THE EFFECTS OF FORCE LEVEL AND FORCE DIRECTION ON FORCE DISCRIMINATION AND ISOMETRIC TRACKING PERFORMANCE

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(ABSTRACT)

An isometric, zero-order, two-dimensional pursuit tracking task utilizing a tracking path that incorporated both linear and circular segments was used to examine the effects of variation in force magnitude, force direction, and direction of target movement upon tracking performance. A contralateral force-matching procedure was also employed to assess the effects of variation in force level and force direction upon force discrimination capabilities.

Increases in force demand were hypothesized to result in degradation of both force discrimination capabilities and accuracy of tracking performance. Variation in force direction was hypothesized to result in tracking performance degradation and force discrimination deterioration that were inversely related to strength-related differences associated with each direction. It was hypothesized that linear tracking performance during inward (force-decreasing) movement of the target would be superior to linear tracking performance in the outward (force-increasing) direction. Finally, it was hypothesized that the direction-sensitive strength:demand ratio, SDR, (a measure of the relationship

between strength and the magnitude of force demand) would correlate with both tracking performance and force discrimination measures and that force discrimination measures would correlate with tracking performance.

The findings robustly supported the hypothesized Force Level effect. The strength-related Force Direction effects were also supported, but somewhat less consistently than those for Force Level. As also hypothesized, linear inward tracking was superior to linear outward tracking. Previously unreported direction-of-movement effects were found for the circular tracking conditions. When measured along the path, clockwise (CW) tracking was superior to counterclockwise (CCW) tracking with the differences being greatest at the higher force level and in the longitudinal (forward and aft) directions. CCW tracking was superior to CW tracking when measured orthogonal to path. The hypothesized correlations among SDR, two of the three force discrimination measures, and tracking performance were found to be small but significant.

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A. W. S.

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INTRODUCTION

Equipment is often built to specified ranges of values in accordance with reference criteria or guidelines. Subsequently, operators must be able to operate the equipment as it has been manufactured. If there has been appropriate human factors input during the design stage to assure that operational ranges do not exceed the capabilities of the intended user population, there will be no (or only a few) instances of mismatch between equipment demands and operator capabilities. However, there are occasions when human factors assistance is sought after-the-fact to examine existing equipment-operator interface characteristics and evaluate their adequacy. Such instances can occur not only as the result of inadequate human factors involvement during the design process, but also as the result of new requirements to meet upgraded standards or to accommodate changes in the intended user population.

The need for the military to accommodate increasing numbers of women in the late 1970s provided the impetus for a number of assessments of operator-equipment characteristics. Among the studies initiated during the ensuing years was an evaluation of the forces inherent in the execution of in-flight helicopter emergency maneuvers (Schopper and Wells, 1986). The study indicated that during a simulated hydraulics-assist failure (disablement of the hydraulic assist mechanism) the upper portion of the distribution of operational control forces required for the collective control exceeded the measured strength capability of "weak" individuals; i.e., those at the lower end of the distribution of the population base of potential aviators (Schopper and Mastroianni, 1984).

The situation described is representative of the circumstance last cited above--that wherein a change in the user population has resulted in human interface problems that did not exist at the time the equipment was initially introduced. Under such conditions, the alternatives are to either undertake an appropriate retrofit program or to place constraints on the user population to assure that those who are permitted to operate the equipment possess the attributes necessary to assure that a satisfactory operator-equipment match exists.

The findings of the helicopter study just cited instigated the present research. Prior to making a decision regarding the possible adoption of strength-related personnel selection criteria, questions surfaced regarding the relationships among force demands, performance and strength. The needed information was not available then, nor has it surfaced during the intervening years. The present research represents an initial effort to address these questions.

The pertinent literature will be reviewed in two sections. The first section will review the engineering information likely to be used initially by design engineers and Human Factors Engineering (HFE) practitioners seeking information on the relationship between strength and performance. The second portion of the review addresses the experimental research literature.

LITERATURE REVIEW

Human Factors and Design Guide References

The Human Factors Engineering (HFE) profession focuses on the interface between the operator and the work environment. Because an individual's strength is a primary physical dimension, one would expect that there exists an extensive body of research knowledge relating interindividual differences in strength to performance of various types of visuomotor tasks differing in the degree of force required. Such is not the case, however.

Reviews and summaries of strength-related literature (e.g., Laubach, 1978) describe maximal force exertion capabilities of a variety of populations. Studies such as those reviewed by Laubach typically contain descriptions of the distribution of maximal voluntary forces applied to a variety of handles and controls placed in a number of orientations and locations relative to the subject. These data provide information regarding the magnitude of brief maximal force exertion capabilities; they also clearly demonstrate (a) the large range of force capabilities demonstrated by various individuals for any given exertion, and (b) the large force variation evidenced among the orientations and locations of the exertions addressed. While such data may supply the HFE practitioner with information useful in determining the upper design limits for short-time strength exertions, they do not provide the basis for appropriate decisions regarding prolonged or sustained motor control activities. Nor do they address the potentially large role that strength differences may have upon the performance of physically demanding visuomotor tasks.

If the descriptive studies of maximal strength are not a viable source, then one may seek the needed information from the various engineering design guides (e.g., Van Cott and Kinkade, 1972; Woodson, 1982), HFE texts (e.g., Oborne, 1982; McCormick and Sanders, 1982), or texts on biomechanics (Chaffin and Andersson, 1984). However, these sources are also lacking relevant information.

Force-related guidelines, when they are proffered, are often very narrow in scope and based on few empirical findings. McCormick and Sanders (1982) discuss control resistance, but cite only two primary sources (both published more than 20 years ago) and one secondary source. Oborne (1982) completes his entire treatment of the topic of the level of control forces in a single paragraph and a brief table from the initial, 1963 version of the Human Engineering Guide to Equipment Design (Morgan, Cook, Chapanis, and Lund, 1963).

Chapanis and Kinkade's (1972) chapter on control design in the 1972 edition of the Human Engineering Guide to Equipment Design (Van Cott and Kinkade, 1972) addresses the topic of control resistance. They state that the "Limits of the resistance of hand controls are difficult to determine because of (a) the wide variations in the operator population; (b) type and location of controls; and (c) frequency, duration, direction, and amount of control movement" (p. 351). The authors give control resistance design guidelines which are based extensively on military handbooks. In the writer's experience, these resources too often rely on "professional opinions" rather than empirical findings.

Woodson's (1981) more recent handbook provides little updated or additional information. He cites "common control operational force limits" (p. 775), but provides no reference. On succeeding pages, however, he has extracted force descriptive data pertaining to various hand control positions from Morgan et al.'s (1963) earlier handbook.

The Military Standard: Human Engineering Design Criteria for Military Systems, Equipment, and Facilities (MIL-STD-1472C, Department of Defense, 1981) contains guidance pertaining to the limiting forces applicable to the operation of a variety of controls and handles. The recommendations are spotty, however. Whereas linear distance limitations are given for a variety of controls, many lack recommendations pertaining to force-related limitations.

In the very recent Handbook of Human Factors (Salvendy, 1987), the roles of strength and variation of force demand in visuomotor performance are hardly addressed. Knight's (1987) chapter on manual control discusses control resistance and biomechanical factors in just three paragraphs, citing only the 1966 study by Hammerton and Tickner (1966). Bullinger, Kern, and Muntzinger's (1987) chapter on control design provides a figure (Figure 5.3.3) which cites ranges of forces for several types of controls. Even with Kroemer's (1987) discussion of biomechanical factors which affect force exertion (in his treatment of strength assessment), this handbook provides little information on the possible roles of strength or variation in force demand upon visuomotor performance.

As pertains to the type of control of primary relevance to the present research proposal, the manually grasped lever, Chapanis and Kinkade (1972) indicate that "The maximum resistance for one-hand push-pull (fore-and-aft) movements along the midline of the body is 30 to 50 lb., depending on how far away the control is from the body (the farther away, the greater the recommended resistance)" (p. 369). A value of 20 lb is recommended as the maximum for lateral movements. (In SI units, the fore-aft range corresponds to 133.5-222.5 N; the lateral value corresponds to 89 N.) Woodson's (1981) handbook indicates that the operational force limits for a joy-stick or lever from a seated position are 45 lb (200.25 N) for fore-aft inputs and 18 lb (80.1 N) for lateral inputs. Bullinger, Kern, and Muntzinger (1987) cite a range of 10-200 N for a manually operated lever without further discussion regarding the direction of force input.

Recently, the Aeronautical Design Standard Handling Qualities Requirements For Military Aircraft, ADS-33, Amendment 1 (U.S. Army Aviation Systems Command, 1986) was published. It indicates that under normal flight conditions, the maximum force for fore-aft and lateral inputs to the cyclic control are to be 133 N (30 lb) and 67 N (15 lb), respectively. Under failure/malfunction emergency conditions, these maximums are increased to 178 N (40 lb) and 111 N (25 lb).

In conclusion, although the cited references provide recommendations regarding limits or ranges of force demand for particular controls, they give no information on potential changes in performance as a consequence of variation in force demands within the ranges cited. They do not even acknowledge the likelihood or possibility that interindividual differences in strength may affect performance of a demanding, force-loaded visuomotor task.

Experimental Literature

The proposed research addresses integrated visuomotor activities performed by the hands wherein accuracy of performance is a primary concern. As a consequence, the following review excludes the voluminous literature on human lift capabilities and work physiology studies that focus upon assessments of energy demands associated with performance of globally defined tasks and various exercise tests or regimens. Such literature does not address accuracy-of-performance. Additionally, the review does not include the substantial research literature pertaining to athletic performance because it, too, deals predominantly with gross, whole-body activities. Much of that literature has been reviewed previously (Gutin, 1972; Martens, 1974). Additionally, the research pertaining to rather elementary, speed-oriented motor performance (e.g., that pertaining to reaction times and discrete movement times) has not been included.

Strength and force discrimination. Prior to examining the more performance-oriented literature, research pertaining to relevant strength capabilities and psychophysical (force discrimination) findings is cited to provide additional perspective regarding the issue.

STRENGTH. The level of force which can be brought to bear upon a control is both a function of individual strength and of the geometrical relationship between the person and the control. An elementary finding regarding interindividual differences in strength is that, on the average, males are stronger than females (McCormick and Sanders, 1982). Laubach (1976) has addressed the topic in more detail. The strength of the upper extremities varies substantially with the particular limb/extremity addressed. Female upper body strength ranges from 35-79% of that of males depending on the particular exertion examined; the mean is 55.8% (Laubach, 1978). Laubach (1978) has commented that the value for the fifth percentile male exertion often exceeds the value for the 95th percentile female.

Laubach's (1978) review of previous research has clearly shown that differences in the relative geometry between the operator and the control, and differences in the direction of exertion yield substantial variation in the amount of force an individual can bring to bear upon a control. Research addressing the strength capabilities of individuals using an isometric control placed at the location of an aircraft "stick" control has been reported previously (Laubach, Kroemer, and Thordsen, 1972; McDaniels, 1981; Schopper and Mastroianni, 1984). (A "stick" is a vertical control whose null position is just forward of the aircraft seat in the midsaggital plane.) A consistent finding is that individuals are able to effect markedly larger force inputs in the longitudinal (fore-aft, F-A) directions than they are in the lateral (left-right, L-R) directions. Forces to the right exerted by the right hand of a right-handed individual, in particular, are likely to be considerably smaller than are longitudinal force inputs. McDaniel's (1981) data shows the largest difference in this regard. For the 50th percentile male he reported 553.8, 382.5, 234.0 and 157.5 N in the F, A, L, and R directions, respectively; i.e., the right-directed force input was only 28.4% of the forward input, 41.1% of the aft input, and 67.3% of the left input.

FORCE DISCRIMINATION. Early research addressed weight discrimination. It is noted that "weight" is the term employed by experimental psychologists who have studied the perceived "heaviness" of lifted objects. From a biomechanical perspective, the task (in its most elementary form) is more appropriately described as one of discriminating among different masses. It is a topic which has been examined extensively by experimental psychologists to determine the visual and contextual factors which affect one's perceptions of the weight of various objects. Corso (1967) and Jones (1986) provide further discussion of these phenomena. Jones (1986) makes no distinction between force discrimination and weight discrimination when discussing research undertaken to examine such perceptions without manipulating such factors as size, density, shape, etc. of the object lifted or the container in which it is placed.

Another observation regarding weight discrimination research pertains to the use of the term "lift" to describe subjects' behavior.

The actual behavior involved is generally not well described in biomechanical terms. For example, in Fleishman and Rich's (1963) research, the exertions were described in the following manner (p. 8): "Each S was blindfolded and received 24 such pairs, where each weight was lifted one at a time. The S's arm was on the table with lifting done from the wrist." No information was provided regarding the duration of each exertion, the interexertion interval, or whether or not the subject was instructed to maintain the weight (mass) in a static position (to minimize additional motion-related cues) for any given period before rendering his or her judgement. Unfortunately, the absence of more detailed biomechanical and temporal information make the interpretation of such research difficult from a biomechanical perspective.

The discussion provided below uses the term "weight" when referring to research in which individuals "lifted" an object to assess its "heaviness" (mass). The term "force" is employed when referring to research wherein the individual pushed or pulled against an isometric handle or control.

While there exists some debate about the precise form of the relationship, there is agreement among investigators that as the magnitude of the referent exertion increases, increasing deviations are required for an individual to be able to discern that a change has occurred. The ratio of the magnitude of the change relative to the magnitude of the referent level is interpreted as a measure of "sensitivity" to change; i.e., for a given referent level, a smaller ratio would indicate that the individual can detect a smaller change. An experimental paradigm typically requests an individual to lift a referent mass or exert a referent-level force and then attempt to identify another mass of the same value or exert a force of the same level as the referent. The magnitude of the referents are changed between trials.

The weight discrimination ratio is nearly constant for values in excess of 150 g (Engen, 1971; Victor Raj, Ingty, and Devanandan, 1985). Carlson, Drury, and Webber (1977) have reported no significant change in sensitivity (i.e., magnitude of the ratio) over a much higher range of values (20-40 kg) than are typically addressed during laboratory investigations. The ratios they encountered, approximately 0.04 at all levels, was somewhat lower than the ratios reported by early researchers, 0.06 to 0.10 (Woodworth and Schlosberg, 1965), but well within the range of ratios, 0.03-0.12, reported in more recent studies (Engen, 1971; Victor Raj, et al., 1985).

Recently, a new technique, contralateral limb force matching, has appeared for examining force perception more directly (Cafarelli and Bigland-Ritchie, 1979). In contrast to the rather passive role assumed by the subject in weight discrimination studies, this newer technique requires the subject to make an active exertion with one limb which he or she believes equals the referent force magnitude being exerted by the contralateral limb.

A typical weight discrimination procedure requires the subject to first lift or support a standard (referent) mass and then, using the same limb, similarly lift/support an experimental mass and render a judgement regarding the perceived 'heaviness' of the second relative to the first. The contralateral limb approach enables the researcher to minimize the potential distortion (decay) of the stimulus trace due to the passage of time (Gescheider, 1985), by (nearly) simultaneous generation of the referent and comparison exertions.

Cafarelli and Bigland-Ritchie (1979) made use of the biomechanical fact that muscle strength varies with muscle length. They initially determined the maximal force exertion capability of the thumb's adductor pollicis muscle at various positions (muscle lengths). The magnitudes of the forces exerted by the left thumb during attempts to match specific forces simultaneously exerted by the right thumb were then recorded. They found that the slopes of the plots of the magnitudes of the matching forces (y axis) and the referent forces (x axis) increased as the length (and resultant force exertion capability) of the force-matching muscle increased. These findings support the position that force discrimination is affected by the strength of the musculature involved.

One unusual aspect of some of the force-matching findings is that the slopes of the force-matching plots (change in the magnitudes of the force-matching exertions relative to that of the referent exertions) are less than one. This is most evident in the data depicted in Figure 1 of Jones and Hunter's (1982) research. Therein, a line with a slope of approximately 0.7 can readily be fitted to the data. Small referent force levels (X axis) are overestimated (Y axis), and large referent force levels are underestimated. Jones and Hunter (1982) indicate that the magnitude of the left-hand matching force approximates the actual magnitude of the right-hand referent force most accurately when the latter is in the range of 40-60 percent of its maximum value. To a lesser extent, the same pattern appears in Cafarelli and Bigland-Ritchie's data if one assumes the data appearing in their Figure 2 for one subject is representative of that of the others. For the condition in which the right and left force levels were roughly equated, the slope of the plot was somewhat less than unity, approximately 0.9, and the intercept is slightly above the origin.) Possible reasons for these findings have been discussed by Jones and Hunter (1982), but no research has yet presented a compelling explanation.

Changes in the angle of lift (e.g., the angle at the elbow) can substantially change the muscle force required to support a given weight since the muscle force vector does not remain at the same pull angle to the longitudinal axis of the forearm (Chaffin and Andersson, 1984). For example, Davis (1974) reported that the perceived weights of objects were larger when the objects were supported with the forearm horizontal with an elbow angle of 90 degrees than when they were supported at elbow angles of 30 and 60 degrees.

Whereas the force perception research reviewed to this point has considerable relevance to several aspects of the proposed research, it has not dealt directly with the issue of force discrimination as it pertains to control inputs. There is one early study by Jenkins (1947) that has addressed this issue directly. Because the relevance of

Jenkins' research exceeds that of any subsequently published study, it will be discussed in some detail.

Jenkins (1947) employed a variation of the Method of Average Error (also called the "Method of Adjustment", e.g., Gescheider, 1985) to determine the DL (difference limen--a measure of sensitivity to change) and constant error (CE--a measure of bias) of individuals attempting to exert specified levels of force inputs to three aircraft controls: stick, wheel, and pedals.

The controls were semi-rigid, nearly isometric in their response. (Actually, the stick control moved approximately 1.9 cm when a 225 N force was applied, and the pedal moved 1.3 cm when a force of 270 N was applied. The degree of rotation of the wheel control was not stated.) Each subject wore opaque goggles to eliminate visual cues.

Practice trials were provided at each force level for each control immediately prior to the onset of the test trials. The criteria for ending the practice trials were not explained except that the subject was "approximating the desired pressure (force)" (p. 399). During the practice trials each subject gradually increased the level of applied force until he was verbally informed he had attained the prescribed level. The series of test trials entailed 20 trials for all exertions undertaken on the stick control and 15 trials for the other two controls. During the test trials, 5-second rests were provided after each exertion. Verbal feedback indicating the actual force applied was provided during this interval.

The series with the stick control was undertaken with the right hand (the hand actually used in aircraft) performing exertions in all four directions. Those in the longitudinal direction were undertaken at the 4.5, 22.5, 45.0, 90.0, and 180.0 N force levels. Those directed to the left and right were the same as those for the longitudinal direction with the exception that a value of 135 N was substituted for the 180 N value due to the "considerable difficulty" experienced by subjects in attempting to attain the 180.0 N input in the right direction. The series involving the aircraft wheel control employed all values cited from 4.5-180.0 N. The series for the pedal deleted the 4.5 N value and added a 270 N value to this series. Pedal exertions were undertaken with both the left and the right foot.

