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COMPARISON OF FORCE AND TACTILE FEEDBACK FOR GRASP FORCE CONTROL IN TELEMANIPULATION

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ABSTRACT

This study examines the comparative efficacy of using direct force feedback or a simple vibrotactile display to convey changes in the intensity of remote grasp force relayed from a robotic end effector. Our findings show that a simple vibrotactile cue, in absence of direct force feedback, is effective in signalling abrupt changes in remote grasp force regardless of magnitude, and when changes in force are not too slow or protracted in nature (i.e., ramp times less than 2 s). In cases where the operator must dynamically tract and respond to slow but large variations in grasp force, the comparatively crude vibrotactile display examined in this study would prove helpful; but would not be as effective as that of a direct contact force display. Immediate applications and utility of current generation and near-term prototype tactile displays are discussed.

INTRODUCTION

Many remote manipulators provide only visual feedback to guide remote end-effector pose and grasp force. As a result, operators can command insufficient grasp force to the remote controller. Consequences of inadequate grasp force are: a) slippage and realignment of objects held within the remote gripper, b) complete loss of grasp, and c) increased risk of task or mission failure. Given such consequences, operators usually apply greater than necessary grasp force to the master-controller following a better safe, than sorry strategy for control of remote grasp force.

Unfortunately, sustained or very repetitious overforcing of the master controller can be counterproductive if applied forces are sufficient to:

a) damage to objects held within the remote gripper,

b) provoke localized muscle fatigue and discomfort (Wiker, Hershkowitz, and Zik (1989), see Wiker, Chaffin and Langolf (1989) for bibliography), and

c) promote degradation of manual performance (see Wiker, Langolf, and Chaffin (1989) for bibliography).

A frequently advocated solution for such problems is to provide bilateral, force-reflection between the master controller an remote end-effector. Once equipped, such telemanipulators typically demonstrate much improved manipulative performance. Provision of force reflection is not, however, without its price. Bilateral force reflection:

a) is usually quite expensive to build and then to maintain, and

b) nearly precludes post hoc implementation with existing telemanipulators.

In comparison with force feedback, current generation tactile displays:

a) are usually inexpensive to build, implement, and to maintain,

b) like force reflective displays, can provide sensory information that is consistent with that normally experienced during typical manual activities. Hence, the operator does not have to create novel perceptual models that require constant reinforcement, and

c) can be combined with existing telemanipulators to augment visual feedback to enhance and to extend operation manipulative capabilities.

For these reasons, we were interested in the efficacy of augmenting a telemanipulator with only tactile or vibrotactile cues of grasp force (Wiker, 1988a, b, and c). Specifically, we were interested in how effectively an operator could use either a direct force feedback or cutaneous cue to detect changes in displayed remote grasp force, and to regain desired levels of grasp force.

METHODS AND MATERIALS

Subjects

Seven male and two female university students participated in this experiment on a voluntary, paid, and informed consent basis. All subjects appeared and claimed to be in good health.

Apparatus

An electromechanical, one degree-of-freedom, bilateral, master-slave telemanipulator, was shown in Figure 1, was used this experiment. A microcomputer was used to monitor and actuate direct-drive electric actuators that produced negligible friction and backlash (See Duffie, Wiker, and Zik (1989) and Duffie, Wiker, Zik, and Gale (1990) for a more detailed explanations of the master-slave apparatus employed in this experiment).

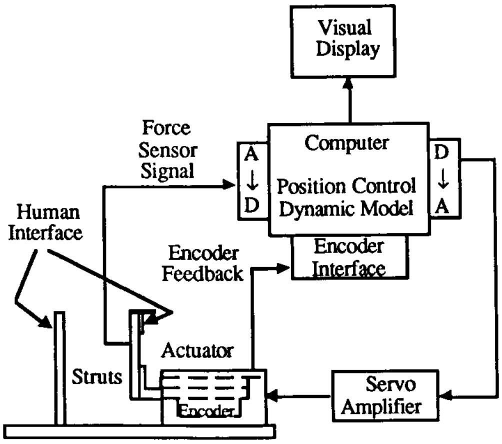

Figure 1.

