORDER	6,68	1.29	0.2750

APPENDIX F

ANOVA SOURCE TABLE FOR THE RMSH MEASURE

Table F-1

ANOVA Source Table For The RMSH Measure
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
RESISTANCE	2	0.00073452	0.00036726	0.22	0.7999
GENDER	1	0.00745538	0.00745538	4.56	0.0396
RESISTANCE*GENDER	2	0.00057119	0.00028559	0.17	0.8404
ORDER	1	0.00016017	0.00016017	0.10	0.7561
RESISTANCE*ORDER	2	0.00118940	0.00059470	0.36	0.6975
GENDER*ORDER	1	0.00000017	0.00000017	0.00	0.9920
RESISTANCE*GENDER*ORDER	2	0.00124565	0.00062282	0.38	0.6859
ERROR	36	0.05884650	0.00163463		

Table F-2

ANOVA Source Table For The RMSH Measure
Univariate Tests of Hypotheses for Within Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
HAND_W	1	0.00007350	0.00007350	1.04	0.3140
HAND_W*RESISTANCE	2	0.00044556	0.00022278	3.16	0.0544
HAND_W*GENDER	1	0.00072600	0.00072600	10.30	0.0028
HAND_W*RESISTANC*GENDER	2	0.00009506	0.00004753	0.67	0.5158
HAND_W*ORDER	1	0.00108004	0.00108004	15.32	0.0004
HAND_W*RESISTANCE*ORDER	2	0.00024502	0.00012251	1.74	0.1903
HAND_W*GENDER*ORDER	1	0.00034504	0.00034504	4.90	0.0334
HAND*RESIS*GENDER*ORDER	2	0.00021527	0.00010764	1.53	0.2309
ERROR(HAND_W)	36	0.00253750	0.00007049		

APPENDIX G

ANOVA SOURCE TABLE FOR THE RMSV MEASURE

Table G-1

ANOVA Source Table for the RMSV Measurement
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
RESISTANCE	2	0.00134740	0.00067370	0.34	0.7114
GENDER	1	0.01368038	0.01368038	6.98	0.0121
RESISTANCE*GENDER	2	0.00085056	0.00042528	0.22	0.8060
ORDER	1	0.00053204	0.00053204	0.27	0.6056
RESISTANCE*ORDER	2	0.00159640	0.00079820	0.41	0.6685
GENDER*ORDER	1	0.00017604	0.00017604	0.09	0.7661
RESISTANCE*GENDER*ORDER	2	0.00040790	0.00020395	0.10	0.9014
ERROR	36	0.07056125	0.00196003		

Table G-2

ANOVA Source Table for the RMSV Measurement
Univariate Tests of Hypotheses for Within Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
HAND_W	1	0.00015504	0.00015504	1.48	0.2317
HAND_W*RESISTANCE	2	0.00018227	0.00009114	0.87	0.4276
HAND_W*GENDER	1	0.00085204	0.00085204	8.13	0.0072
HAND_W*RESISTANC*GENDER	2	0.00037527	0.00018764	1.79	0.1814
HAND_W*ORDER	1	0.00000038	0.00000038	0.00	0.9526
HAND_W*RESISTANCE*ORDER	2	0.00019994	0.00009997	0.95	0.3947
HAND_W*GENDER*ORDER	1	0.00053204	0.00053204	5.08	0.0304
HAND*RESIS*GENDER*ORDER	2	0.00026127	0.00013064	1.25	0.2995
ERROR(HAND_W)	36	0.00377175	0.00010477		

APPENDIX H

ANOVA SOURCE TABLE FOR THE TOT MEASURE

Table H-1

ANOVA Source Table for the TOT Measurement
Tests of Hypotheses for Between Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
RESISTANCE	2	494.415965	247.207982	0.33	0.7183
GENDER	1	4665.578776	4665.578776	6.30	0.0167
RESISTANCE*GENDER	2	259.828290	129.914145	0.18	0.8397
ORDER	1	6.360251	6.360251	0.01	0.9267
RESISTANCE*ORDER	2	742.728702	371.364351	0.50	0.6097
GENDER*ORDER	1	0.131276	0.131276	0.00	0.9894
RESISTANC*GENDER*ORDER	2	414.980227	207.490114	0.28	0.7572
ERROR	36	26646.688562	740.185793		