Several observations are warranted. One is the relationship of discrimination capabilities to the referent values in an absolute sense. As Jenkins indicated, the DL increases in approximately linear fashion with the magnitude of the referent force levels within the 45-180 N range; i.e., individuals can discriminate changes in force level of approximately 3-4 N at the 45 N level, but require changes on the order of 9-11 N to realize the same degree of discrimination at the 180 N level. Hence, although the relative discrimination capability does not degrade as a function of the force level involved (in fact, DLs become slightly smaller over the range cited), the accuracy of perception in an absolute sense is considerably worse at the higher levels of force (i.e., the magnitude of the standard deviation, per se, is larger) .

Another observation pertains to the degree of discrimination involved as a function of the relative strengths of the musculature involved. There exist well documented differences between the forces individuals can bring to bear on aircraft controls: for example, McDaniels (1981) has reported that the average maximum pedal input exceeds the average stick input by a factor of six or more for both "50th percentile" males and females. In Jenkins' data there is some indication that such differences may have affected the discrimination capabilities he encountered. With one exception (wherein equal values were evidenced) at force levels in excess of 45 N, the standard deviations associated with larger force exertion capabilities (pedal inputs and two-handed inputs to the wheel) are less than those associated with smaller force exertion capabilities (one-handed inputs to the stick).

An examination of Jenkins' stick-related findings yields similarly equivocal evidence regarding such a relationship. McDaniels (1981) documented substantial direction-related strength differences associated with force-exertion capabilities on the stick control. He reported that the mean of the maximum fore-aft inputs exceeded those for the left-right inputs by a factor of nearly two (1.8) for males and by a factor of four for females. If a strength/force discrimination relationship holds, one would anticipate that such differences would appear in Jenkins' data. However, the longitudinal-vs-lateral comparison for stick inputs do not yield consistent, supportive findings except at the upper values, 44.5 N and 89.0 N, for which comparable data existed for both types of exertions. At these force levels, the mean CEs for the lateral inputs were in the -0.01 to +0.05 range, while the mean CEs for the longitudinal inputs ranged from +0.07 to +0.14. (The mean DLs were comparable, ranging from 0.07 to 0.09 for both types of inputs.) Too, it is noted that at the highest force level in the forward direction (40 lb, 178 N), the mean CE was -0.47, nearly five times larger than the typical mean CE (although the DL remained at 0.06, consistent with that evidenced during other inputs). The next largest negative CE, -0.20 is encountered at the maximum force level (30 lb, 133.5 N) employed during right-directed forces. While direction-specific strength capabilites were not reported by Jenkins, it is this writer's opinion that the appearance of negative CEs is likely to be associated with force demands that are beginning to approach the limits of force exertion capabilities in these two directions.

While some of the observations cited above are in the correct direction to support the hypothesis of a positive relationship between force-exertion capability (strength) and force discrimination capability, Jenkins found that the overall discrimination limens (DLs) and constant errors (CEs) (averaged over all directions and force levels--inclusive of the much more variable and higher values for the force levels at the 4.5 N and 22.5 N levels) were not significantly different among the three types of controls. Hence, these data provide only very marginal support for the existence of possible strength/force discrimination relationship.

There exist few other studies which have incorporated measures of physical discrimination capabilities. Cox (1977) used a measure of movement discrimination sensitivity in an examination of arm positioning behavior. His results were "mixed", with correlations ranging from less than 0.05 through 0.64 depending upon the nature of the movement performed. An early investigation of golfing skills (Phillips, 1941) employed measures of weight discrimination in an initial large-scale battery of potential predictor variables, but the weight discrimination variables were not included in the final equation. Fleishman and Rich (1963) found the DL for lifted weight discriminations to correlate 0.58 with the total time-on-target (TOT) during forty trials of a two-handed tracking task. This correlation, when coupled with a correlation of 0.49 between a paper-and-pencil measure of spatial ability, resulted in a multiple R of 0.73 with the total TOT tracking task score. An interesting aspect of this research was that over 10 successive blocks of 4 trials each, the correlation between the weight discrimination measure and tracking performance increased from 0.03 to 0.40 while the relationship between spatial ability and tracking performance decreased from 0.36 to 0.01.

DISCUSSION OF FINDINGS. To this point, the relevant literature has provided little in the way of consistent support for the notion that (for visuomotor tasks that are physically demanding) physically stronger individuals can or should be able to perform better than physically weaker individuals. In an absolute sense, force discrimination capabilities degrade with increases in the magnitude of force applied (i.e., for changes to be detected, larger differences are required at higher force levels). Force exertion capabilities and force discrimination capabilities are known to be affected by the biomechanical geometry (elbow angles, effective lever-arm lengths) involved. There is, apparently, no research on the issue of force discrimination as a function of individual force exertion capabilities.

Strength- and force-related positioning and tracking performance. The relevant research has been divided by topic into several sections. The first section addresses the effects of interindividual strength differences on task performance. The succeeding two sections pertain to the effects of "preloading" on tracking task performance. ("Preloading" is a term used in the present review to indicate that fatiguing exertions are required of the subject either prior to engaging in the performance of the criterion task or interpolated within a series of criterion-task trials.) The preloading research has been subdivided into two categories. The first addresses fatiguing exertions involving the limb which performs the criterion task; the second addresses fatiguing exertions of the whole body or noninvolved limb. The next two sections pertain to research wherein the subject simultaneously performs both a fatiguing exertion and the criterion task. The last two sections concern the effects of varying the force requirements inherent in the successful performance of a visuomotor task. One addresses the use of non-isometric controls, the other pertains to isometric control performance.

STRENGTH-RELATED VISUOMOTOR PERFORMANCE DIFFERENCES. The principal, significant finding is that there was no research found which specifically addressed the effects of inherent individual differences in strength upon tracking behavior or related types of motor task performance. With the exception of transient, fatigue-related effects cited in subsequent sections addressing task "preloading", the same negative finding applies to research addressing intraindividual differences in strength.

PRELOADING OF TASK-RELEVANT LIMB. Alderman (1965) employed a pursuit rotor tracking task in his study of the effects of arm exercise upon performance. Subjects performed 20 15-s trials at 78 rpm and then either rested or turned a handcrank at 120 rpm for a period of ten minutes. Subjects who performed the fatiguing exertions evidenced significantly less improvement during the next several trials than did those who rested; however, recovery to the control-group's level of performance was achieved within the succeeding 8-10 trials. There was no difference between the groups on the succeeding day when both performed without extraneous exertions.

Hammerton and Tickner (1969) evaluated the effects of 25 repeated "whole-hand" or "thumb-only" maximal exertions on the subsequent performance of a target acquisition task executed using a spring-centered, thumb-operated joystick. After initial practice sessions, male subjects performed 10 trials and then exercised either their thumb or their whole hand and performed a second set of ten trials. The ratios of postexertion performance to preexertion performance revealed no significant differences between the groups for the last five trials; however, those in the thumb-only exercise group evidenced a significantly greater amount of performance decrement during the first five postexertion trials.

Carron (1969) also fatigued the body limb employed in performing the task. Seventy-five college females performed a series of 80 20-s trials on a pursuit rotor turning at 60 rpm. Twenty second rests were imposed after each trial. After the sixth and 15th trials there was a five minute period in which subjects either rested or performed fatiguing exertions using a hand ergometer. The findings were that those performing the fatiguing exertions evidenced less improvement after their exertions than did those who rested during the interval. The relative degradation was of briefer duration after the earlier fatigue interpolation (recovery within two subsequent trials) than it was after the later one (recovery after ten additional trials).

Bloswick and Ellis (1974) required subjects to squeeze a hand-grip dynamometer at 50% of their maximum exertion to develop varying degrees of muscle fatigue prior to performing a 50-rpm pursuit rotor task. Prior to this preloading manipulation, the subjects had five 30-s trials with a 15-s rest between each trial. Subsequent to the preload manipulation they performed an additional 30-s trial. The results showed that the magnitude of the preloading was positively related to the magnitude and duration of the performance decrement evidenced during the final 30-s trial.

Williams and Singer (1975) required three groups of 12 college women to turn a differentially resistive hand crank until specified levels of heart rate were attained prior to performing a 60-rpm pursuit rotor tracking task. A fourth, control group spent a like interval counting backwards. They then performed a total of ten 20-s trials. Each trial was separated by a 20-s interval. During the first 15 s of these intertrial intervals, subjects were required to resume the fatiguing hand-crank exercise or continue counting backwards. The accuracy of performance was not significantly affected by the degree of preceding level of exercise.

PRELOADING OF WHOLE BODY OR NONINVOLVED LIMB. Hammerton and Tickner (1968) had groups of male subjects perform an oscilloscope-displayed target acquisition task using a thumb-operated joystick control. Subjects were required to keep a circular cursor over a target line for a continuous 2-s period to complete a trial. During the first experiment, subjects performed 20 practice trials using a first-order controller and then performed 200 cycles of a 4-step step test in 400 s using a stepping box 30.5 cm high. In spite of a rise in the mean pulse rate from 79 bpm to 156 bpm, there was no significant change in their performance between the last pre-exercise trial to the succeeding post-exercise trial. In the next experiment, the same sequence was employed using a second-order controller with a group of physically well-conditioned military personnel and a group of "normally fit" individuals. A third group of normally fit individuals also participated as a nonexercise control group. A comparison of the performance during the last pre-exercise trial with the performance during the first post-exercise period trial revealed a significant decrement only for the normally-fit, exercised group. No significant change was evidenced for either the exercised military group or the control group. The same applied when the analyses was expanded to compare the last five pre-exercise trials with the first five post-exercise trials.

Welch (1969) utilized 70 males to investigate the effects of a ten-minute 45.7 cm step-up exercise upon the performance of the same pursuit rotor task earlier used by Alderman (1965, see previous description). Following six practice trials, 35 subjects rested and 35 performed the 600 repetition step-up exercise. At the end of this period, all subjects performed another six tracking trials. The results showed no statistically significant difference between the experimentally fatigued group and those in the control group.

Two groups of 29 female college students participated in a study by Williams and Cooper (1976) to assess the effects of 60 s of an interpolated step-up/pull-up exercise on the performance of a large-scale, whole-body pursuit rotor tracking task. Subsequent to initial familiarization and practice trials, the subjects performed six 60-s pursuit rotor trials and then either 60 s of exercise that elevated heart rates to at least 170 bpm (experimental group), or 60 s of a vowel-cancellation task (control group). Six additional trials were then performed. The tasks were performed on two successive days by each subject. The analysis of the data revealed no significant effects due to the presence or absence of interpolated exercise.

A transient decrement in the right-handed performance of a pursuit rotor tracking task following left-handed cranking of a bicycle ergometer for either 60, 90, or 120 s has been reported by Benton and Bateman (1980). Twenty males and five females participated in the study. The procedures utilized were only briefly described; no particulars of the tracking task or cranking task were given. Pursuit tracking with the contralateral arm was performed simultaneously with cranking for some unstated portion of the cranking period. Pursuit tracking then continued without concomitant cranking. (No findings were provided which related to that period of simultaneous activity; hence, this research is included in this portion of the review rather than the succeeding section.) Statistically significant main effects were obtained for the between-group, duration-of-cranking factor and for the within-group duration of effect factor. All three groups were significantly different from one another with the least affected being the 90-s cranking group and the most adversely affected being the 120-s cranking group. Only the initial 10 s of the 30-s post-cranking tracking performance period were significantly degraded relative to pre-cranking levels of performance.

CONCURRENT FORCE LOADING. The term "concurrent loading" indicates that the subject performed the fatiguing exertion with one limb (or limbs) and the criterion task simultaneously with another limb. Courts (1942) study required 16 male and 16 female subjects to perform a pursuit rotor tracking task while simultaneously maintaining a left-hand isometric handgrip exertion at one of seven subject-normalized levels. The subjects performed 50 trials at each of the levels. The results showed the performance of males to be less affected than that of females. Performance deterioration was greatest at the two uppermost levels of exertion, particularly during the final 30 trials. During the initial 20 trials, exertions at all but the lowest (zero) and highest levels enhanced performance.

NON-ISOMETRIC TASK-RELATED FORCE-DEMAND VARIATION. There are few studies which have varied the forces inherent in the performance of the task itself. Weiss (1954) required subjects to rotate a lever forward and rearward by amounts necessary (3-30 degrees) to achieve specified positive and negative vertical displacements of a referent line shown on the face of an oscilloscope. Each of these rotations were attempted in conjunction with maximum force requirements ranging from 26.7-133.4 N. The control:display ratio was kept constant throughout the study. The findings revealed the greatest errors (overshoots) at the smaller displacements and force levels. Pulling performance tended to be less variable and more accurate than pushing performance.

Bahrick, Bennett, and Fitts (1955) examined the effects of various types of spring loading upon angular positioning responses of a lever (adjusted to the individual's forearm length) rotated by blindfolded subjects clockwise in a horizontal plane. Various types of torsion rods and springs were employed to achieve a variety of experimental conditions. Terminal position torques (TPTs) ranged from zero to 2.56

Nm. These were used in conjunction with starting torques of zero, 0.5 TPT, and the full TPT to yield a total of 10 experimental force combinations. These 10 combinations were employed with three angular displacement requirements (17.5, 35, and 70 degrees) to form a total of 30 experimental conditions. The analyses revealed the poorest performance was associated with the zero torque condition. Among the three full-TPT conditions, performance was best at the largest range (0-2.55 Nm) for all displacements. Larger ranges of torque change were found to be associated with relatively better performance at the two smaller rotations (17.5 and 35 degrees) than at the largest rotation (70 degrees).

In another study, Bahrick, Fitts, and Schneider (1955) manipulated the level of task-relevant force requirements. They had seated subjects follow a circular path (or, on subsequent trials, a triangular path) with the handle at the upper end of a nonresisted, floor-mounted lever. Then, without benefit of visual feedback, the subjects attempted to reproduce the path with varying degrees of spring-centering force (3.7 N to 14.7 N) applied to the lever. The data revealed no significant effect associated with the variation of the small forces employed.

The most unusual study to manipulate the magnitude of task-relevant forces was that by Henry (1953). He required standing, blindfolded subjects to press against a shoulder-high padded block under two experimental conditions. In one task they were to attempt to maintain the position of the block constant; in the other they were to maintain the magnitude of force exerted against the block constant. In both instances, the block which the subjects pushed against was attached to a long cantilever, the lower end of which was attached to a spring. Because the other end of the spring was attached to another lever caused to move by an irregularly-shaped, motor driven cam, the pull exerted by the spring against the lower end of the cantilever varied irregularly. In general, performance was better during the constant position trials than during the constant force trials. As regards the latter, it was observed that performance, measured in terms of the degree of variability evidenced, appeared to be more directly related to the rates of change in the forces appearing at the block than the were to the absolute magnitude of same.

A subsequent study using the same apparatus (Mofford, 1966) required separate groups of subjects to execute a total of 10 constant force trials. Trials 3-8 were performed under one of three conditions: no visual feedback, or one of two levels of visual feedback (achieved by blanking out either the center 10 or 12.8 cm of the analog feedback display). Under these conditions, significant improvement between the first two trials and the last two trials was observed only for the group receiving the greatest amount of visual feedback (i.e., feedback for a lesser degree of error). Errors were expressed as values averaged over the entire trial, hence it is not possible to relate performance to the variation in the force demands inherent in the task.

Stelmach (1968) has examined the ability of blindfolded subjects to recall a previously experienced angular displacement of a lever as a function of differences in resistive forces generated by pulley-supported weights attached to the lever. The pulley cord was attached 40.6 cm from the base of a 53.3 cm lever. In addition to a no-resistance condition, masses of 2.27 and 4.54 kg were attached to provide resistive forces of 22.4 and 44.8 N. (The velocity of movement was controlled by the subject; hence, inertial effects and actual forces are unknown.) Each trial involved a verbal instruction for the subject to move the lever forward (from the initial vertical position in the midsaggital plane) to a mechanical stop at either 25 or 65 degrees of rotation. After a 3-s stay at that position the subject was instructed to return to the starting position. He then attempted to duplicate the extent of the movement, indicating to the experimenter when he believed he had done so. Each subject performed 10 trials at 30-s intertrial intervals. A full factorial design was employed with 10 male subjects per cell. The finding of particular interest was that no force-related effect was statistically significant. (The results of an a priori comparison performed by Stelmach among the absolute error data associated with the three tension levels at the most extreme, 65 degree position did yield significant differences thereby suggesting that increased lever tension was associated with improved performance. As such, these findings provided some support for Stelmach's hypothesis that increased levels of proprioceptive feedback would result in better performance.)

More recently, Notterman and Weitzman (1981) employed a unidimensional, horizontal pursuit tracking task in an examination of all nine possible combinations of step-, velocity-, and acceleration-forcing functions used in conjunction with elastic, damping, and inertial control loadings. Trials consisted of single left-to-right, 10.56 cm sweeps across the face of an oscilloscope. Two spring constants were examined: 9.2 and 21.5 N per radian of control movement. The gain was the same at both spring-constant levels. Within the present context, the spring-constant, zero-order tracking condition is of principal interest. The maximum forces involved (i.e., those encountered at the control displacement required to track the target at its extreme position) were approximately 10.4 and 23.9 N. Subjects performed alternating blocks of five cursor-present and cursor-absent trials. Because the focus of the research was the rate of learning involved, an effort was made to decrease the effect of any prior experience by requiring the participants to perform the task with their nondominant hand and without benefit of prior practice. The velocity of the target was such that each trial required 4 s. There was no significant difference in performance (absolute error) between the two spring-constant levels. The overall results demonstrated superior performance for conditions that reflected "match-ups" between the forcing function and the type of control loading employed; i.e., spring-constant loading was best step function target movement, damping was best with when a velocity forcing function was employed, and inertial loading was best with an acceleration forcing function. These differences were evident only under the "cursor absent" tracking condition.

ISOMETRIC TASK-RELATED FORCE-DEMAND VARIATION. Several investigators have employed an isometric control in a variety of tracking and position reproduction tasks: Gibbs (Gibbs, 1954; Burke and Gibbs, 1965), North and Lomnicki (1961), Notterman (Notterman and Page, 1962; Notterman and Weitzman, 1981), and Ribot, Roll, and Gauthier (1986). Those which employed zero-order (position-related control/display relationships) are the most relevant to the present research.

Both studies by Gibbs and his collaborator (Gibbs, 1954; Burke and Gibbs, 1965) involved comparisons between isometric controllers and "free-moving" lever controls, commonly referred to as "isotonic" controls, i.e., those which do not entail any movement-resistive characteristics beyond those resulting from their mass and the friction in the bearings used to provide support. (It is noted that these factors do not result in actual constant muscle tension, per se, as the term implies; Kroemer, Kroemer, and Kroemer-Elbert, 1986).

A two-dimensional, first-order, compensatory tracking task was utilized in the initial study (Gibbs, 1954). A CRT was used to display the task. Three different cam-driven velocity forcing functions were employed in repetitive fashion (one cycle every 80 s for 11 successive cycles). The gain of the free-moving control was 0.53 degrees (visual angle) per second per millimeter of hand movement. The gain of the isometric control was 0.26 degrees per second per 0.28 N of input force. No data pertaining to the actual forces exerted were cited. The nature of the control display dynamics (velocity control) permit little insight regarding the relationship between force levels and performance, per se, beyond the fact that the (a) gains selected for both types of controls represented optimal values based on pretesting performance, and (b) performance during some periods of target deceleration were superior to those during other selected periods when the target was accelerating. Findings pertaining to each of the three forcing function were not separately addressed (except in observations regarding specific portions of the velocity waveforms depicted). Overall, performance with the isometric control was superior to that of the free moving control.