Diagram of the master-controller system used in the experiment.

A calibrated strain gage was mounted on the master controller to measure forces exerted by the subject's fingers when squeezing the master controller digits. A high-resolution encoder monitored the actual position and velocity of the controller's digits. The microcomputer was used to command and to monitor the position of the master-controller, and to record:

a) position commands sent to the master-controller,

b) actual position of the master-controller,

c) force or vibrotactile intensity presented to the subject, and

d) time.

Force cues were produced by monitoring commanded and actual position, and converting the position error into a reactive force using a spring constant of 0.833 N per mm.

To provide vibration stimuli to the subject, the master controller actuator was oscillated at 250 Hz. Cues of changes in remote force were signalled by altering peak-to-peak amplitudes of master controller digit oscillations. To avoid the difficulties of mechanical couplings, we maintained contact between the master controller digits and subject's fingers using a servo-controlled contact force of 1.43 N. This strategy helped to stabilize the mechanical impedance of the finger tissues and reduced the potential for variable mechanical damping of the vibration stimulus.

Perceived intensities of the force and vibrotactile cues were matched for each individual subject using a cross-modal matching technique (See Lodge (1981) and Wiker et al. (1989) for detailed procedures). Thus, a change in remote grasp produced a change in master-controller force reflection, or in vibrotactile vibration intensities, that were perceived to be of equal intensity.

PROCEDURES

Subjects performed a series of trials in which they maintained a pulp-pinch grasp of fixed force magnitude at a "remote gripper." The magnitude of the remote grasp force was fixed for each subject based upon their psychophysical estimate of 5 N. The average grasp force produced across all subjects was 6.2 N. Grasp force applied by the subjects was indicated by a corresponding adjustment of a visual cursor position on a CRT. Subjects exerted and maintained the required pinch grasp until they felt confident that they could recognize and correct any changes in the level of grasp force held without the aid of visual feedback.

Once subjects had signalled to eliminate the visual indicator of grasp force, a random time interval ranging between 2 and 5 s passed before the computer moved the digits of the master-controller either 2, 4, or 6 mm away from the subject's finger. The maximum displacement (6 mm) produced a reduction in force or vibration cue without significant change in the hand's posture. Subjects were instructed to use force or vibrotactile cues, depending upon the trial, to detect a change in remote grasp force, and to initiate and guide adjustments in grasp posture required to return grasp forces back to the objective force as quickly and as accurately as possible.

Once the disturbance in force or vibrotactile cue was initiated, adjustments in the master controller digit position and actual grasp force or vibrotactile intensity were recorded at 166.7 Hz until completion of a 6 s post-disturbance period.

Experimental Paradigm

As shown in Figure 2, subjects performed a series of trials with, either force or vibrotactile feedback, in which we changed the magnitude of the grasp force disturbance (i.e., change in master controller position of 2, 4, or 6 mm), and the rate at which the disturbance was invoked (a step change, a 2 s linear ramp, or a 4 s linear ramp). All nine combinations of positional displacement and displacement rate were presented five times, in random order, using either force or vibrotactile feedback, during a single 1 hour period. Subjects received, on average, one minute rest intervals between trials. Trials performed using the alternative display mode were completed within a few days of the initial day's testing. The order of experience of grasp force display format was randomly assigned.

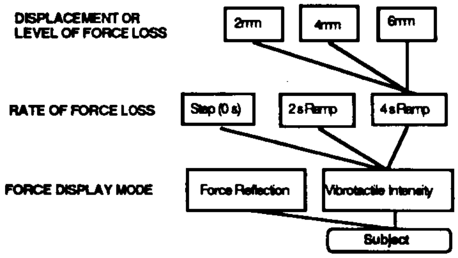

Figure 2.

Levels and rate of change in grasp force displayed to each subject using a repeated measures experimental paradigm.