Table H-2

ANOVA Source Table for the TOT Measurement
Univariate Tests of Hypotheses for Within Subjects Effects

Source	DF	Type III SS	Mean Square	F Value	PR>F
HAND_W	1	150.52545937	150.52545937	3.68	0.0631
HAND_W*RESISTANCE	2	109.25574375	54.62787188	1.34	0.2758
HAND_W*GENDER	1	452.01100104	452.01100104	11.05	0.0020
HAND_W*RESISTANC*GENDER	2	81.52752708	40.76376354	1.00	0.3792
HAND_W*ORDER	1	1358.93975104	1358.93975104	33.22	0.0001
HAND_W*RESISTANCE*ORDER	2	106.62356458	53.31178229	1.30	0.2842
HAND_W*GENDER*ORDER	1	13.94612604	13.94612604	0.34	0.5630
HAND*RESIS*GENDER*ORDER	2	48.41966458	24.20983229	0.59	0.5587
ERROR(HAND_W)	36	1472.85651250	40.91268090		

APPENDIX I

MEANS AND STANDARD DEVIATIONS FOR RMSH, RMSV, AND TOT FOR FEMALE SUBJECTS

Table I-1

MEANS AND STANDARD DEVIATIONS FOR RMSH, RMSV, AND TOT FOR FEMALE SUBJECTS

Hand	Dependent Variable	N	Mean	Standard Deviation
Bare				
Small				
	RMSH	8	0.140	0.039
	RMSV	8	0.149	0.044
	TOT	8	51.1	23.6
Medium				
	RMSH	8	0.112	0.015
	RMSV	8	0.117	0.027
	TOT	8	69.5	12.1
Large				
	RMSH	8	0.116	0.023
	RMSV	8	0.114	0.026
	TOT	8	32.0	18.8
Glove				
Small				
	RMSH	8	0.147	0.035
	RMSV	8	0.153	0.033
	TOT	8	45.2	22.0
Medium				
	RMSH	8	0.120	0.017
	RMSV	8	0.129	0.023
	TOT	8	60.6	14.9
Large				
	RMSH	8	0.123	0.027
	RMSV	8	0.123	0.029
	TOT	8	62.2	21.0

APPENDIX J

MEANS AND STANDARD DEVIATIONS FOR RMSH, RMSV, AND TOT FOR MAIN EFFECTS

Table J-1

Means and Standard Deviations for RMSH, RMSV, And TOT for Main Effects

Main Effect	Dependent Variable	N	Mean	Standard Deviation
Hand wear				
Bare hand	RMSH	48	0.117	0.028
	RMSV	48	0.117	0.333
	TOT	48	67.7	19.4
Glove	RMSH	48	0.118	0.029
	RMSV	48	0.120	0.031
	TOT	48	65.2	22.0
Resistance				
Low				
	RMSH	32	0.120	0.035
	RMSV	32	0.120	0.039
	TOT	32	66.3	20.2
Medium				
	RMSH	32	0.119	0.027
	RMSV	32	0.123	0.031
	TOT	32	63.7	20.6
High				
	RMSH	32	0.114	0.021
	RMSV	32	0.114	0.022
	TOT	32	69.2	16.4
Gender				
Female				
	RMSH	48	0.126	0.028
	RMSV	48	0.130	0.033
	TOT	48	59.4	20.2
Male				
	RMSH	48	0.108	0.024
	RMSV	48	0.106	0.025
	TOT	48	73.4	16.8
Hand-wear condition order				
Bare-Glove				
	RMSH	48	0.118	0.028
	RMSV	48	0.121	0.033
	TOT	48	66.1	20.2
Glove-Bare				
	RMSH	48	0.116	0.027
	RMSV	48	0.116	0.029
	TOT	48	66.7	19.5