Burke and Gibbs' (1965) study compared free moving "isotonic" control performance with isometric control performance over a substantial range of control/display ratios using a zero-order pursuit tracking task with zero lag. The CRT-displayed target dot moved laterally in an irregular fashion in response to a forcing function comprised of a series of abrupt changes in velocity and direction. The C/D ratios utilized with the isometric control were: 4.98, 2.67, 1.78, 0.89, and 0.45 N/cm (Newtons of force input per cm of cursor movement). The maximum displacement of the target in all conditions was five cm, hence the maximal force appearing in the highest C/D condition was 2.22 N, and the maximal force appearing in the lowest C/D condition was 17.79 N. Several findings are of principal interest to the present research: (a) there were no significant differences among the C/D ratios employed albeit the best performance was associated with the highest force demand (highest C/D ratio), (b) there was evidence of considerable transference of skill among the force levels employed and between the "isotonic" and isometric conditions, and (c) isometric performance was significantly better than "isotonic" performance.

North and Lomnicki (1961) also compared isometric and 'isotonic' control performance. Various C/D ratios were employed while performing a unidimensional, first-order compensatory tracking task. The forcing function was generated by sum-of-sine and sum-of-cosine functions. With the isometric control, the change in velocity per unit of force applied was varied over a range of 50:1 with highly significant differences evidenced in the degree of tracking error encountered. The findings were expressed in terms of optimal sensitivities based on estimations from hyperbolic regression curves derived from the data. Within the range of sensitivities evaluated (22.5-9000, measured in thousands of an inch (mils) per second per pound), the optimal values ranged from 72-450; i.e., clearly at the lower end of the range investigated. Because the input resulted in a velocity-controlled output, it was not possible to determine the forces actually required to perform the task. Moreover, the findings failed to provide any data to indicate the magnitude or range of forces actually evidenced in the performance of the task. Consistent with the results of Burke and Gibbs (1965), the comparison between the results of "isotonic" and isometric tracking revealed isometric control to be superior.

Because North and Lomnicki (1961) provided some descriptive data for each of the six subjects, it is possible to obtain an appreciation of the considerable extent of interindividual differences which existed. The initial scores evidenced a wide range with the least proficient having an RMS error score that was 6 times that of the most proficient. The best tracking scores achieved by the subjects were down to only 7-10% of their initial RMS error scores. The data presented, however, indicated that after approximately 400 s exposure to the task, performance had improved to an extent that the mean RMS error was but 20% of the initial levels, and after 12 minutes exposure performance had reached an asymptote.

The research by Notterman and Page (1962) proves about as difficult to interpret as that of North's in attempting to relate it to the present research topic. They employed spring-centered, isometric, and "isotonic" controls in conjunction with variation of gain, spring constant, inertia, and viscous damping (as appropriate) to assess the effects of operator-related proprioceptive feedback on otherwise comparable system transfer control functions. Three subjects were employed in each of the three conditions. A vertical compensatory tracking task using a random (Gaussian noise) forcing function was employed throughout.

The isometric control was utilized in the second of the three experiments. Variations of the C/D ratios (hence, force demands) occurred in the presence of simultaneous variation of other factors to assure that the transfer function remained the same; therefore, it is impossible to describe the effects of force, per se, on tracking performance.

As pertains to the role of practice, these researchers provided an additional "Experimental Note I" which depicted the learning curves for two of the subjects who performed the task a large number of trials. The data for one subject evidenced a nearly linear decrease in error for the three data points plotted (each representing the mean performance of succeeding blocks of 980 trials each). The data for the second subject evidenced a similar trend for the initial two points (encompassing the first 1960 trials), but a somewhat shallower slope (less decrease in error) during the last 980 trials. Apparently, for this type of task at least, improvements in tracking performance were still occurring after nearly 3000 trials.

Most recently, Ribot, Roll, and Gauthier (1986) have employed conventional helicopter cyclic and side arm controllers in both a displacement ("isotonic") mode and an isometric mode during vibration and nonvibration conditions to perform a two-dimensional compensatory tracking task. The forcing function used to drive the cursor from the center, null position was a counterclockwise circular path at 0.1 Hz. In the absence of a recentering input from the control, the cursor traced a circle 10 degrees in diameter (visual angle). In the isometric mode, the torques required to achieve null, recentering inputs were 10 Nm and 13 Nm for the side-arm and cyclic controls, respectively. The authors neglected to cite the effective lengths of the lever arms for the two controls. However, by using estimations derived from the drawing provided, it is likely that the forces required to achieve a centered output were approximately 50-60 N for the side-arm control and 20-25 N for the cyclic. The vibration condition utilized an 18 Hz sinusoidal input with an intensity that resulted in +/- 0.4 G at the tracking hand level.

Six males 23-40 years of age with normal vision were employed as subjects. Each received some (unspecified) practice prior to participating in four experimental sessions. Each session addressed only one of the four control configurations. The description of the experimental procedure is unclear as to the nature of each session. It appears that each experimental session consisted of three 50-s exposures to the task in the nonvibration condition (each exposure being separated by a two-minute rest interval) followed by 150 s wherein only the middle 50-s exposure involved vibration.

The results of Ribot, Roll, and Gauthier's (1986) research showed the isometric mode superior to the displacement mode. Also, performance with the cyclic was superior to that with the side-arm control. The presence of vibration degraded performance with all combinations of controls; however, it appeared that the degree of post-vibration residual effect was worse for the displacement mode. Albeit statistical findings were not cited, the authors indicated that their visual examination of the data suggested that the magnitude of the error was greatest at the extreme right, left, up, and down positions of the display.

Ribot, Roll, and Gauthier's (1986) discussion regarding the possible reasons for the superiority of the cyclic control emphasized neurophysiological factors which purportedly favor the sensory sensitivity and motor control capacities of the shoulder (relative to those which are pertinent during the use of the side-arm controller). There was some acknowledgement that the lower sensitivity with the cyclic (relative to that of the side-arm control) may have contributed to the superior performance of the cyclic; however, this fact was clearly considered to be of less importance than the neurophysiological factor. The authors also ignored the fact that the length of the effective lever arm of the cyclic was nearly three times that of the side-arm control. Therefore, the cyclic (a) is much more likely than the side-arm control to have provided displacement cues during the isometric condition, and (b) required proportionately less force than the side-arm control to perform the task.

DISCUSSION OF FINDINGS. Little can be said regarding the possible interaction of interindividual differences in strength, force demands, and accuracy of motor task performance because literature directly addressing that topic was not found to exist. In considering the studies which employed the preloading fatigue-induction manipulation, the most consistent difference observed among them was that fatiguing a task-relevant limb induces performance decrement whereas fatiguing task-irrelevant limbs does not. With one exception, those studies employing gross fatigue-induction procedures (e.g., bicycle ergometer or step-up exercises) yielded largely insignificant effects on subsequently performed motor tasks. The only study in which this was not the case was the second experiment reported by Hammerton and Tickner (1969) wherein care was taken to discriminate between the levels of physical fitness of the subjects (relative to those in better condition, those in poorer condition performed less well).

Among the investigations which addressed the effects of fatiguing the task-relevant limb, the only study not to report a significant effect was that by Williams and Cooper (1976). A general observation regarding those which did report significant effects helps explain Williams and Cooper's failure: the effects are quite transient in nature. The studies which did report performance decrements also indicated that recovery to control group levels of performance was attained within a matter of a few trials after performing the fatigue-induction procedures. In contrast to the other "preload" investigators (who focused on the trials immediately following the fatiguing exertions), Williams and Cooper reported their nonsignificant findings based upon all postexertion trials considered collectively.

Among the studies involving manipulations of task-relevant forces, two evidenced significant effects and one did not. Significant decrements were found with discrete limb-positioning responses (Weiss, 1954; Bahrick, Bennett, and Fitts, 1955) while the more continuous and complex (albeit brief) task of path tracing failed to show significant effects (Bahrick, Fitts, and Schneider, 1955). The Bahrick, Fitts, and Schneider study (which failed to demonstrate a significant effect) involved maximum force levels (1.5 N to less than 15 N) five to nine times smaller than those employed in the other two.

Other non-isometric tracking research wherein resistive force was a factor failed to report the findings in a manner which was compatible with the assessment of the role of force requirements (Henry, 1963; Mofford, 1966). A nonsignificant finding was reported by Notterman and Weitzman (1981) while an earlier study by Stelmach (1968) provided findings that rather tenuously supported the existence of superior performance at the highest force levels employed in the study.

Among the studies which included isometric controls, most (Burke and Gibbs, 1965; Gibbs, 1954; North and Lomnicki, 1961; Notterman and Page, 1962) addressed combinations of factors or employed higher order tracking conditions that precluded an independent assessment of the effects of force level, per se. It is Ribot, Roll, and Gauthier's (1986) research on the effects of vibration upon helicopter cyclic and and side-arm controller used in the isometric which could have been most readily interpreted in terms of force requirements. Unfortunately, there was little evidence of formal statistical analyses. The depictions and descriptions provided suggested that, in spite of their neurophysiological explanations, the reason for better performance with the cyclic was likely to have been the lower force levels required.

Summary of Literature Reviewed.

Little knowledge is available regarding the likely interrelationships among force demands and strength capabilities as they affect accuracy of motor task performance. The dearth of such information in "standard" HFE references and texts appears to reflect accurately the status of extant knowledge. The research which does exist is severely limited. Regarding forces applied to controls, no data were encountered which reflected manipulations of the magnitude of the forces involved in any tasks other than those involving either short-duration, discrete-trial behaviors (e.g., limb positioning tasks) or tasks involving very low levels of force. Even these efforts were confined to tasks which entailed a substantial motor memory component and were performed without concurrent visual feedback. No visuomotor research was found which examined the effects of "medium" or larger magnitude forces on continuous or prolonged motor tasks that did not also either (a) simultaneously manipulate other factors or (b) omit force-related considerations in evaluating their data.

RESEARCH OBJECTIVES AND HYPOTHESES

Objectives

The principal objectives of the research are to examine the effects of variation in force level and force direction upon force discrimination capabilities and isometric tracking performance, and to assess the relationships among individually determined strength:demand ratios, force discrimination capabilities, and isometric tracking performance.

Hypotheses

Force level. It is hypothesized that increases in force level will degrade both force discrimination and isometric tracking performance.

Variation in force level is hypothesized to have several effects upon force discrimination capabilities. The concept of the Weber fraction (Gescheider, 1985) plus the findings of Jenkins (1947) suggest that as the magnitude of the referent force level increases, increases will occur both in the differences between the referent force exertion and the matching force exertions, and in the variability of the matching exertions. The CE (constant error) findings of Jenkins (1947) and the force-matching findings of Bigland-Ritchie (1979) and Jones and Hunter (1982) also indicate that lower force levels will be overestimated and larger forces will be underestimated.

As regards tracking performance, previous tracking research provides some, but not emphatic support for the hypothesis that increasing force levels will degrade tracking performance. Because the present research addresses change in the direction of target movement, effect of force is hypothesized to differ depending upon the direction of the reactive force of the isometric control ("recentering force"). It is hypothesized that when the recentering force direction is the same as that of target movement (during inward movement toward the center, null position of the display) error will be less than when the direction of the recentering is opposite to that of target movement (during outward movement away from the center of the display).

Force direction. It is hypothesized that variation in force direction will significantly affect both force discrimination capabilities and tracking performance.

Direction-related strength differences have been demonstrated repeatedly (Laubach, Kroemer, and Thordsen, 1972; McDaniel, 1981; Schopper and Mastroianni, 1984). Therefore, from the perspective of relative force demand, it is hypothesized (as a derivative of the force level hypothesis) that both force discrimination and tracking performance will evidence degradation that is inversely related to the levels of strength associated with each direction. That strength is relevant is indirectly supported by Jones and Hunter's (1982) finding that left and right exertions during contralateral force matching were linearly related when the magnitudes of the exertions were expressed as proportions of their respective strengths. Bigland-Ritchie's (1979) manipulations of the muscle length (and, therefore strength) showed better force discrimination capabilities when the force exertion capabilites were larger.

Correlational findings. Given the force-related nature of the tasks, it is hypothesized that strength, force discrimination, and isometric tracking performance will be significantly correlated with one another. Bigland-Ritchie's (1979) research suggest that strength measures will be correlated with force discrimination measures. The findings of Fleishman and Rich (1963) evidenced significant correlations between weight discrimination capabilities and pursuit tracking performance. Accordingly, force discrimination measures are hypothesized to correlate with tracking performance. In view of the findings cited, it is also hypothesized that force discrimination measures will correlate with tracking performance as well. It is also hypothesized that the strength-related correlations will be enhanced if they are expressed in terms of strength/demand ratios.

METHOD

Overview

Each subject participated in a single experimental session of approximately 2.5 hours duration. The session consisted of seven phases:

1. Initial Briefing and Vision Screening.
2. Anthropometric Measurements.
3. Force Discrimination Assessment.
4. Initial Strength Assessment (Set I).
5. Isometric Tracking.
6. Post-tracking Strength Assessment (Set II).
7. Debriefing.

Subjects

Thirty-four right-handed college students, 17 males and 17 females, with corrected or uncorrected 20/20 visual acuity participated as paid volunteers. They were solicited via posters placed about the campus. All were free of relevant health problems. Subjects were paid $15.00 for their participation.

Predicated on a strength criterion derived from the need to be able to meet or exceed the maximum force encountered in the isometric tracking task, only the data from those 21 subjects (16 males and 5 females) whose strength equalled or exceeded 66.75 N in all directions tested were included in the present analyses.

Briefing and Vision Screening.

Subjects initially completed a brief questionnaire (Appendix A) to determine if there existed any previous or current health problem or injury which might constitute reason for concern regarding his or her ability to participate fully and without danger or disadvantage in the research activities (e.g., a prior history of high blood pressure or arm trauma with residual impairment). Subjects then read the informed consent form and its attachment (Appendix B). These documents described participant rights and provided a description of the activities that were to occur during the session. After answering any questions posed, each subject underwent a vision screening conducted with a Bausch & Lomb Master Ortho-Rater using the procedures for the assessment of visual acuity (far vision). Only those demonstrating 20/20 visual acuity (corrected or uncorrected) were permitted to participate.

Anthropometric Measurements

The following anthropometric measurements, described in NASA's Anthropometric Sourcebook, volume II (NASA, 1978), were obtained: weight, stature, elbow-grip length, shoulder-elbow length, and biacromial breadth. The participant's age and gender were also recorded.

Force Discrimination Assessment

Equipment. Two vertical handles of the same diameter (3.8 cm) as the handle employed in both the strength assessment procedure and isometric tracking task were used. They were nearly isometric in their response characteristics, displacing 4 mm at the gripping reference location (see below) when a 60.75 N force was applied there. On the forward surface of each handle were two horizontal ridges approximately 0.1 cm in height separated by a vertical distance of 1.5 cm. These were used to designate the location of the middle finger of each hand during each exertion.

The handles were separated by a center-to-center distance of 55.8 cm. The vertical centerlines of the handles were 36.8 cm forward of the seat reference point. The padded seat back was 52 cm in height. The padded seat pan was 44 cm long. The seatback angle was 18 degrees from vertical. The angle of the seat pan above horizontal was 4.5 degrees.

The handles were rigidly affixed to a steel mount which could be adjusted vertically. The adjustable mount was attached to a steel frame which served as the support base for the chair used in the research. The apparatus also provided an elbow positioning-support device which, too, could be adjusted vertically. This device provided a padded, v-shaped platform of 7.5 cm length to support and contol the position of the elbow and forearm relative to the location of the hand-grip. Prior to beginning the task, the height of the elbow positioning-support device was adjusted to provide comfortable support for the individual (i.e., assure that the subject did not feel that the shoulders either were being pushed upward because the support was too high, or that they were bearing the weight of the arm because the adjustment was too low). The subject then gripped the handles in the proper position, and the heights of the force-application handles were adjusted to align the forearm in a horizontal position thereby assuring the forearm was perpendicular to the vertical handle.

Strain gauges were attached to each handle to measure the forces applied in the fore-aft and left-right directions. Voltages from the strain-gauge circuitry were amplified and then sampled at 10 hz via a Metrabyte Dash-8 A/D-D/A board installed in an IBM XT computer. This technology provided 12-bit resolution. The handles were calibrated with weights (18.9 N, 40.5 N, and 60.75 N) which were comparable to the force levels of interest.

Procedure. The procedure employed was a simultaneous force-matching procedure similar to that used by Jones and Hunter (1982). Three levels of force, 22.25 N, 44.50 N, and 66.75 N were employed in each of four directions: 0, 90, 180, and 270 degrees. These 12 combinations of force level and force direction were the same as those examined in the isometric tracking task.

Referent forces were applied with the left hand. Matching force inputs were attempted by contralateral exertions with the right hand. Longitudinal referent forces were matched by forces input in the same direction by the contralateral arm; lateral referent forces were matched by opposing exertions.

The task entailed four CRT-directed phases (inclusive of the rest period). The initial phase readied the subject for the task. For a 5-s period prior to the beginning of each exertion, the words "GET READY, GRASP CONTROLS" were shown in the upper portion of the display. Concurrent with the appearance of these instructions, just below the text, there appeared two arrows approximately 5 cm in length to indicate the direction of the exertions to be undertaken. The arrows appeared on the left and right halves of the display; their centers were separated by approximately 12 cm. The direction of exertion was also indicated by the appearance of the appropriate word (in, out, forward, aft) between the two arrows.

The referent force exertion was established during the second phase. Five seconds after the initial appearance of the arrows, two rectangles, one above the other, appeared beneath the left arrow. The number in the lower rectangle informed the subject of the magnitude of the referent exertion to be achieved by the left hand during the 6 s interval which began with the appearance of the rectangles. This force level was cited in Newtons to two decimal points. The upper rectangle provided real-time feedback regarding the magnitude of the left-hand exertion in the same units. The subject began the referent exertion with his or her left hand immediately after noting the magnitude of the force level to be matched. The right hand had no active role during this 6-s period. Figure 1 depicts the display as it appeared at this time in the procedure.