Graphically displayed in Figure 3, metrics used to characterize subject grasp control capability were:

a) maximum loss of grasp force, or force error, following grasp disturbance,

b) time intervals needed by subjects to return grasp forces to within 90 percent of the pre-disturbance grasp force magnitude (i.e., the grasp force recovery period), and

c) difference between pre- and post-disturbance grasp force during the last 2 s of 6 s recovery period.

Ideal performance would be characterized by no grasp force error during the disturbance period. If some force loss was experienced, then a subject should rapidly reestablish the desired force level with no differences in grasp forces measured during pre- and during the final stages of post-disturbance force recovery period.

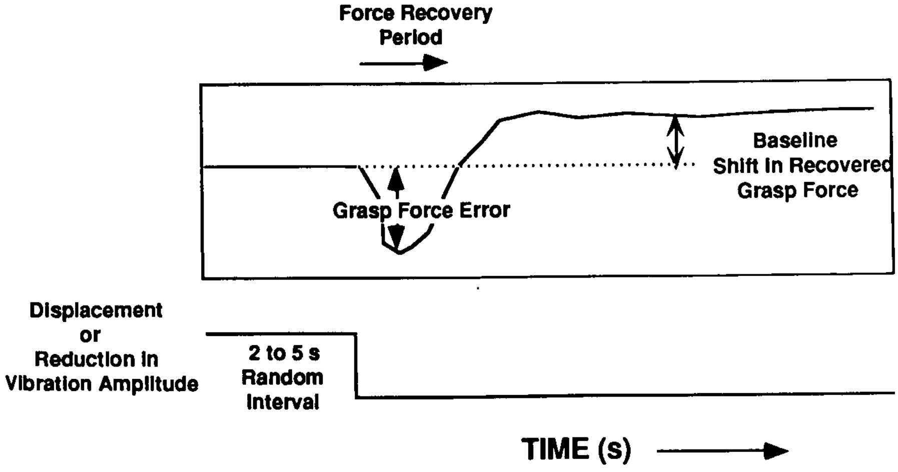

Figure 3.
Diagram showing subject performance criteria used to evaluate their force control capacity following an unexpected reduction in remote gripper grasp force indicated by a change in the intensity of contact force or vibration amplitude at the master-controller's digits.

RESULTS

Remote Grasp Force Display Mode and Initial Grasp Force Error

A repeated-measures ANOVA was performed to test whether remote grasp force feedback display mode, the magnitude of the grasp force disturbance, the rate at which the disturbance occurred, and their interactions were important determinants in the control of remote grasp force. All tests were conducted fixing Type I and Type II errors at p=0.05 and p=0.10 respectively. The mode of force display, the magnitude of shift in force (i.e. controller displacement), the rate at which changes in force cues occurred (i.e., period of the displacement ramp), as well as all two- and three-way interactions of these factors, showed statistically significant impacts upon operator grasp force control ($p < .05$; see ANOVA tables in Appendix for F-tests).

As shown in Figure 4, regardless of feedback mode, subjects were unable to maintain grasp force control with zero error following either a step or ramp change in master controller force feedback. Loss of grasp force control was directly proportional to the speed at which the master controller indicated that the "remote" grasp force had declined. On average, the force display was more effective in minimizing grasp force error following a decline in feedback intensity. However, vibrotactile feedback produced equivalent performance with that of the force display when disturbances were rapid (i.e., a step-reduction in vibration intensity), and when shifts in intensity of grasp force cues were small. The vibrotactile display was inferior in maximizing grasp control when changes in force remote intensity were quite slow and protracted in nature.

Remote Grasp Force Display Mode and Force Recovery Period

In addition to reduction of the maximum loss of gripper force, an effective display should help the operator to quickly regain desired grasp force once lost. Our analysis of the period of time required for subjects to regain 90 percent of initial force levels following a step or ramp loss of force, showed that:

a) for small reductions in grasp force, the amount of time required to increase force to 90% of the original force were equivalent between vibrotactile and force reflective displays. However, as the magnitude of grasp force change increased, direct force feedback improved performance while vibrotactile cues were associated with longer recovery periods,

b) use of vibrotactile display of remote grasp force produced an opposite effect from that observed with direct force reflection. Recovery was more rapid when vibrotactile stimulus changes were small (i.e., in the face of small manipulator displacements from the finger).