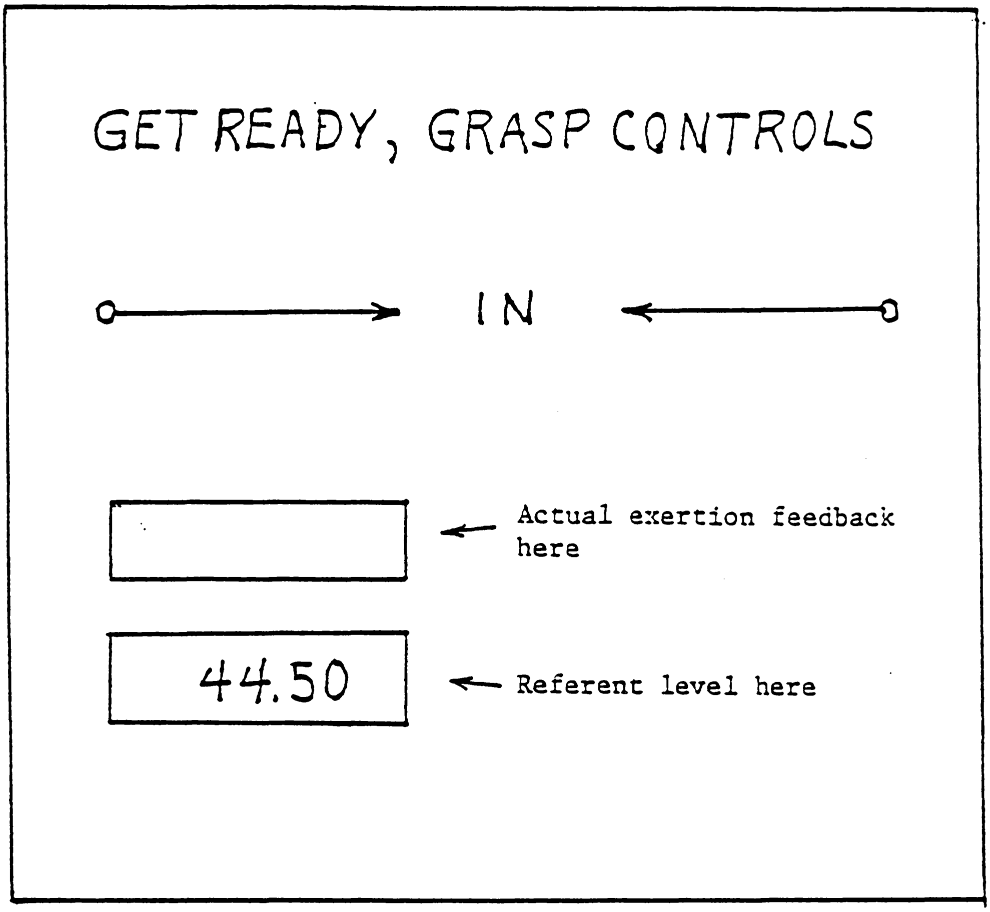

Figure 1. Annotated representation of the force discrimination display at the end of the referent force generation phase.

The disappearance of the display marked the end of the preceeding phase. The succeeding 4-s force-matching phase began immediately afterward with the appearance of text instructing the subject to concentrate on matching the force being exerted with his left hand with a corresponding exertion from his right hand: "CONCENTRATE ON MATCHING LEFT-HAND FORCE WITH RIGHT-HAND FORCE." The subject was instructed to maintain the level of left-hand exertion that he or she had attained at the time the display changed and not to engage in any further corrective efforts or adjustments in the absence of feedback. No feedback was provided regarding either left-hand or right-hand exertions during this period. The trial ended 4.2-4.5 s after the matching instructions appeared with the display of the words "TRIAL FINISHED, RELAX."

Variability was incorporated in the duration of the force-matching portion of each trial in an attempt to minimize the likelihood that participants would learn to anticipate the end of the trial and inadvertantly terminate the exertions prematurely. Only the ten data points generated from each hand during the final second of the matching exertion were recorded.

The sequence described above was explained thoroughly to each subject prior to undertaking the task. Additionally, each subject was given a minimum of four familiarization trials prior to beginning the sequence of 36 trials described below. The exertions used in these familiarization trials were randomly selected from all 12 possible combinations. If the subject requested, or if the experimenter believed the subject did not yet fully understand the task requirements, additional familiarization trials could be performed. In no instance did the total number of these familiarization trials exceed seven. The required four were typically all that were necessary.

Each subject performed a total of 36 pairs of force-matching exertions at 23-s intervals. The sequence of presentation was generated by using a random-selection-without-replacement technique. Hence, each succession of 12 trials exhausted all possible combinations of force level and direction. The initial 12 trials served as practice trials and were excluded from the analyses. The data for corresponding exertions of the last two sets of 12 exertions were averaged to yield single measures of the mean and standard deviations of the ten data points recorded for each hand.

The mean of the values recorded during the fourth second of the matching portion of each trial were used to compute two measures of force discrimination capability. The first was termed "relative error" (RE). It was the algebraic difference resulting from the subtraction of the mean magnitude of the left-hand referent exertion from the mean magnitude of the right-hand matching exertion. The second was obtained by subtracting the magnitude of the referent itself (22.25 N, 44.50 N, or 66.75 N, as appropriate) from the mean magnitude of the matching exertion. This value is referred to as the "standard-referenced error" (SRE). The third measure utilized, "force variability" (FV), was the standard deviation of the ten data points recorded for each matching exertion.

Strength Assessment

The strength assessments were undertaken while the subject sat in a padded chair with a back rest for support. The back rest was 58 cm in height. The angle between the back rest and the seat pan was 108 degrees. The seat pan was 47.5 cm in length. The seat pan angle was 3 degrees above horizontal. Both the back rest and the seat pan were 46 cm in width. The centerline of the 3.8 cm diameter vertical gripping handle (smooth surface) was located 28.2 cm laterally from the center and 36.2 cm forward of the seat reference point. On the forward surface of the handle were two horizontal ridges of the same configuration and for the same purpose as employed with the handles used with the force discrimination apparatus. The center of the grip location on the handle was 28.2 cm above the seat reference point.

The same procedure was employed in both strength assessments (sets) undertaken during the study. Each set included exertions in four directions (0, 90, 180, and 270 degrees) by both the left and right arms. All exertions were sustained for a period of 4.2-4.5 s. The right and left arms alternated. This permitted an interexertion interval of 120 s for successive exertions involving the same arm. To further minimize the demand on the same principal musculature during successive exertions, the following sequence (or its reverse) was employed: Forward (F), Aft (A), Left (L), Right (R). The sequence employed for each arm was independently determined for each assessment on a random basis.

Subjects were instructed to build up to maximal force in a rapid-but-controlled manner without jerk within one second after the signal to begin. They were then to hold this maximal force for at least 4 s. The data were sampled and recorded at 10 Hz during seconds 2-4 of each exertion. Exertions evidencing a maximum or a minimum which deviated more than 10% from the mean of the 30 sampled values were discarded and repeated (Caldwell, Chaffin, Duke-Dubos, Kroemer, Laubach, Snook, and Wasserman, 1974). The subject repeated these exertion(s) at the end of the initially programmed sequence. The size of the handle upon which the exertions were made and the relative position of the subject's arm vis-a-vis the handle were the same as those existing in the isometric tracking task.

At the beginning of each trial, 12 s prior to the onset of the exertion, a CRT displayed an instruction to grasp the handle in preparation for beginning the exertion. The instruction also indicated the hand to be used and the direction of the exertion to be made. Five seconds prior to the onset of the exertion, the display changed to pictorially show a circle with an arrow emanating from it, pointing in the desired direction of exertion. At the center of the circle a numeric countdown was displayed. The numbers 5, 4, 3, 2, 1, and the word "Begin" appeared at 1 s intervals. This display remained fixed until the word "Stop" replaced "Begin" at the center of the circle 4.2-4.5 s later. The subjects were encouraged to move about between trials.

The average of the data recorded during seconds two through four of each exertion were recorded as the subject's strength in that direction.

The same procedure was employed during both the pre-tracking strength assessment (Set I) and the post-tracking strength assessment (Set II).

Isometric Target Tracking

Equipment. The task required the subject to follow a target displayed on the surface of a computer color monitor with a cursor whose position was determined by force inputs to an isometric control. The monitor was a Princeton HX-12E used in the 640 x 200 mode. The contrast and brightness controls were turned to their fully clockwise positions. The color attributes of the monitor were not employed. The target and cursor appeared as white dots on an achromatic background. The target consisted of a single pixel. The cursor consisted of seven pixels arranged as a modified plus sign, "+". To accommodate the resolution characteristics, five of the pixels were aligned with the vertical axis of the monitor and three were aligned with the horizontal axis. To the observer, the overall appearance of the cursor was that of a dot that was somewhat larger and brighter than that of the target. The target moved about the screen at a speed of 3.55 cm per second.

The task was performed in a room that was illuminated with recessed overhead flourescent lights. Selected lights were disabled to avoid glare. The ambient light incident upon the center of the surface of the display was 18.2 foot candles.

The monitior was oriented so that it was perpendicular to the subjects' line-of-sight. The mean distance from the pupil of the subjects' eyes to the display surface was 81 cm. Viewing angles ranged between 22 and 27 degrees below a horizontal line-of-sight.

The adjustable chair, computer, and A/D circuitry were those used during the force discrimination assessment. The effective sampling rate was 71 Hz. The force inputs controlling the cursor's movement were applied by the right hand to the right handle of the apparatus previously described. As in the force discrimination task, the position of the subjects' arms was defined by the designated gripping location on the control and the elbow support platform. Subjects were instructed to maintain that position while performing the tracking task.

Tracking task. The selection of the target path described below was based on a number of considerations. Fatigue-related concerns were of substantial importance. Because the task required exertions which approached the limits of the strength capabilities of weaker subjects, it was necessary to assure that the duration of any such high-demand requirement was relatively brief. Additionally, to mitigate the potential for fatigue which might accrue as a result of having to employ the same musculature for lengthy periods, it was desirable to utilize target paths which did not entail sustained travel in the same direction.

Additional factors were those pertaining to the intrinsic interest of the task and its possible generalizability to other situations. While the variables of principal concern are those which could be addressed with a large series of short-duration trials (2-5 s), e.g., tracking of relatively short lines and arcs, it was believed that participation in an experimental session comprised of such sterile, disconnected tasks would prove boring to the subject. Additionally, the use of a more continuous, variable task appears to have more relevance to "real world" applications than would brief, discrete trials. Accordingly, the data associated with linear and circular tracking performance was obtained from selecting points on a composite, continuous tracking path.

The target path devised permitted the assessment of force-loaded tracking performance as a function of the magnitude, direction, and nature (increasing vs decreasing) of force required during both linear and circular target movement (Figure 2). It was 135 cm in length. The distance between the two outermost circular portions of the path was 13.5 cm.

To address all experimental conditions required 45 and 90 degree rotations of the path as well as reflections of the path about both principal axes. The combination of four rotations and two sets of reflections yielded a total of 16 separate paths.

Accurate tracking along the straight-line portions of the path required only that the magnitude of the applied force be modified. Along the circular segments of the path the force demand was perpendicular to the direction of target movement. Correct tracking performance along these segments of the path required that the absolute magnitude of the force remaine constant while the direction of the requisite force vector continually changed. The circular arc segments

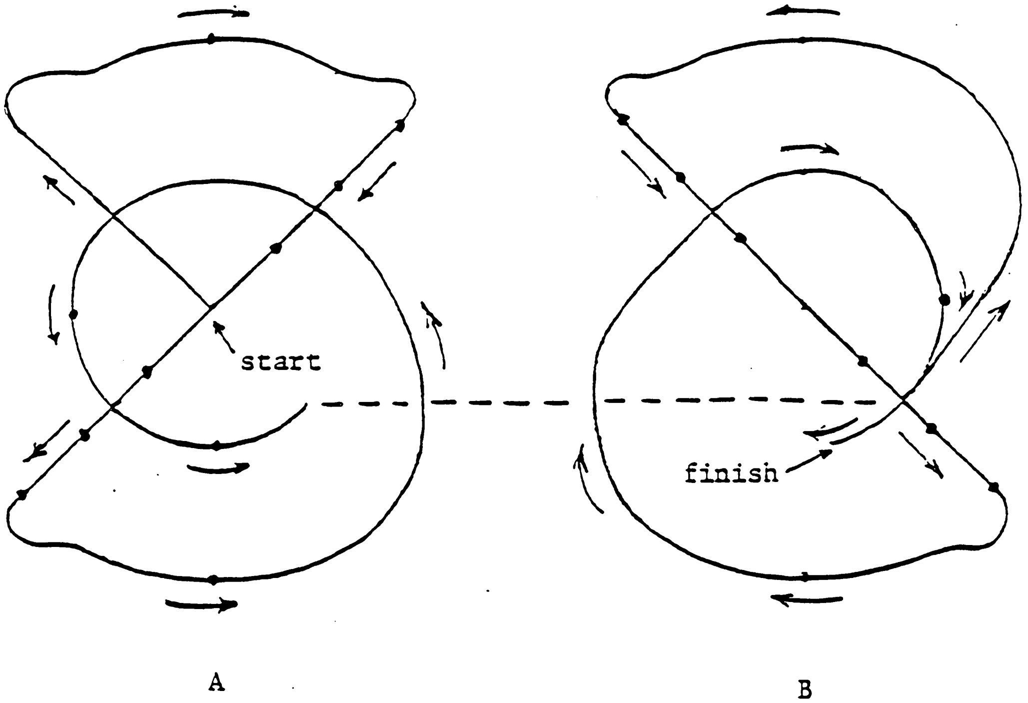

Figure 2. Representation of one of the 16 target paths used in the isometric tracking task. Part A depicts the initial portion of the path; part B depicts the continuation. Dots indicate the target-referenced data collection points. Arrows indicate the direction of target movement. Neither dots nor arrows appeared during the actual task.

employed two levels of force demand: 33.375 N (hereafter truncated and referred to as 33.37 N) and 66.75 N.

During each trial, the outer arc segments were traversed in both clockwise and counterclockwise directions, and the linear portions were traversed once each in one direction. The inner circular path is traversed once in its entirety in a single direction. Hence, at the lower force level, all four directions of circular tracking are presented each trial. The path depicted in Figure 2 shows the outer circular arcs in the 0- and 180- degree positions. Rotating the path 90 degrees provides a complementary path which places the "figure eight" in a horizontal position with the outer circular arcs appearing at the 90 degree and 270 degree positions. A 45-degree rotation of Figure 2 produces linear tracking conditions coincident with the directions at which strength assessments were made and force discrimination capabilities assessed (i.e., 0, 90, 180, and 270 degrees). During each trial, the linear portions of the path are each traversed once in a single direction. By employing all 16 possible paths resulting from four successive 45-degree rotations and their reflections about their respective "X" and "Y" axes, it was possible to present all possible combinations of target travel such that each combination of force level and force direction occurred four times.

The task itself was a zero-order, two-dimensional pursuit tracking task with no lag. Because the control was isometric, cursor (follower) displacement was proportional to the force applied. Hence, it was possible to define force-specific points on the path by determining the distance from the center, null position. For the linear portion of the path, three force-defined target reference locations were identified corresponding to 22.25 N, 44.50 N and 66.75 N. The outer circular arc radius corresponded to a force demand of 66.75 N; the inner to 33.37 N. The target-referenced data collection points for each circular segment occurred at the 0, 90, 180, and 270 degree locations for both the smaller and larger diameter segments. The locations of the data collection points was unknown to the participants.

At each target-referenced location on the path, the algebraic mean of seven successive data points (those corresponding to the position of the reference point +/- three sampled points) constituted the value recorded for that force level and direction during each pass of the target through that position. Since the sampling rate was 71 Hz, and the target traveled at 3.55 cm per second, each datum represented the mean error occurring when the target was within +/- 1.75 mm of the target-referenced location. All trials started from the center, null position of the display. No data were recorded during the initial outward, linear movement of the target to the first "corner" of the path.

The 22.25 N force value, that selected as the lowest value to be examined along the straight-line path, corresponds to the lower end of the range in which Jenkins (1947) found a linear relationship between force discrimination capabilities and referent force levels. The upper end of the range, 66.75 N, corresponds to the limit for (lateral) control force inputs to military aircraft during normal flight conditions.

The data pertaining to the circular arcs described performance associated with two force levels and two modes of target movement (CW and CCW) at the 0, 90, 180, and 270 degree positions about the periphery of the circles. The data examined along each of the linear paths represented three force levels, two modes of target movement (outward and inward directions of movement which corresponded, as well, to increasing and decreasing modes of force application) and the same four force directions.

Trial sequencing. Each subject performed a total of 24 trials, the first eight of which were for practice. The final 16 paths employed represented all of the possible path configurations used in the study. The eight practice trials represented one-half of the entire set (i.e., eight trials representing the reflections about one axis were omitted). Trials were presented in blocks of eight. Each trial was 38 s in duration. A 33-s rest was given between each trial (inclusive of the 10-s countdown provided, see below). A 120-s rest was provided between each block of eight. With the constraint that no two successive trials be similarly oriented, the sequencing of the block of eight practice trials was achieved on a random-sampling-without-replacement basis. The same technique was used for the succeeding 16 recorded trials. The constraint was imposed to help prevent fatigue by minimizing the employment of the same principal musculature on successive trials. The randomization was performed by the computer independently for each subject immediately prior to the beginning of the tracking phase.

The beginning of each trial was preceeded by a muted beep that signalled the onset of a ten-second countdown. The subject was instructed to place his or her hand on the control at the beginning of the countdown. The numbers 10 through 1 then appeared at 1-s intervals at the center of the screen. One second after the number 1 appeared, it was replaced by the target. This procedure was employed to assure the subject was ready and visually attending to the correct portion of the display at the start of each trial.

The subject was informed of the nature of the task, the number of trials involved, and the rest sequence employed prior to undertaking the initial trial.

Dependent variable. Coordinate axes moved with the target path to permit a meaningful analysis of the data. In each instance, the positive portion of the transformed "Y" axis was in the direction of target travel. (No referent axes were displayed on the screen.)

Because the task was one of pursuit tracking, errors in the direction of target travel wherein the cursor position was "ahead" of the target were assigned positive values. Errors associated with cursor positions which "lagged" (i.e. were "behind") the target position were assigned negative values. Hence, during linear tracking, errors which were closer to the center, null position during movement away from the center position were considered negative (lagging errors). During movement toward the center position, cursor positions farther from the center than that of the target constituted lagging errors and were negative in sign.

Corresponding assignments were made for clockwise and counterclockwise circle-related tracking errors. The positive "Y" axis was in the direction of target movement along a tangent to the circle at the target reference point. The positive "X" axis was designated as being farther from the center of the circle than the referent target position regardless of the direction of travel (CW, CCW).

Debriefing Phase

After the post-tracking strength assessment was completed, the subject was paid and given the opportunity to ask questions regarding the research.

RESULTS

For all analyses of variance (ANOVA) and the Newman-Keuls tests an alpha level of 0.05 was adopted. Full ANOVA tables are presented for each analysis; therefore, individual F- and p-values are not cited redundantly within the text.

Anthropometric Assessment

There were five females and 16 males whose minimum strength equalled or exceeded 66.75 N (the maximum force demand associated with the isometric tracking task) during the initial strength assessment. The characteristics of these subjects, collectively considered, are provided in Table 1. Male statures ranged from 166.0-189.2 cm. Their weights (masses) ranged from 57.7-90.5 kg. The range of statures among the five females was 158.1-171.5. Their weights ranged from 62.7--99.9 kg.

Strength Assessment

The results of the ANOVA of the strength data are provided in Table 2. Only the main effect for Direction is statistically significant. The mean force exerted in each direction is plotted in Figure 3. Clearly, the lateral exertions are smaller than those in the foreward and aft direction. Newman-Keuls tests revealed all four means to be significantly different from one another.

TABLE 1

SUMMARY OF PARTICIPANT CHARACTERISTICS

CHARACTERISTIC	MEAN	STANDARD DEVIATION
STATURE (CM)	174.0	8.18
WEIGHT (KG)	73.8	10.63
AGE (YEARS)	22.2	2.99
ELBOW-GRIP LENGTH (CM)	35.8	2.05
SHOULDER-ELBOW LENGTH (CM)	36.7	1.97
BIACROMIAL BREADTH (CM)	37.4	2.23

TABLE 2

ANOVA Summary Table for Maximum Force Exertion Capabilities (Strength)

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	10449.6		
Within				
Set	1	2487.9	2.28	0.1469
Set x S	20	1092.2		
Direction (D)	3	285454.7	109.60	0.0001
D x S	60	2604.6		
Set x D	3	1075.9	2.22	0.0950
Set x D x S	60	484.5		
Total	167			

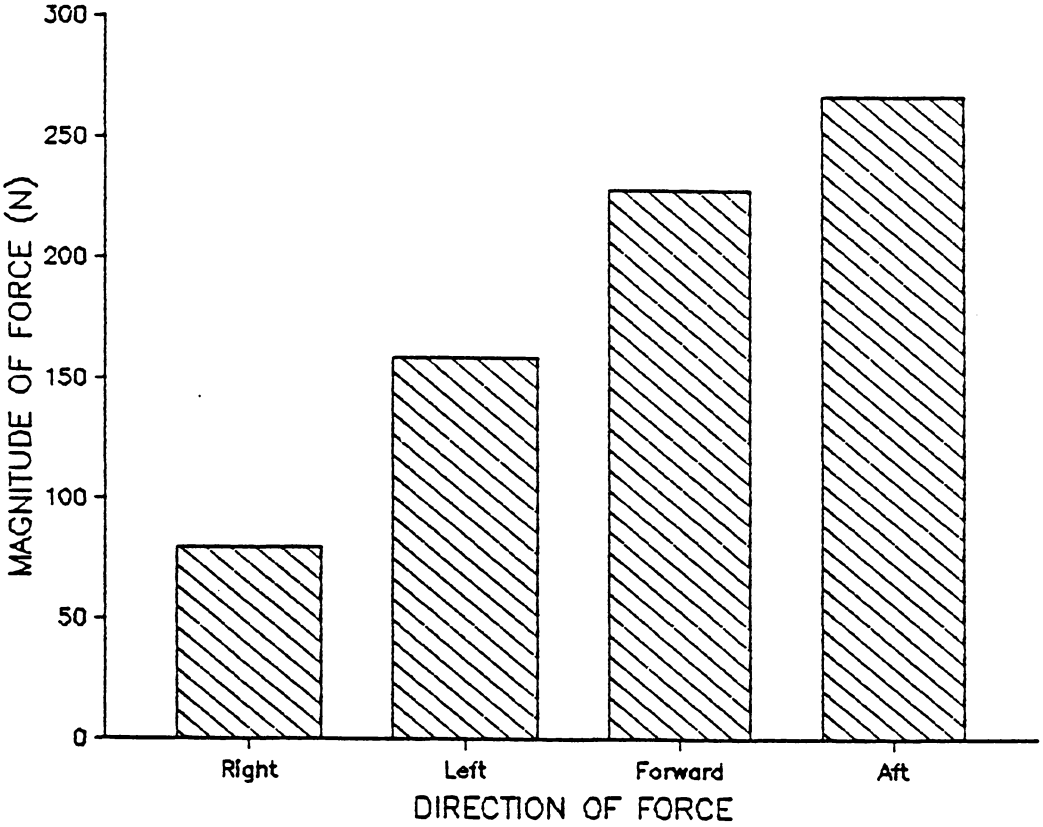

Figure 3. Strength as a function of force direction.

The factor "Set" which appears in the analysis refers to the two sets of strength assessments that were undertaken: one before and one after performing the isometric tracking task. The nonsignificant finding indicates that performance of the isometric tracking task did not significantly affect the strength of the participants.

Force Discrimination

Relative error. The ANOVA results for the Relative Error (RE) measure of force discrimination are provided in Table 3. The Direction x Force Level interaction was statistically significant. The nature of this interaction is depicted in Figure 4. The mean right-hand force-matching exertion exceeded the left-hand referent exertion in all cases. The largest difference occurs when attempting to match the highest force (66.75 N) in the right ("out") direction with the right hand. Newman-Keuls tests for the interaction revealed this mean to be significantly different from the means for all other combinations of force and direction. The mean for the 44.50-forward combination was also found to be significantly different from the mean for the 66.75-left combination. No other differences were found to be significantly different by Newman-Keuls tests. With the exception of the 44.50-forward mean at $t(1,20) = 2.15$, $p = 0.0431$, all means differed significantly from zero at $p \leq 0.002$. The overall correlation between the left-hand and right-hand exertions was $r = 0.73$. No significant differences were observed among the correlations evidenced in each of the four directions.

TABLE 3

ANOVA Summary Table for the Relative Error (RE) Measure of Force Discrimination

Source	df	MS	*F*	*p*
Between				
Subjects	20	714.16		
Within				
Direction (D)	3	180.39	1.73	0.1695
D x S	60	103.98		
Force Level (F)	2	56.65	0.72	0.4606
F x S	40	71.65		
D x F	6	133.13	4.01	0.0011
D x F x S	120	33.18		
Total	251			

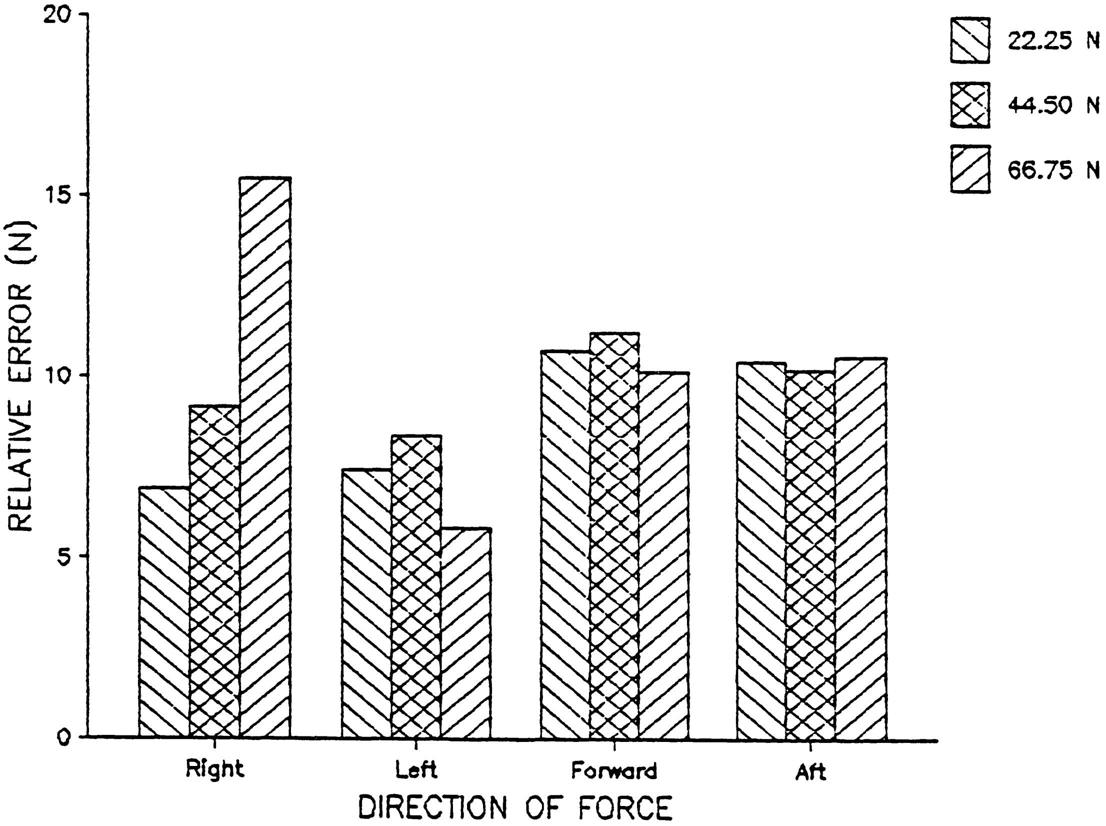

Figure 4. Relative error (RE) as a function of force level and force direction.

Standard-referenced error. Table 4 provides the ANOVA results. The main effects for both Direction and Force Level were significant, but their interaction was not. The plots for the means associated with these two effects are provided at Figures 5 and 6, respectively. As reflected in Figure 5, the average matching-force error in the right (out) direction (SRE-right) by the right hand was smaller than the "standard" by approximately 2 N. The positive SREs in all other directions indicate that matching force exertions were larger than the standard. Newman-Keuls tests revealed that the right-directed SRE was significantly different from those in all other directions. None of the positive SREs differed significantly from one another.

The result of t-tests revealed that the means associated with the lateral directions in Figure 5 did not differ significantly from zero. The means for both the forward ($\underline{t}(1,62) = 3.09$, $\underline{p} = 0.0003$) and aft ($\underline{t}(1,62) = 2.30$, $\underline{p} = 0.0249$) directions did differ significantly from zero.

Figure 6 shows the main effect associated with the magnitude of the referent force level. At 22.25 N the mean matching force exceeded the standard substantially (7.69 N). At the highest force level, the matching force was smaller than the standard (-3.38 N). The mean SRE error (2.05 N) associated with the middle force level, 44.50 N, was approximately midway between those at the highest and lowest force levels. Newman-Kuels tests indicated that all three means differed significantly from one another. The degree of excess force employed in matching the lowest force level was significant, $\underline{t}(1,83) = 8.96$, $\underline{p} <$

TABLE 4

ANOVA Summary Table for the Standard-Referenced Error (SRE) Measure of Force Discrimination

Source	df	MS	*F*	*p*
Between				
Subjects	20	609.87		
Within				
Direction (D)	3	477.81	5.30	0.0026
D x S	60	90.18		
Force Level (F)	2	2575.80	45.21	0.0001
F x S	40	56.97		
D x F	6	8.89	0.34	0.9150
D x F x S	120	26.22		
Total	251			

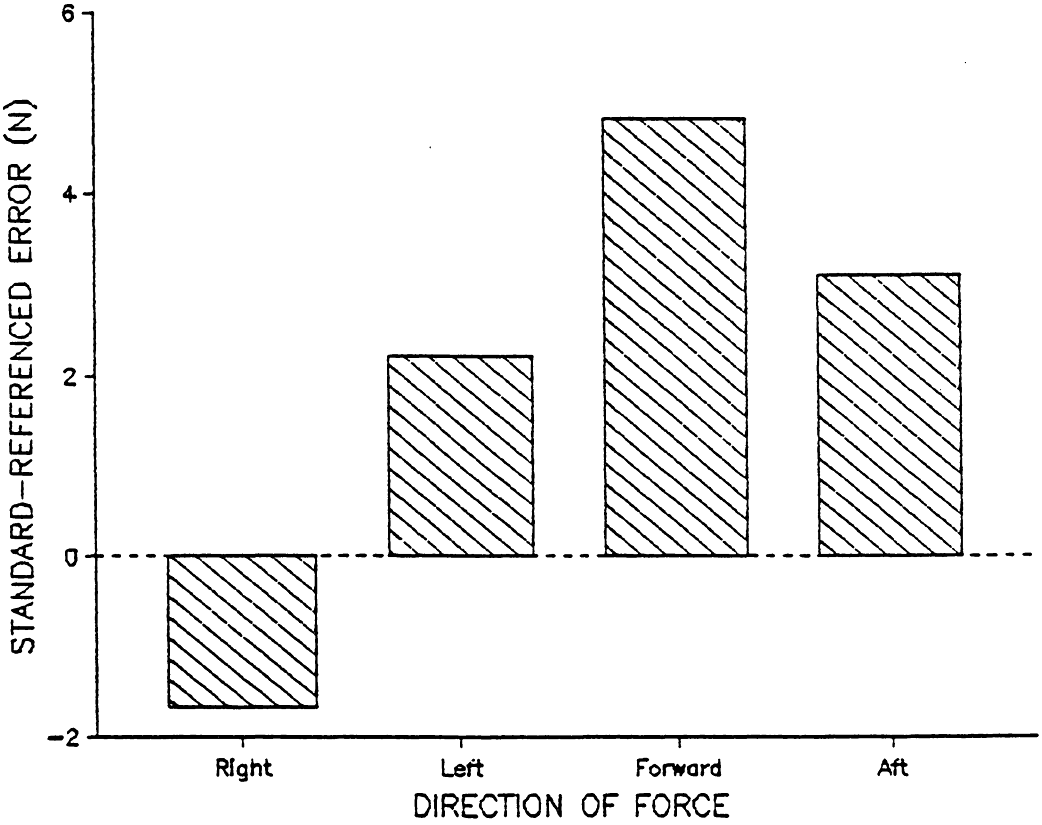

Figure 5. Standard-referenced error (SRE) as a function of force direction.

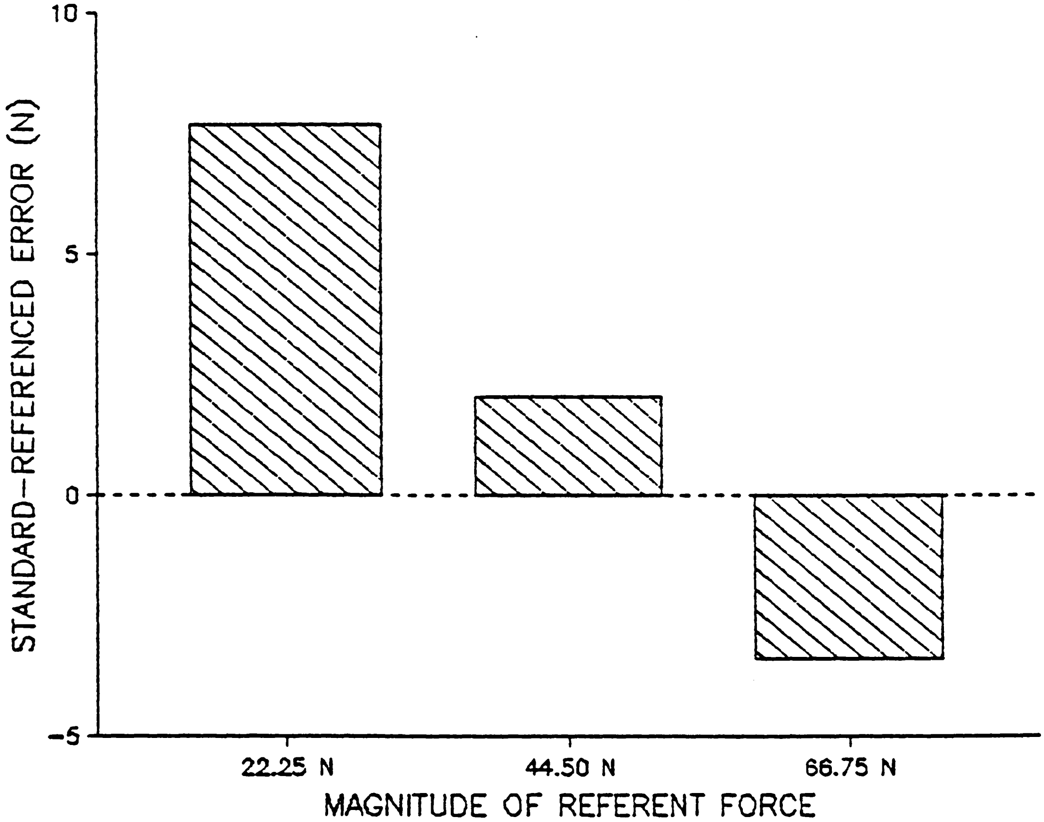

Figure 6. Standard-referenced error (SRE) as a function of the magnitude of the referent force level.

0.0001, as was the force deficit evidenced at the highest force level, _t_(1,83) = -2.82, _p_ = 0.0061. The difference at the middle force level approached, but did not attain, statistical significance, _t_(1,83) = 1.77, _p_ = 0.0881.

Force Variability. The ANOVA summary table (Table 5) for the Force Variability (FV) measure of force discrimination shows only the main effect of Force Level to be statistically significant. Figure 7 depicts the pattern of this effect. Variability increased with increasing levels of the referent force. The FV (1.76 N) associated with the highest force level was approximately twice that (0.85 N) associated with the lowest force level. Newman-Keuls tests revealed all three means to be significantly different from one another.

Isometric Tracking

The results of the analyses of the linear tracking data are presented first, followed by those for the circular tracking data. Within each section, tracking errors along the path are addressed first. Then the analysis of the errors orthogonal to the path are presented.

Linear tracking. The nature of the tracking task itself required that the analyses be conducted in a series of separate ANOVAs. It was the consensus of those participating in the pilot testing that tracking the target at the "corners" of the path as it transitioned from outer circular movement into linear inward movement was substantially different from and more difficult than the performance of the remainder of the task. At these locations, the target executes a pair of rather

TABLE 5

ANOVA Summary Table for the Force Variability (FV) Measure of Force Discrimination

Source	df	MS	*F*	*p*
Between				
Subjects	20	4.281		
Within				
Direction (D)	3	0.406	0.48	0.6888
D x S	60	0.854		
Force Level (F)	2	17.473	42.59	0.0001
F x S	40	0.410		
D x F	6	1.162	1.39	0.2564
D x F x S	120	0.836		
Total	251			

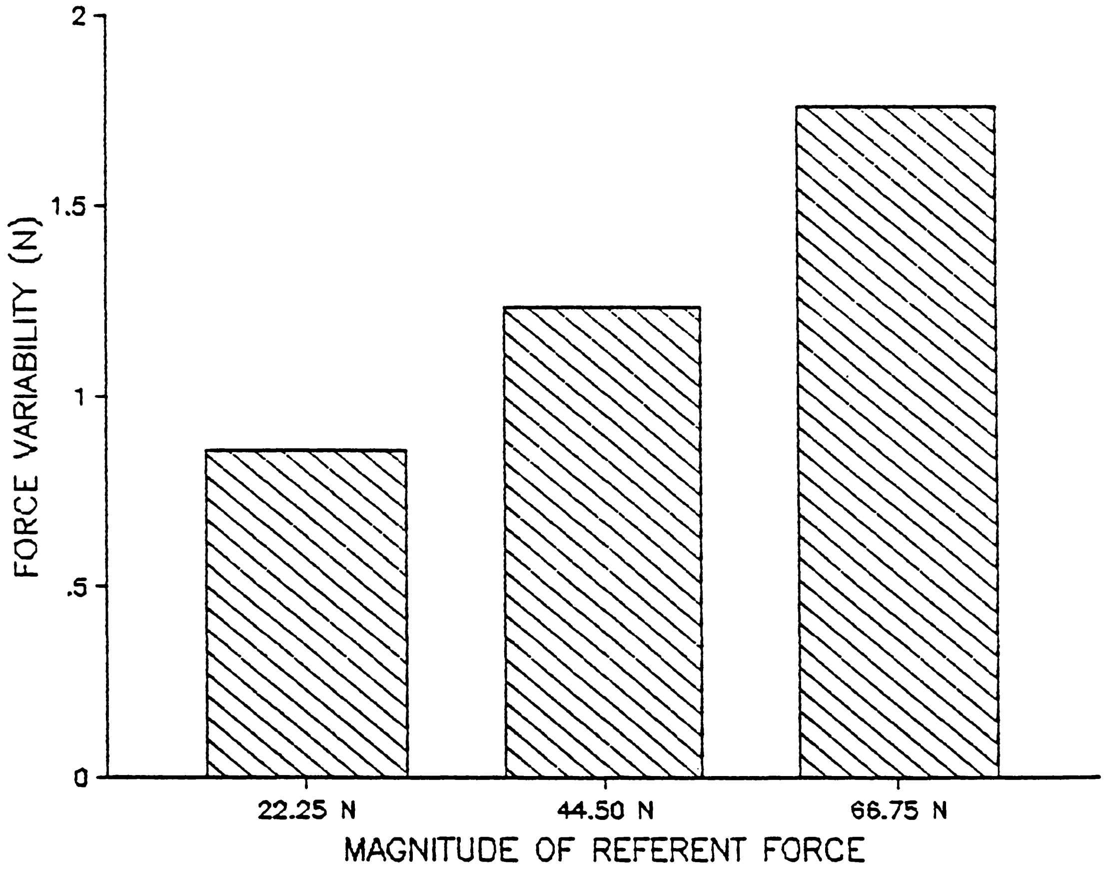

Figure 7. Force variability as a function of the magnitude of the referent force level.

abrupt changes in direction within a brief period of time (see Figure 1). This allows the subject less than 0.5 cm of linear tracking opportunity before the target reaches the location corresponding to the highest force level. In contrast, for all other linear tracking conditions, a straight path of at least 2.4 cm length preceeded the location of each data-point-of-interest. Accordingly, the data from these locations were omitted from the analyses.