Remote Grasp Force Display Mode and Error in Recovered Grasp Force

Another metric of the subject's ability to control grasp force is the error between the pre- and post-disturbance level of grasp force. About 70 percent of the trials produced under-force errors. If displacement or loss of force was small (i.e., 1.7 N), then vibrotactile displays produced the most accurate return to desired grasp force. However, as the magnitude of force disturbances increased, use of the vibrotactile display produced a progressively lower levels of recovered grasp force and, thus, greater errors in recovered grasp force. This outcome was exacerbated when rates of changes in displayed force, or lengths of time subjects had to spend tracking changes in grasp force, were increased. All remaining effects were not found to be statistically significant.

Relationships Found Among Force Display Modes and Grasp Force Disturbance Parameters

Correlation analysis was performed among dependent metrics of grasp force as well as independent factors such as force display mode, magnitude of force loss or manipulator displacement, and rate of force loss or change in manipulator displacement. The analyses showed the following material relationships:

a) grasp force error was directly associated with the rate at which the loss of grasp force occurred ($r = -0.78$ for force display and $r = -0.55$ for vibrotactile display),

b) the magnitude and direction of error in recovered grasp force was directly related to the magnitude of the initial loss of grasp force when using the vibrotactile display ($r = -0.61$),

c) differences between pre- and post-disturbance grasp force were lower when subjects spent more time establishing the desired grasp force ($r = -0.78$ for vibrotactile displays, $r = -0.66$ for force displays),

d) maximum loss in grasp force was greatest when ramp periods were small or when the rate of change in displayed force was high ($r = -0.40$ vibrotactile, $r = -0.65$ for force display)

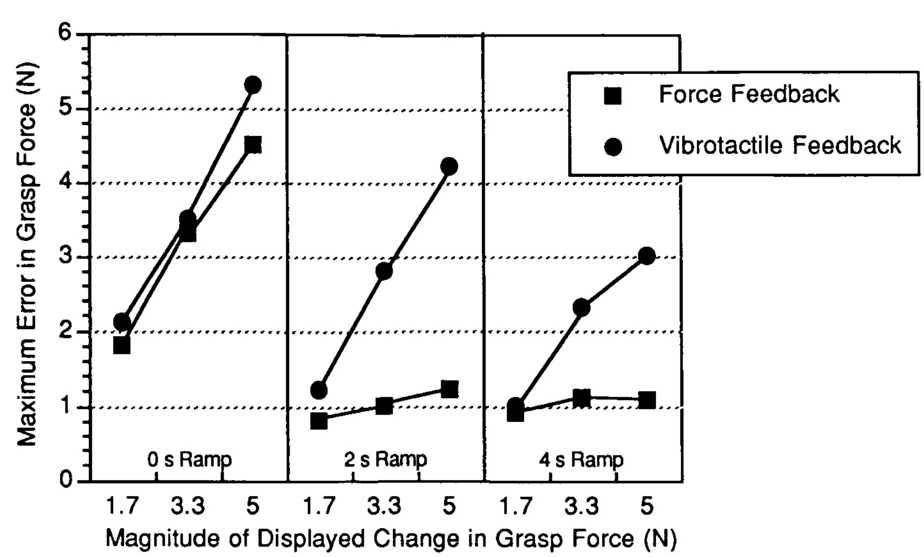

Figure 4.

Maximum error in remote grasp force following a change in contact force or vibration intensity displayed at the master controller. Errors are plotted against plotted across display mode, and magnitude and rate of change in force displayed .

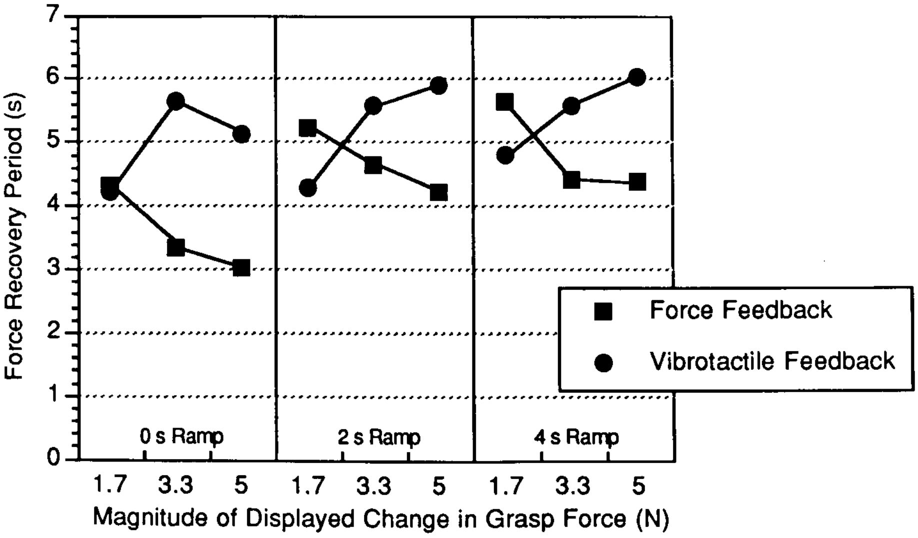

Figure 5.

Time period required to reestablish 90 percent of the pre-disturbance level of grasp force plotted across display mode, and magnitude and rate of change in force displayed.

Predictions of Grasp Force Response Error

$$GFE = 0.55 - 0.16\,D + 0.42\,F + 0.33R + 0.30\,DF - 0.20\,DR - 0.30\,FR + 0.10\,DFR \qquad R^2 = 0.71$$

where:

GFE = Magnitude of Maximum Difference Between Pre and Post-disturbance Grasp Force

D = Display Mode (0 = force, 1 = vibrotactile)

F = Magnitude of Displayed Change in Grasp Force (N)

R = Duration of Ramped Change in Displayed Grasp Force (s)

The interrelationships between the magnitude and rate of change of displayed shifts in remote grasp force and error in commanded grasp force predicted by the above equation are summarized in the following response surfaces plotted for each display mode:

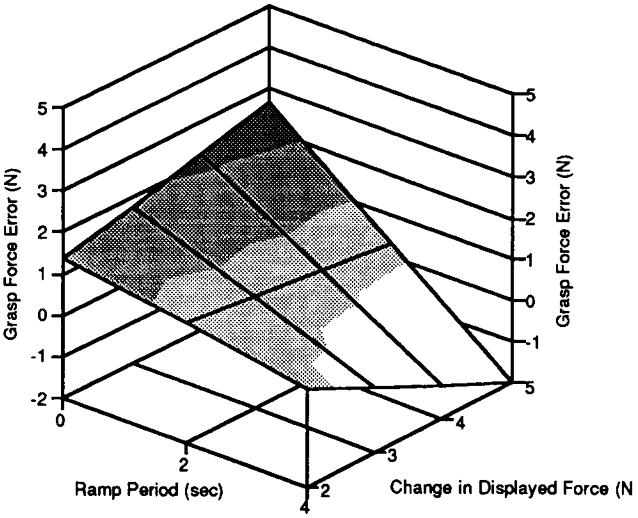

Figure 7.
Predicted grasp force error produced by direct force feedback of changes in remote grasp force.