Because the data from the transitional portions of the path were excluded, it was not possible to analyze the linear tracking data with a single ANOVA. Therefore, two separate ANOVAs were undertaken. One was a two-factor repeated-measures ANOVA that addressed all four force directions, all three force levels, but only performance during the outward mode of target movement. The second was a three-factor (Force Direction, Force Level, and Mode) repeated-measures ANOVA. All four force directions and both modes of target movement (in and out) were included; however, only the two lower force levels (22.25 N and 44.50 N) common to both in and out modes of target movement were addressed.

The results of the ANOVA of tracking errors along the path during outward, linear target movement appear in Table 6. The main effects of Force Level and Force Direction were statistically significant; their interaction was not. Figure 8 depicts the effects of Force Direction. Negative values denote lagging tracking performance (the cursor follows behind the target). The greatest error occurs in the right force direction, and the smallest error in the left force direction. Newman-Keuls tests indicated that errors in the right, aft and forward force

TABLE 6

ANOVA Summary Table for Tracking Error Along the Target Path During Outward Linear Movement.

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	0.9980		
Within				
Force Direction (D)	3	0.3412	3.59	0.0188
D x S	60	0.0952		
Force Level (F)	2	1.5919	48.25	0.0001
F x S	40	0.0330		
D x F	6	0.0376	1.43	0.2100
D x F x S	120	0.0267		
Total	251			

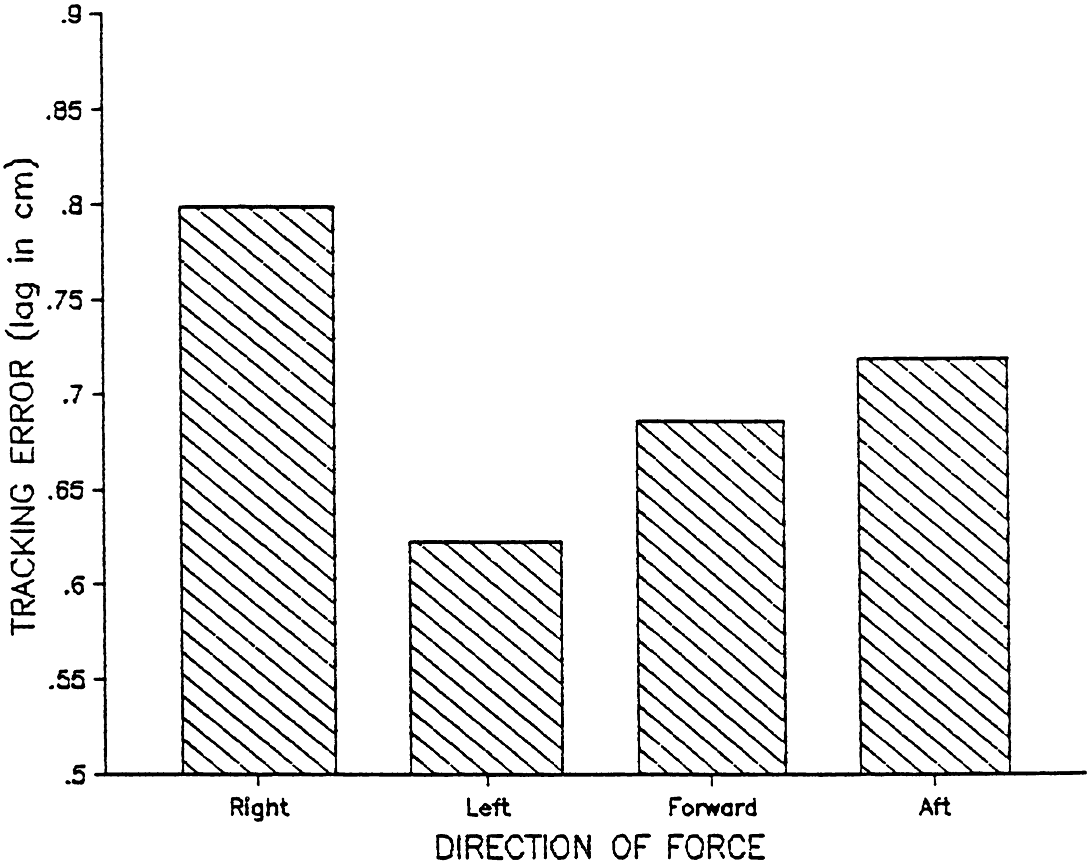

Figure 8. Tracking performance as a function of force direction for error measured along the path during linear target movement.

directions did not differ significantly from one another. The same applied to errors in the left, forward, and aft force directions.

Figure 9 illustrates the nature of the significant effect of Force Level. Higher force levels were associated with larger tracking errors. Newman-Kuels tests showed all means to differ significantly from one another.

The results of the ANOVA for tracking errors orthogonal to the path during outward, linear target movement are provided in Table 7. Only the main effect of Force Direction attained the $p < 0.05$ level of statistical significance. The smallest error is associated with tracking conditions requiring force inputs in the left direction. Newman-Keuls tests revealed this error to be significantly different from that in any other direction. There were no significant differences among the other directions. Figure 10 shows the main effect of Force Direction. (Recall, in examining figures which relate to errors orthogonal to the path, that errors which are positive in sign represent errors to the right of the path as viewed from a cursor position which is "behind" or "following" the target. Errors with negative signs represent errors to the left of the target path.)

The effects of the mode (in-out) of target movement are introduced in the succeeding two ANOVAs. The initial ANOVA addresses tracking errors along the path during linear target movement. Table 8 contains these findings. The main effects of Force Direction and Mode were both significant, as was the interaction between Force Level and Mode. The Force Direction effect is shown in Figure 11. Tracking errors

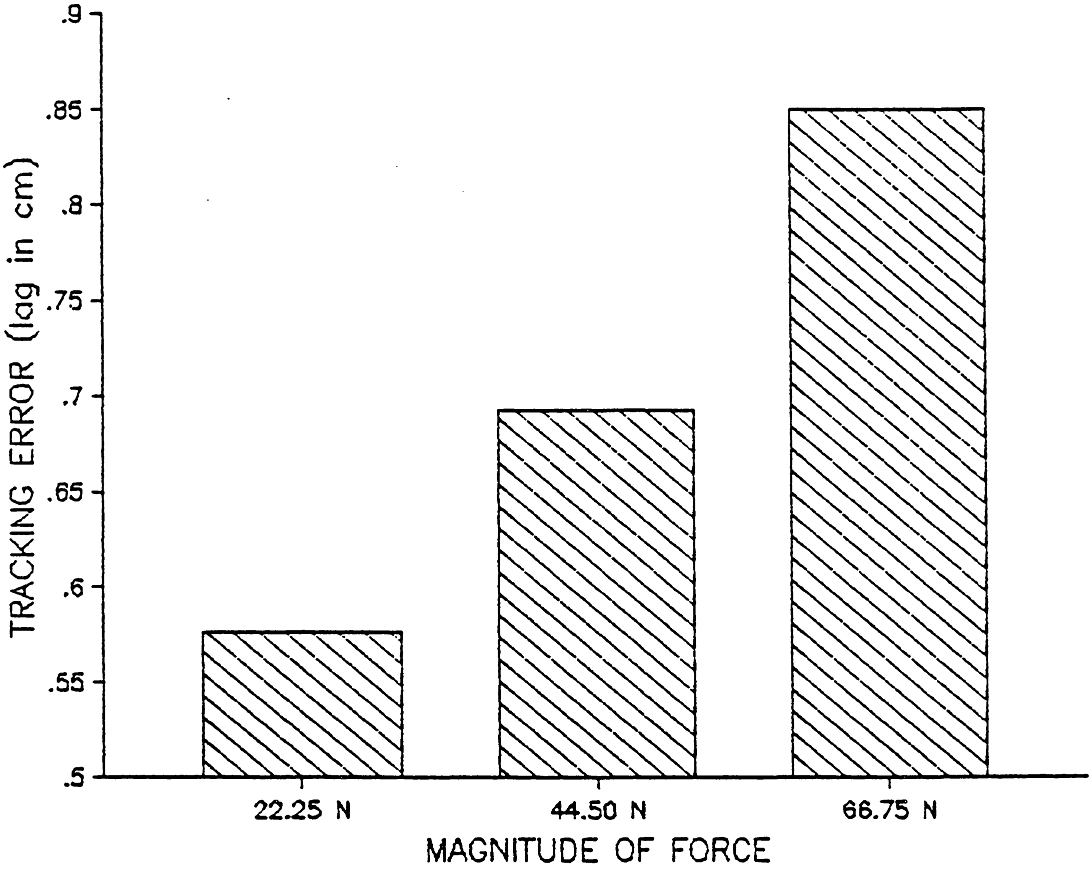

Figure 9. Tracking performance as a function of force level for error measured along the path during linear target movement.

TABLE 7

ANOVA Summary Table for Tracking Error Orthogonal to the Target Path During Outward Linear Movement.

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	0.7534		
Within				
Force Direction (D)	3	0.4300	8.57	0.0001
D x S	60	0.0502		
Force Level (F)	2	0.0248	0.98	0.3857
F x S	40	0.0254		
D x F	6	0.0387	2.01	0.0699
D x F x S	120	0.0193		
Total	251			

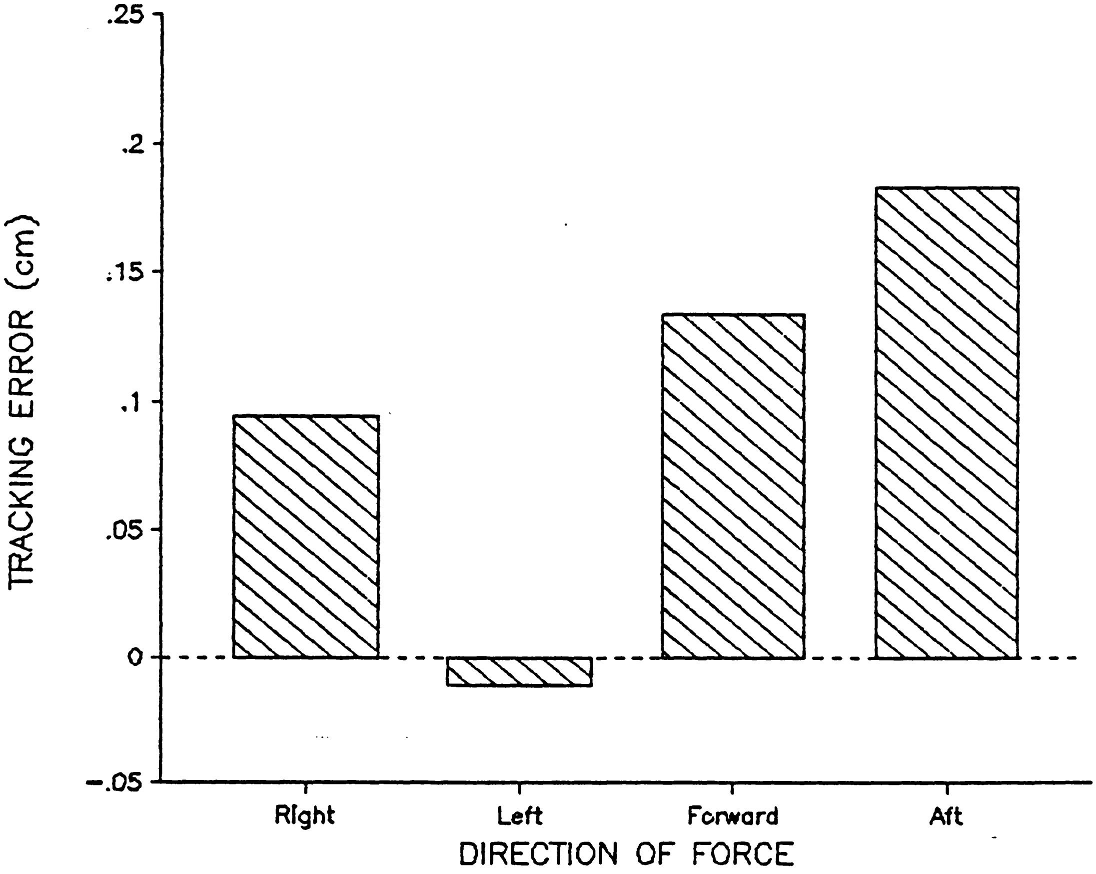

Figure 10. Tracking performance as a function of force direction for error measured orthogonal to the path during linear target movement.

TABLE 8

ANOVA Summary Table for Tracking Errors Along the Path of the Target During Linear Movement at Force Levels 22.25 N and 44.50 N

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	1.1963		
Within				
Force Direction (D)	3	0.1607	2.94	0.0400
D x S	60	0.0545		
Force Level (F)	1	0.2400	3.16	0.0905
F x S	20	0.0758		
Mode (M)	1	18.2840	70.31	0.0001
M x S	20	0.2522		
D x F	3	0.0877	2.41	0.0754
D x F x S	60	0.0363		
D x M	3	0.1400	1.44	0.2401
D x M x S	60	0.0972		
F x M	1	2.4242	30.31	0.0001
F x M x S	20	0.0800		
D x F x M	3	0.0730	1.71	0.1449
D x F x M x S	60	0.0427		
Total	335			

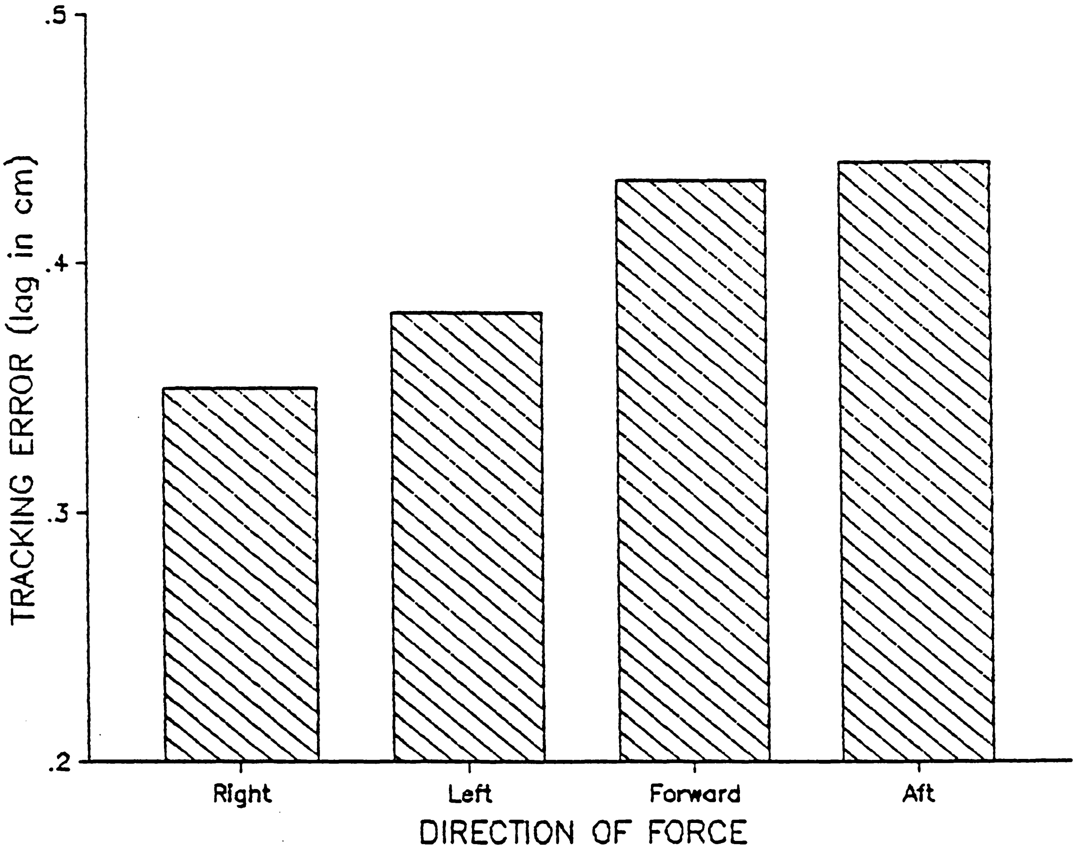

Figure 11. Tracking performance averaged over inward and outward directions of target movement and force levels as a function of force direction for error measured along the path during linear target movement.

associated with lateral force requirements are observed to be less than those associated with fore-aft force requirements. The Force Level x Mode interaction is depicted in Figure 12. Simple-effects tests revealed that the differences between force levels to be highly significant for both the inward mode, F(1,20) = 16.59, p = 0.0006, and the outward mode, F(1,20) = 19.25, p = 0.0003. The differences are, however, in opposite directions. During outward tracking, the error associated with the larger force level significantly exceeded the error associated with the smaller force level. The reverse was true during inward tracking.

The ANOVA results for tracking errors orthogonal to the path during linear tracking are provided in Table 9. The main effect of Force Direction and its separate interactions with Force Level and Mode were each statistically significant. The main effect of Mode was also significant.

Figure 13 depicts the Force Direction x Force Level interaction. The means associated with the higher force level appear to parallel the strength capabilities that individuals possess in each direction, whereas those associated with the lower force level do not. Simple effects test revealed that there was no significant effect for Force Direction at the lower force level (p > 0.2). At the higher force level, Force Direction effects are significant, F(3,60) = 4.50, p = 0.0065. Newman Keuls tests for this effect indicated that the three smallest of the 44.50 N means were not significantly different from one another, nor were the three largest means.