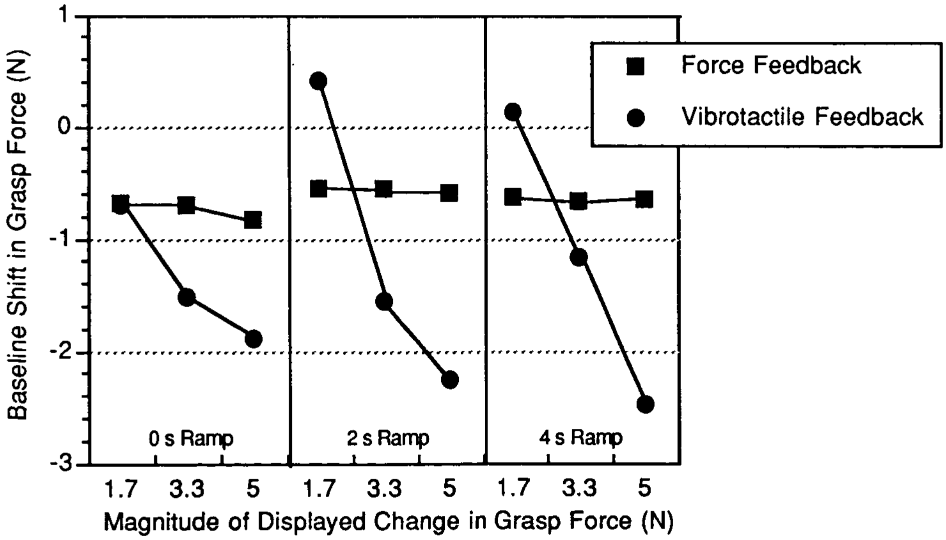

Figure 6.

Error in recovered grasp force plotted across display mode, and magnitude and rate of change in force displayed.

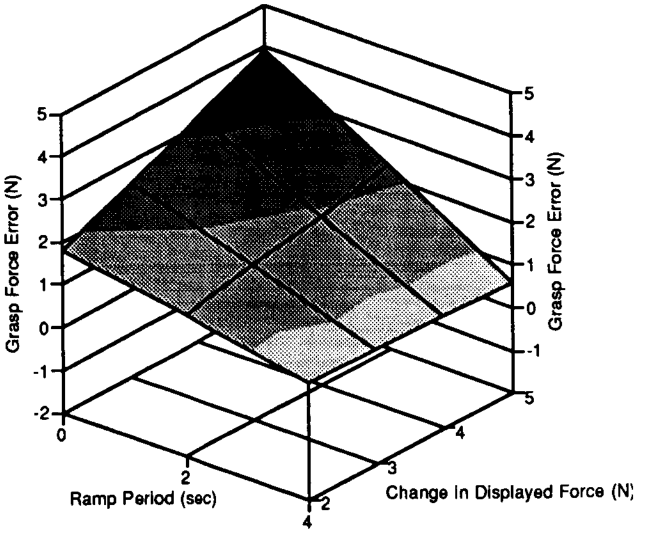

Figure 8.
Predicted grasp force error produced by vibrotactile feedback of changes in remote grasp force.

DISCUSSION AND CONCLUSIONS

Our findings show that a vibrotactile display can signal changes in and guide control of remote grasp force. A comparatively simple vibrotactile display showed equivalent or improved performance with that of a force reflective display when changes in displayed remote grasp force were abrupt (i.e., step changes) or when magnitudes of shifts, regardless of ramp period up to 4 s, were small. However, when changes in remote grasp force were larger in magnitude, and required sustained adjustment of the position of the master controller, the direct display of force produced better control of remote grasp force.

With extremely abrupt or step-like changes in remote grasp force, perceptual and motor response delays produced decrements in grasp force that were directly proportional to the magnitude of the disturbance; regardless of display mode used. In short, subjects were able to recognize and respond to the displayed disturbance with equal capability across display modes. Given a fixed response delay due to basic neuromotor reaction time requirements, the errors found were proportional to the magnitude of the abrupt change in grasp force.

If force adjustments were greater in magnitude or more sustained in nature, performance using the vibrotactile display was worse than that found with display of direct contact force. This outcome may be due to one or all of the following:

a) greater delays in processing changes in vibratory cutaneous stimuli in comparison to those found with force perception, (light touch transition to muscle tension sense),

b) efferent masking of cutaneous feedback as the subject's digits continued to adjust the position of the master controller's digits,

c) masking of small changes in the vibratory stimulus by the stimulus itself.

The ever-present and tenacious phenomena of efferent and afferent masking of cutaneous stimuli have been reported in the literature. Although further basic research is needed to fully characterize the nature and magnitude of masking effects, such effects can be mitigated to some degree. We expect that future experiments will show that changes in tactile display locus and changing both the intensity and spatial organization of the stimulus representing grasp force intensity and distribution will produce displays that are far more competitive with direct force reflection displays that the simple system investigated here.