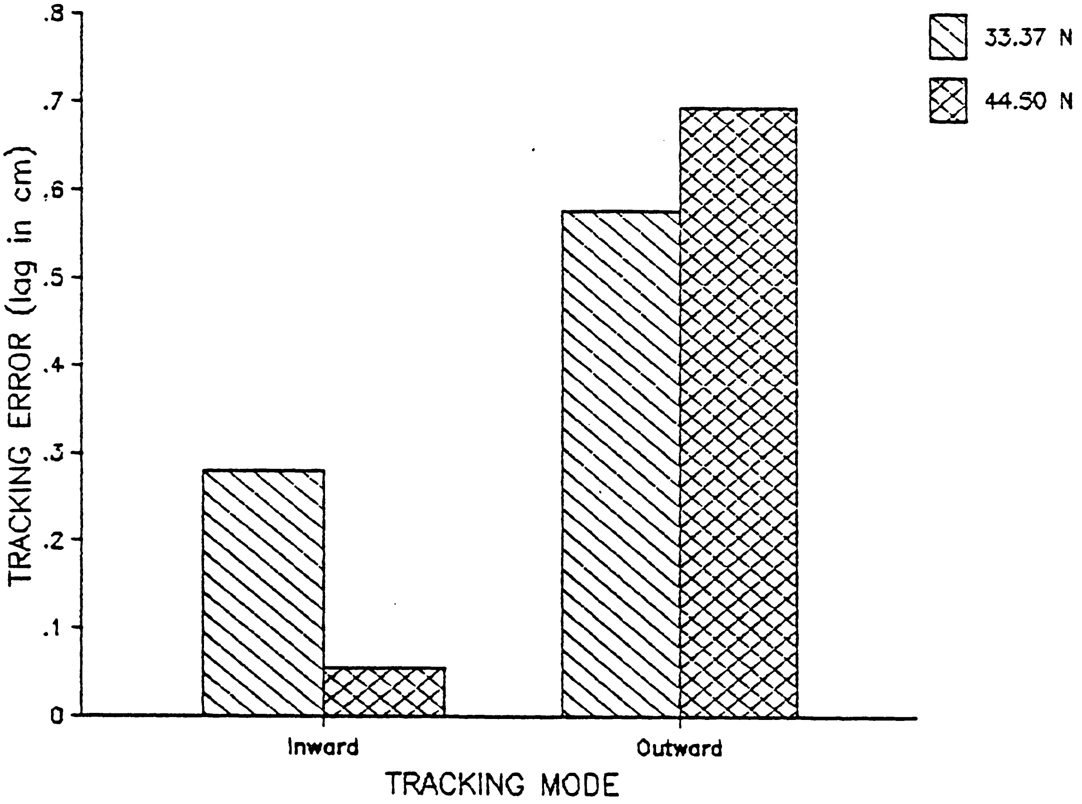

Figure 12. Tracking performance as a function of force level and tracking mode (direction of target movement) for error measured along the path during linear target movement.

TABLE 9

ANOVA Summary Table for Tracking Errors Orthogonal to the Path of the Target During Linear Movement at Force Levels 22.25 N and 44.50 N

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	0.0884		
Within				
Force Direction (D)	3	0.1143	3.02	0.0367
D x S	60	0.0379		
Force Level (F)	1	0.1071	4.09	0.0568
F x S	20	0.0262		
Mode (M)	1	0.2211	6.46	0.0195
M x S	20	0.0343		
D x F	3	0.0804	4.31	0.0081
D x F x S	60	0.0187		
D x M	3	0.2885	3.94	0.0124
D x M x S	60	0.0580		
F x M	1	0.1144	4.16	0.0549
F x M x S	20	0.0275		
D x F x M	3	0.0354	1.48	0.2297
D x F x M x S	60	0.0240		
Total	335			

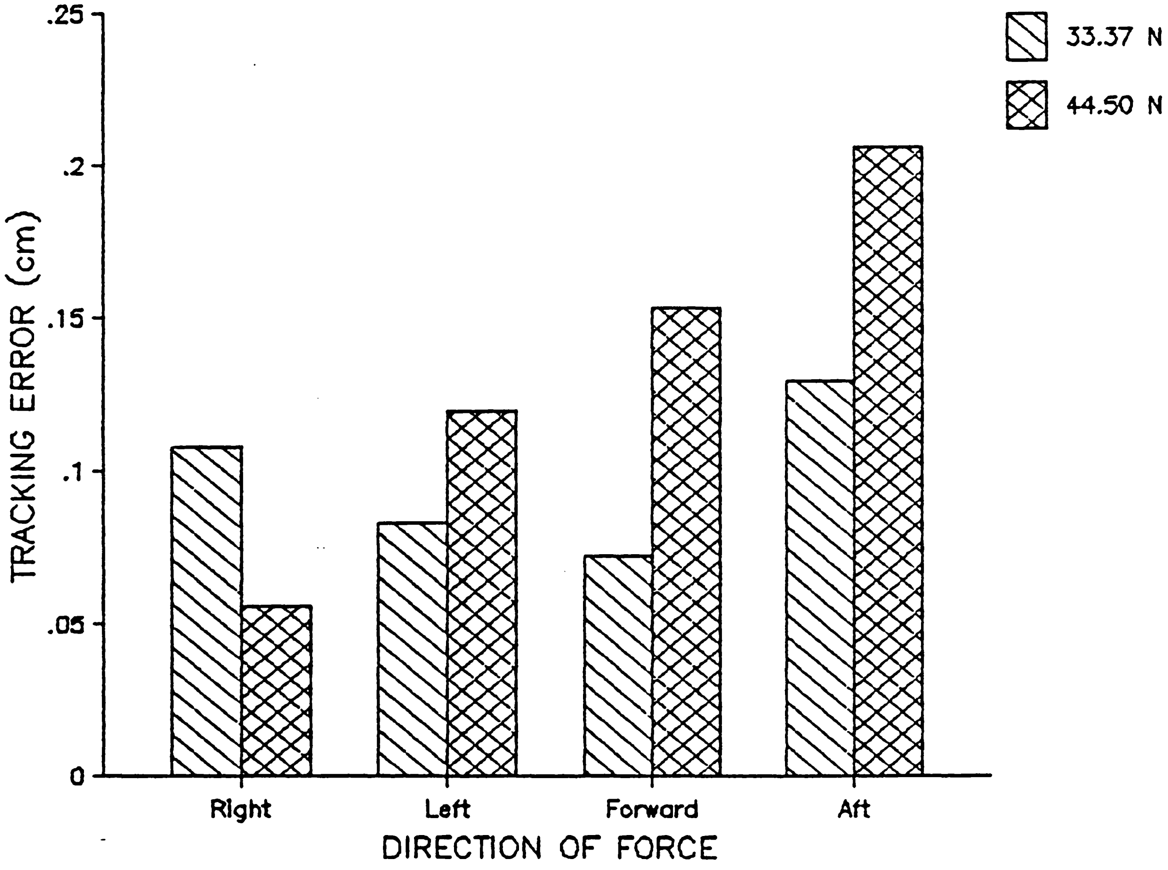

Figure 13. Tracking performance as a function of force level and force direction for error measured orthogonal to the path during linear target movement.

The nature of the significant Force Direction x Mode interaction is readily apparent from Figure 14. In contrast to the relative absence of differences in the other directions, in the left force direction a significantly larger error occurred during inward target movement than during outward target movement (Fisher's LSD test, $p < 0.05$, Kirk, 1968).

Circular tracking. With some qualification, the tracking path posed no obstacle to the use of a three-factor repeated-measures ANOVA for the analyses of circular tracking performance. The caveat derives from consideration of the path geometries involved at the two levels of force.

The circular components of the tracking path employed to address the two force levels entailed, of necessity, two radii. The 6.75 cm radius for the portion of the path associated with the 33.37 N force level was one-half that used for the 66.75 N force level. Since the target traveled at a constant velocity, the rate-of-change of direction for the 33.37 N condition was greater than that for the 66.75 N condition. Therefore, the path used for tracking at the lesser force level should have been more difficult to follow than the path employed at the larger force level. Accordingly, on the basis of path geometries alone, the task was biased in favor of attaining better performance while tracking at the higher force level than at the lower force level.

Table 10 presents the results of the ANOVA of errors measured along the path of the target while tracking circular portions of the path. Here, the factor "Mode" refers to the fact that both clockwise (CW) and

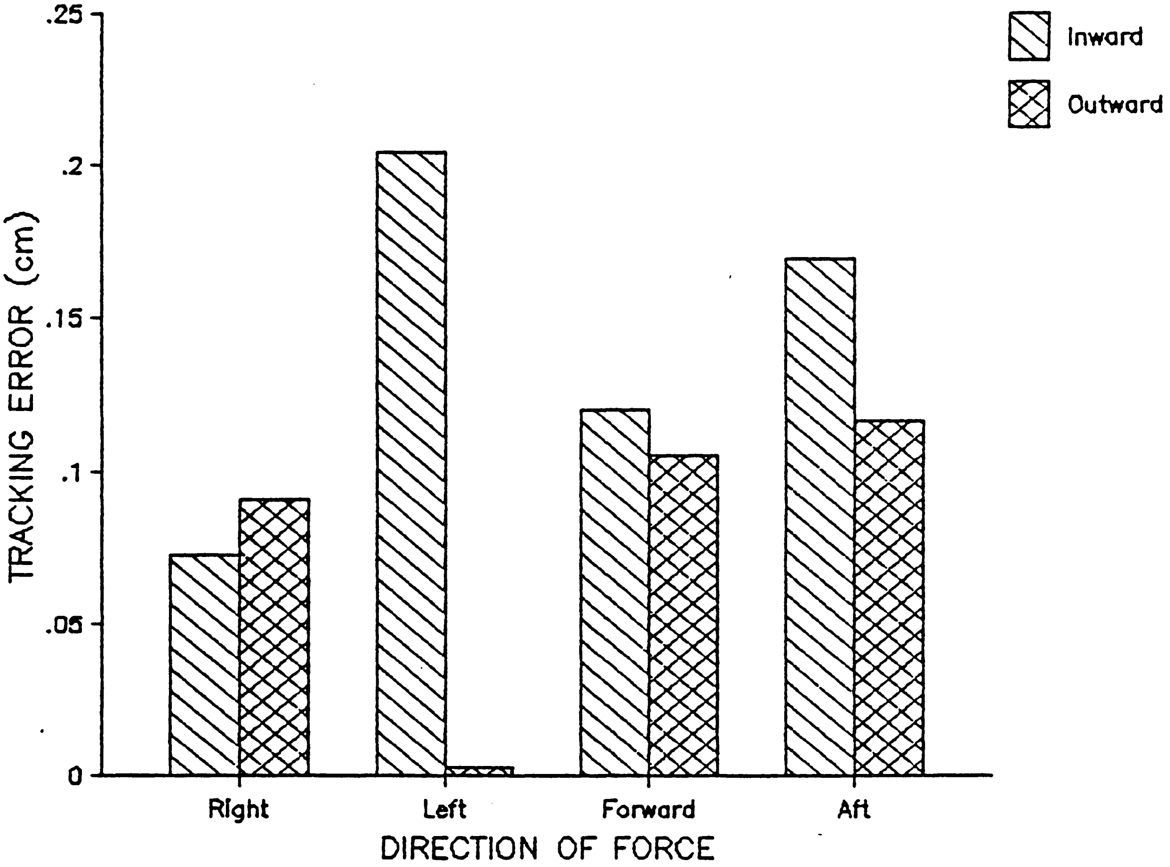

Figure 14. Tracking performance as a function of force direction and tracking mode (direction of target movement) for errors measured orthogonal to the path during linear target movement.

TABLE 10

ANOVA Summary Table for Tracking Errors Along the Path of the Target During Circular Movement

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	1.2927		
Within				
Force Direction (D)	3	0.3790	13.16	0.0001
D x S	60	0.0288		
Force Level (F)	1	0.0799	1.26	0.2741
F x S	20	0.0631		
Mode (M)	1	1.7761	15.64	0.0008
M x S	20	0.1129		
D x F	3	0.0144	0.46	0.7087
D x F x S	60	0.0311		
D x M	3	0.3069	5.40	0.0024
D x M x S	60	0.0569		
F x M	1	0.1867	5.83	0.0255
F x M x S	20	0.0320		
D x F x M	3	0.0213	0.65	0.5882
D x F x M x S	60	0.0330		
Total	335			

counterclockwise (CCW) directions ("modes") of target movement were employed. The main effects of Force Direction and Mode were statistically significant, as was their interaction. The interaction between Force Level and Mode was also significant.

Figure 15 presents the Force Direction x Mode interaction. Newman-Keuls tests indicated that while not significantly different from one another, the similarly small mean errors evidenced for the CW-forward and CW-aft conditions were significantly different from all others except that for CW-right. The mean for the CW-right condition did not differ significantly from any other mean. No other significant differences existed.

The Force Level x Mode interaction is plotted in Figure 16. Newman-Keuls tests indicated that the two CW means did not differ significantly from one another. The smaller CW mean occurred in conjunction with the 66.75 N force level. The mean for the 66.75-CW condition differed significantly from both CCW means, whereas the other CW mean (33.37-CW) did not differ significantly from either CCW mean. The CCW means did not differ significantly. The nature of the overall significant main effect of Mode is readily apparent in Figure 16: CCW errors are, overall, clearly larger than CW errors.

The results of the ANOVA for errors orthogonal to the path while tracking circular portions of the path are summarized in Table 11. All three main effects were significant. None of the interactions were significant.

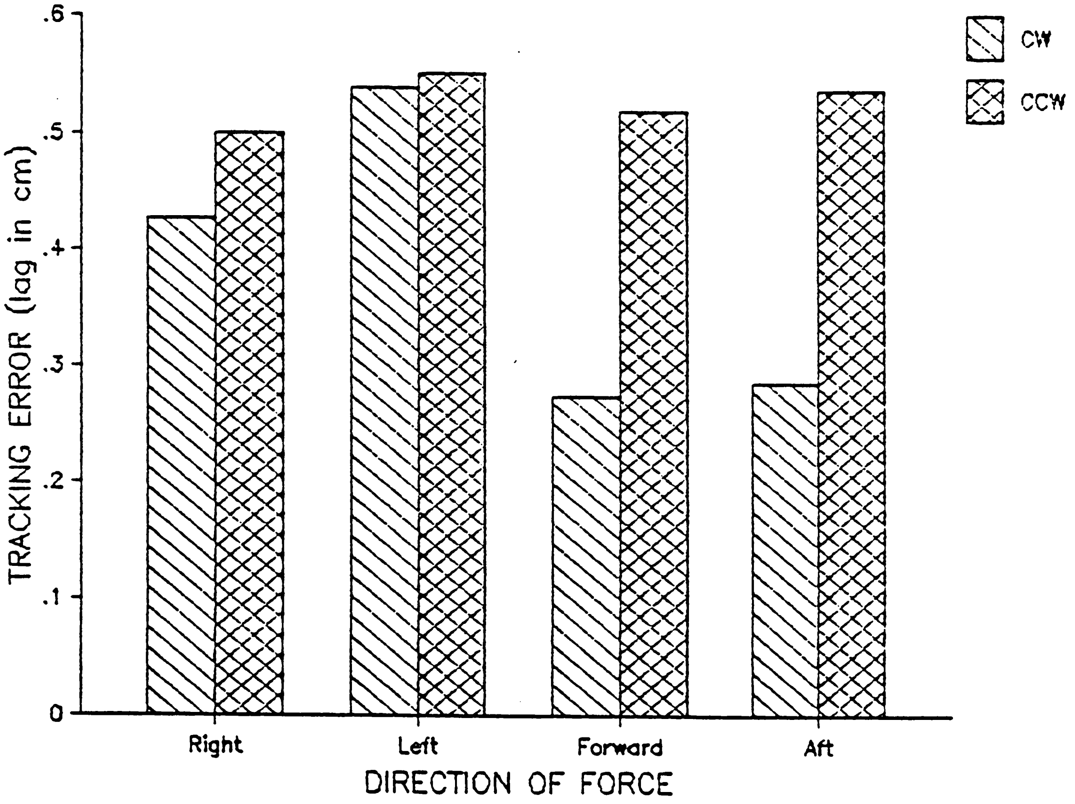

Figure 15. Tracking performance as a function of force direction and tracking mode (direction of target movement) for error measured along the path during circular target movement.

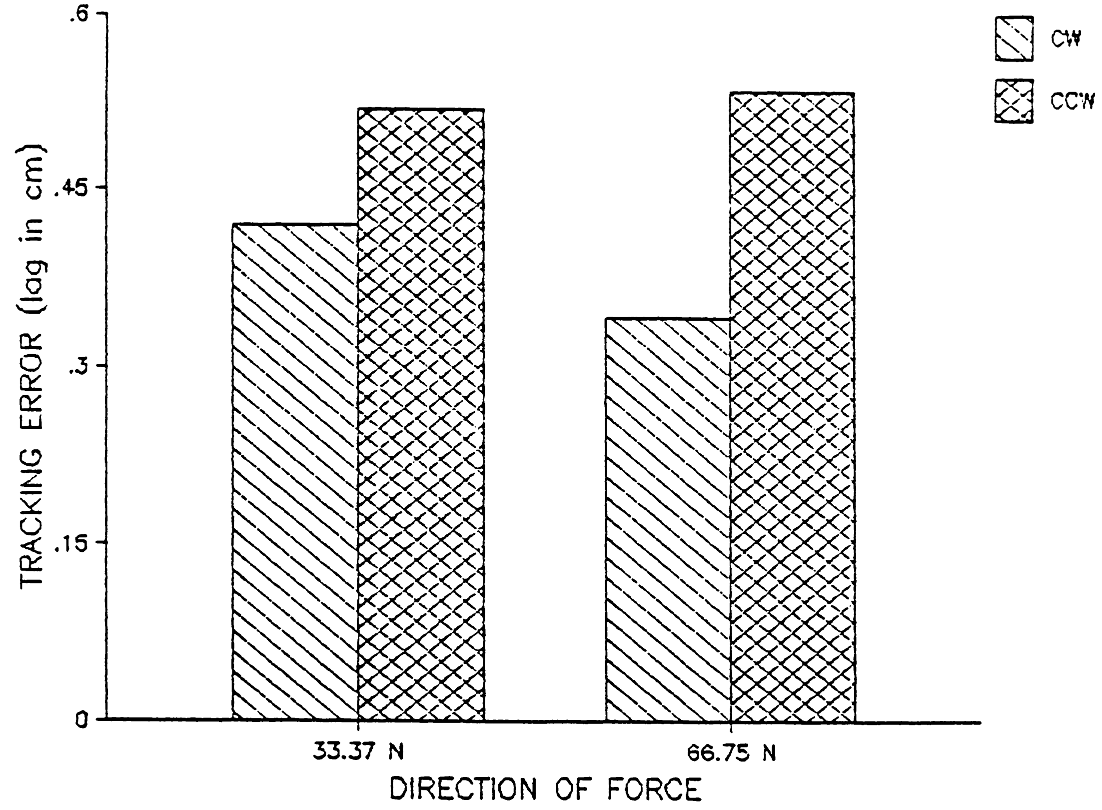

Figure 16. Tracking performance as a function of force level and tracking mode (direction of target movement) for error measured along the path during circular target movement.

TABLE 11

ANOVA Summary Table for Tracking Errors Orthogonal to the Path of the Target During Circular Movement

Source	df	MS	*F*	*p*
Between				
Subjects (S)	20	0.3323		
Within				
Force Direction (D)	3	0.9189	14.37	0.0001
D x S	60	0.0640		
Force Level (F)	1	6.4408	74.56	0.0001
F x S	20	0.0864		
Mode (M)	1	0.7392	19.05	0.0003
M x S	20	0.0388		
D x F	3	0.0076	0.27	0.8471
D x F x S	60	0.0282		
D x M	3	0.0865	1.88	0.1429
D x M x S	60	0.0460		
F x M	1	0.0720	2.69	0.1164
F x M x S	20	0.0268		
D x F x M	3	0.0442	1.14	0.3407
D x F x M x S	60	0.0388		
Total	335			

The mean orthogonal error at the higher force level (-0.33 cm) was more than six times larger (closer to the center) than that at the lower force level (-0.05 cm). The mean CW error (-0.24 cm) was significantly closer to the center) than the CCW error (-0.14 cm). The nature of the significant main effect for Force Direction is depicted in Figure 17. While all mean errors were to the inside of the circular portions of the path, the smallest error occurred when force inputs in the aft direction were required. Newman-Keuls tests revealed the aft-direction mean to be significantly smaller than all others. The forward mean differed significantly from the aft and right means, but not from the left mean. The largest, right mean differed significantly from the forward and aft means, but not from the left mean.

Correlations.