Our findings show that a simple vibrotactile cue, in absence of direct force feedback, can be very effective in signalling abrupt changes in remote grasp force regardless of magnitude, and when changes in force are not too slow or protracted in nature (i.e., ramp times less than 2 s). For a large variety of remote manipulation tasks, force cues needed would not be expected to exceed those examined in this experiment. If so, vibrotactile or similar forms of tactile displays would be effective in aiding remote grasp and manipulation. In cases where the operator must dynamically tract and respond to slow but large variations in grasp force, the vibrotactile display examined in this study would still prove helpful; but not as effective as that of a contact force display.

We are pursuing development of tactile displays that are more comfortable to use for long periods of time (i.e., between 1 and 2 hours), that provide patterns of cutaneous cues that are more resistant to masking effects, and that can provide cues of variations in magnitude and direction of forces distributed across the remote contact surfaces. Current generation and near-term prototype tactile displays under development by WCSAR industrial consortia members will provide additional sensory information needed by operators of visually remote manipulators that cannot practically employ high-quality bilateral direct force feedback, to wearers of prosthetic limbs, and to operators of telemanipulator systems in microgravity environments where applying forces to the operator's body becomes problematic.

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APPENDIX

ANOVA Table for Maximum Force Error

Source of Variation	df	Sum of Squares	Mean Square	F	p <
Subjects	8	16.787	2.098		
Feedback Mode (M)	**1**	**49.093**	**49.093**	**22.3**	**.0015**
Error	8	17.603	2.200		
Force Magnitude (F)	**2**	**98.612**	**49.306**	**155.8**	**.0000**
Error	16	5.065	.317		
MF	**2**	**18.551**	**9.276**	**23.2**	**.0000**
Error	16	6.388	.399		
Ramp Speed (R)	**2**	**102.197**	**51.099**	**71.95**	**.0000**
Error	16	11.362	.710		
MR	**2**	**10.773**	**5.387**	**16.64**	**.0001**
Error	16	5.180	.324		
FR	**4**	**17.540**	**4.385**	**11.55**	**.0000**
Error	32	12.145	.380		
MFR	**4**	**5.750**	**1.437**	**4.39**	**.0061**
Error	32	10.484	.328		

ANOVA Table for Force Recovery Period

Source of Variation	df	Sum of Squares	Mean Square	F	p <
Subjects	8	100.163	12.520		
Feedback Mode (M)	1	31.210	31.210	1.51	.2534
Error	8	164.818	20.602		
Force Magnitude (F)	2	.380	.190	.06	.9349
Error	16	44.920	2.807		
MF	2	47.108	23.554	14.3	.0003
Error	16	26.239	1.640		
Ramp Speed (R)	**2**	**21.881**	**10.941**	**4.87**	**.0222**
Error	16	35.899	2.244		
MR	2	5.515	2.758	2.17	.1468
Error	16	20.346	1.272		
FR	4	3.047	.762	.65	.6295
Error	32	37.368	1.168		
MFR	4	1.124	.281	.18	.9450
Error	32	48.860	1.527		

ANOVA Table for Baseline Shift in Force

Source of Variation	df	Sum of Squares	Mean Square	F	p <
Subjects	8	56.803	7.100		
Feedback Mode (M)	1	13.015	13.015	.994	.3479
Error	8	104.735	13.092		
Force Magnitude (F)	**2**	**33.900**	**16.950**	**7.599**	**.0048**
Error	16	35.688	2.230		
MF	**2**	**30.426**	**15.213**	**8.35**	**.0033**
Error	16	29.156	1.822		
Ramp Speed (R)	2	1.208	.604	.345	.7135
Error	16	28.039	1.752		
MR	2	.081	.041	.054	.9478
Error	16	12.108	.757		
FR	4	3.327	.832	1.15	.3527
Error	32	23.220	.726		
MFR	4	4.461	1.115	1.73	.1662
Error	32	20.544	.642		