A series of correlational analyses were undertaken to assess the extent to which strength, force discrimination measures, and tracking performance were interrelated at each combination of force magnitude and direction. As in the preceeding sections, a p-value $\leq$ 0.05 was adopted as the criterion for significance.

Strength x force discrimination. Correlations between the force discrimination measures and derived strength/demand ratios (SDRs) were examined. SDRs were computed by dividing each of the direction-specific strength values for each subject by each of the three force-demand values (22.25 N, 44.50 N and 66.75 N). These 12 values were then paired with the corresponding values for each of the three force discrimination

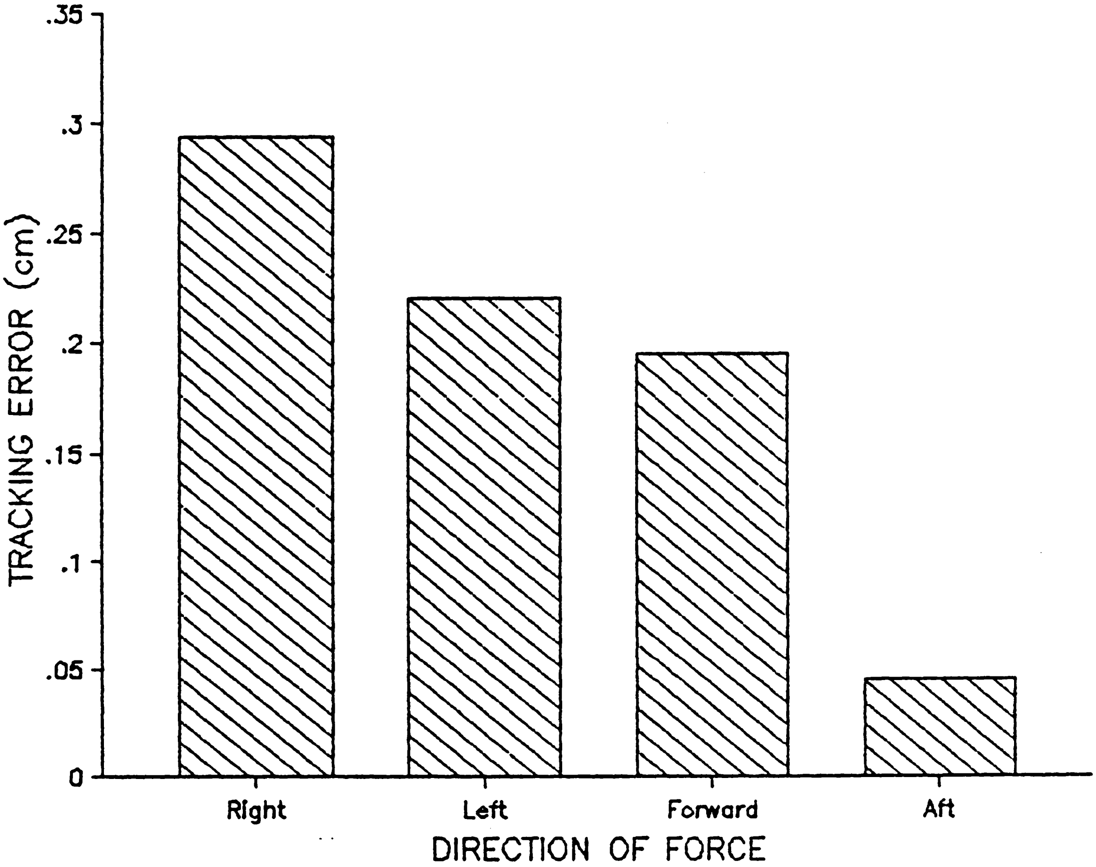

Figure 17. Tracking performance as a function of force direction for error measured orthogonal to the path during circular target movement.

measures. Among the correlations, only the SDR x SRE ($\underline{r} = 0.39$) and the SDR x FV ($\underline{r} = -0.24$) were significant ($\underline{p} \leq 0.0001$ in both instances). In contrast to the SDR-related correlations, no significant correlation was obtained between the direction-specific measures of strength and any of the force discrimination measures. The differences between the direction-specific strength-related correlations and the SDR-related correlations showed larger values for the latter for all force discrimination measures. However, only the difference associated with the SRE measure attained statistical significance, $\underline{t}(1,249) = 2.30$, $\underline{p} < 0.05$. The SDR x SRE correlation ($\underline{r} = 0.39$) was significantly larger than the strength x SRE correlation ($\underline{r} = 0.19$).

Strength x tracking performance. As previously discussed, the data associated with tracking performance at the highest force level during inward, linear target movement were excluded from the analyses. Correlations were computed between tracking errors associated with each combination of force level and force direction and the corresponding force/direction-specific SDR. The resulting correlation coefficients are provided in Table 12.

The only significant correlations obtained were those associated with tracking errors measured coincident with the line-of-action of the force required to perform the task; i.e., along the axis during linear tracking conditions and orthogonal to the axis during circular tracking conditions. Among the significant correlations, all are positive except that relating to the inward linear tracking condition. Note that since lagging (linear) and inward (circular) tracking errors are negative in

TABLE 12

Correlations of Direction-Specific Strength and Strength/Demand Ratios (SDRs) with Tracking Errors for Each Tracking Condition and Measurement Axis

Tracking Conditions		Measurement	r	
Type	Mode	Axis	Strength	SDR
Linear1	In	Along	-0.09	-0.21*
Linear1	In	Orthogonal	0.08	-0.06
Linear2	Out	Along	0.03	0.20*
Linear2	Out	Orthogonal	0.18*	0.07
Circular1	CW	Along	0.21*	0.09
Circular1	CW	Orthogonal	0.34**	0.46**
Circular1	CCW	Along	0.05	0.05
Circular1	CCW	Orthogonal	0.21*	0.50**

1 N = 168
2 N = 252
* $p < 0.05$
** $p < 0.005$

sign, positive correlations indicate that higher SDRs are associated with smaller tracking errors. The significant correlations pertaining to circular tracking are more than twice the magnitude of those associated with linear tracking.

The significant SDR-related correlations were all larger than the corresponding correlations calculated using direction-specific strength. However, only the difference pertaining to CCW target movement was statistically significant, $\underline{t}(1,249) = 2.40$, $\underline{p} < 0.05$.

Force discrimination x tracking performance. The correlations between each force-discrimination measure and tracking errors for all tracking conditions and measurement axes appear in Table 13. They are notable only because they are unexpectedly small. While one-half or more of the SRE- and FV-related correlations are statistically significant, only one exceeds 0.30; i.e., that between FV and tracking errors measured along the axis during outward linear target movement ($\underline{r} = -0.34$, $\underline{p} \leq 0.0001$). Only one of the RE-related correlations was significant--that encountered under the same conditions as described for the significant FV-related correlation just cited. Seven of the ten significant correlations pertain to circular tracking conditions.

TABLE 13

Correlations Between Force Discrimination Measures and Tracking Errors for Each Tracking Condition and Measurement Axis

Tracking Conditions		Axis of	Force Discrimination Measure		
Type	Mode	Measure	RE	SRE	FV
Linear1	In	Along	0.00	-0.24***	0.13
Linear1	In	Orthogonal	0.04	-0.13	-0.01
Linear2	Out	Along	0.21*	0.02	-0.34***
Linear2	Out	Orthogonal	-0.15	0.11	0.09
Circular1	CW	Along	0.10	-0.19*	-0.08
Circular1	CW	Orthogonal	0.09	0.21**	-0.18*
Circular1	CCW	Along	0.13	-0.19*	0.20**
Circular1	CCW	Orthogonal	0.10	0.27***	-0.26***

1 N = 168
2 N = 252
* $p < 0.05$
** $p < 0.01$
*** $p < 0.005$

DISCUSSION

Anthropometric and Strength Characteristics of the Subjects

A comparison of the present anthropometric data with anthropometric data summaries from previously conducted large scale surveys of several U. S. military populations (NASA, 1978), indicates that the statures and weights of the males who participated in the study represented values which fell within the 5th-10th percentile range at the low end and the 95th-99th percentile range at the high end. Among the females, the shortest individual's stature corresponded approximately to the 25th percentile of the military populations surveyed. The tallest female's stature fell within the 90th-95th percentile range. Percentile equivalents for the female weights encountered ranged from the 75th-80th at the low end to the 99th-plus at the high end. These data indicate that the males who participated in the study encompassed a range which is consistent with the male population at large. Among the females achieving the required strength, however, the sample is clearly above average in both height and weight.

The strength findings are generally consistent with those previously reported (Laubach, Kroemer, and Thordsen, 1972; McDaniel, 1981; Schopper and Mastroianni, 1984). That horizontal exertions are considerably larger than lateral exertions is a common finding (Laubach, Kroemer, and

Thordsen, 1972; McDaniel, 1981; Schopper and Mastroianni, 1984). The present data do differ significantly, however, from those reported earlier by Laubach, Kroemer, and Thordsen (1972) regarding strength in the forward and aft directions. These researchers found that mean strength measured in the aft direction was about one-third less than that measured in the forward direction. The present findings are in the reverse direction; aft exertions exceeded forward exertions by 17 percent. The reason for the discrepancy is believed to be in the differences in the locations of the handles relative to the subjects' positions. In Laubach, Kroemer, and Thordsen's study, the handle was located 2.3 cm lower, 2.8 cm farther out, and 14.6 cm farther forward than was the handle in the present research. This substantial difference resulted in a markedly more obtuse elbow angle for their subjects than for the participants in the present research. The existence of this large elbow angle (estimated to range between 140-160 degrees) permits individuals to exert much larger forces than can be exerted when the angle is in the 89.5-105.6 degree range observed in this study (Hertzberg, 1972; Laubach, 1978).

Force Discrimination.

Among the force discrimination data, it is notable that all means for the RE measure (that computed by subtracting the magnitude of the left-hand referent exertion from the magnitude of the matching right-hand exertion) were positive. This indicates that the matching exertion was larger than the referent exertion. This bias is believed to be due to timing factors present in the procedure. The left-hand referent exertion was developed during the initial 6 s of each trial. Feedback was removed, and the subject then focused on efforts to match the magnitude of the left-hand exertion with a comparable right-hand exertion. Hence, before feedback is removed, the left hand has already sustained the required exertion for 6 s. After nine seconds, at the beginning of the measurement period (the last second of the trial), the left-hand exertion has been maintained nearly three times as long as the right-hand exertion.

Findings pertaining to the time course of sustained isometric exertions undertaken without feedback indicate that (a) such forces decline over time, (b) the amount of decay is most rapid during the initial seconds, and (c) the rapidity of the decay is positively correlated with the initial level of force sustained (Cain, 1973; Caldwell and Grossman, 1973). Therefore, it is likely that, during the no-feedback period, the force in the left hand decreased.

While there exist no data with which to show the purported decline, per se, an examination of the magnitudes of both the left-hand and right-hand exertions used in the computation of the RE scores does provide indirect support for the proposed explanation. If one assumes that at the end of the feedback period the force level in the left hand closely approximated the referent force level, then force magnitudes recorded during the tenth second should indicate whether or not a force decrement has occurred. The left-hand forces at the 66.75 N level clearly indicated that this has occurred: "out" = 44.1 N, "in" = 58.0 N, forward = 56.1 N, aft = 56.1 N. Corresponding values for the right hand evidenced much less decrement: 59.6 N, 63.8 N, 66.2 N, and 63.9 N.

Related findings have been encountered elsewhere. In a somewhat different context, Schopper and Mastroianni (in press) have examined the effects of making more than one exertion simultaneously. In their study, they found that a requirement to simultaneously attempt multiple maximal exertions resulted in significant force decrements relative to the magnitudes of the same exertions attempted singly. The degree of decrement was inversely related to the magnitude of the single exertion, a finding that parallels, to some extent, the present findings of greater decreases in the "out" (weakest) direction.

It is also possible that the shift in attention, from a total focus on the magnitude of the left hand force level to an emphasis on the right hand force level, contributed to the decline in the force level which occurred in the left hand. Mastroianni and Schopper (1986) have shown that in divided-attention tasks, deficits are related to the relative level of the force requirements. Since the present task assumes a dual-task nature when the matching requirement is introduced, it is possible that the shift in the focus of attentional resources may also have contributed to the greater decline in left-hand force levels.

The absence of a significant correlation between the RE measure and the strength-related measure is believed to be due largely to the manner in which RE is calculated. It represents the difference between the magnitude of the matching force and the magnitude of the referent force. Since both values are substantially correlated ($\underline{r}$ = 0.73), a large portion of the strength-related variance is removed. Apparently, that which remained was insufficient to yield a significant correlation with SDR.

In contrast to the consistent bias encountered in the present RE findings, the results of Jones and Hunter (1982) indicated that the right arm force-matching exertion exceeded the left arm referent exertion only at referent force levels which were less than 40 percent of the maximum force attainable by the respective arms. This discrepancy is believed to be related to procedural differences. One important difference was that Jones and Hunter (1982) provided visual feedback during the entire trial regarding the magnitude of the force output of the arm providing the referent-level exertion. Hence, in contrast to the present findings, their subjects were likely to have been better able to maintaine the referent force exertion at the desired level during the force-matching interval. A second procedural difference is that Jones and Hunter (1982) used a shorter force matching period, 3 s, rather than the 6 s employed in the present research. Hence, the present study allowed an even longer period of no feedback than existed in Jones and Hunter during which the magnitude of the referent exertion could decay.

Proceeding to the second force discrimination measure, SRE, it is noted that it is independent of the magnitude of the left-hand referent measure. (It is calculated by subtracting the value of the referent from the magnitude of the right-hand matching exertion.) The findings (Figure 5) revealed that the matching force was larger than the referent value at the lowest, 22.25 N level and smaller than the referent value at the highest referent force level, 66.75 N. This overshoot-undershoot phenomenon has been observed in previous research. Jenkins (1947) found the same bias in his force-reproduction research using aircraft controls. Jones and Hunter's (1982) data also showed this effect. The results of the correlational analysis yielded a modest positive value (*r* = 0.39) between the SDR measure of relative force exertion capability and SRE. This suggests that the tendency to overshoot lower values and undershoot larger values was exacerbated to some extent among individuals possessing greater strength.

Jenkins (1947) offered no explanation or hypotheses regarding the possible reason for this finding. Jones and Hunter (1982) were unable to offer a satisfactory explanation of the fact that the slope obtained in their data was shallower than the theoretical value. They noted that Cain (1973) had previously proposed a psychoperceptual hypothesis, a 'centering tendency', which attributed the behavior to the propensity of individuals to constrict the range of the responses over which they have control. Jones and Hunter, themselves, proffered a more physiological explanation, suggesting that the principal muscle involved in their study, the brachial biceps, may be relatively insensitive to the grading of low levels of force because the muscles were previously found to have been classified as a "mixed muscle" (based on fiber type composition) generally better suited to gross movements involving power. This hypothesis was offered mainly as a means of addressing the overestimations evidenced at referent force levels less than 40% of one's MVC (maximal voluntary contraction). It appears, however, that this hypothesis would not fare as well in addressing the higher force levels (> 60% MVC) wherein referent force levels were underestimated.

The writer's hypothesis derives from his own experience and the comments of others during the initial pilot testing. In executing the force discrimination task, there existed a rather marked tendency to use temporal cues in conjunction with a reasonably consistent rate of force incrementation when gauging the force to be applied. This was most apparent in the initial trials when, after performing a series of trials at the two lesser force levels, one encountered the highest force level and found that the trial ended before one had attained the intended level of force. In the absence of any other cues, one begins to develop one's own strategies to assist in performing the task. In this instance, the development of a rather limited range of force incrementation rates occurred. When employed with a sense of temporal discrimination, the coupling of the passage of time with a suitable "force ramp" provided a strong ancillary cue.

This tactic is not without its disadvantages, however. For the sake of efficiency, the "overall" force incrementation rate adopted (or the range about which it varies) is apt to reflect the subject's experience to that point in the task--perhaps weighted in such a manner as to reflect the outcomes of the more recent trials more heavily. In the interest of efficiency and economy of effort, ongoing efforts to optimize the rate or constrain the range of rates employed bias any perturbations in the direction of "testing out" less demanding rates.

The consequence of such excursions will inevitably be occasional rates that are too slow--ones that result in apparent underestimations of forces at the highest referent force level.

Conversely, at the lowest force level, the consequence of attempting to develop an optimal, "medium" range of force application rates is to experience occasional longer-than-necessary periods of time for force application. This results in 'overshooting' the correct level. That this has occurred is not nearly so obvious to the subject as it is in the 'undershoot' case; i.e., there is no cue (e.g., change in the display) to emphasize the fact that a potential timing/force error has occurred. As such, the participant is apt to be less aware of the error and less apt to attempt to make corrective adjustment. Overshoot errors exceeded the magnitude of undershoot errors in Jenkins' (1947) and Jones and Hunter's (1982) research as well.

There exist no data in the present study with which to further empirically examine this hypothesis. It is considered to be a plausible alternative explanation that is as viable as any of the others. Moreover, in contrast to those cited earlier, it possesses the advantage that it explains both the overshoot and undershoot aspects of the behavior.

Other possible factors may also be relevant to this phenomenon, e.g., the existence of interactive, time-dependent magnitude-related force decay rates associated with isometric exertions undertaken with and without benefit of feedback (e.g., Caldwell and Grossman, 1973; Jones and Hunter, 1983). However, to develop a reasonable understanding of the phenomenon would require a concerted research effort closely addressing time-referenced changes in the force levels, electromyographic activity of the muscles involved, relative magnitudes of strength to force requirements, rates of increase in the force input, and parameters descriptive of the intra-exertion force patterns over extensive numbers of trials.

As regards the force variability measure, the finding that FVs increased significantly with increases in the referent force level is consistent with Jenkins'(1947) results. The finding of a small-but-significant negative correlation between FV and the strength-normalized, direction-sensitive SDR measure suggests that the increased variability associated with larger force levels is counteracted to some small extent by an individual's strength. While Jenkins indicated no relationship between an individual's size and his performance, he did report that the group standard deviation increased directly as a function of the level of force involved. On the other hand, Jones and Hunter (1982) reported no significant differences in the variability encountered at the force levels they addressed.

There are two, and perhaps more, possible explanations for the discrepancy between Jones and Hunter's (1982) findings and those in the present study. One reason for the difference observed may be the difference in the dependent variable employed. The standard deviation calculated by Jones and Hunter (1982) appears to have been based on mean force levels associated with each exertion by each subject. Their measure reflects, therefore, the interexertion variability stemming from both intrasubject and intersubject sources. In contrast, the standard deviation used in the present study represents the mean intraexertion variability. It may be that the measure utilized in the present study is a more sensitive one.

The force variability data are interesting from another perspective. The manner in which the present data were collected is consistent with the procedures employed in the study of muscular fatigue (Lippold, 1981). It is well established that muscular tremors are observed during isometric exertions at or near maximal force capabilities and during sustained isometric exertions at lower force levels. The results of research addressing these conditions consistently reveal that the greatest degree of tremor (force variation) is evidenced in the 8-12 Hz range (Lippold, 1981). The present study utilized a sampling rate, 10 Hz, that coincided with the center of this range. The finding of highly significant main effect for force-level suggests that the "fatigue-sensitive", 8-12 Hz frequency range is also sensitive to force-related changes at less-than-maximal force levels and less-than-fatigued states. Within this context, it is interesting to note the role of interindividual differences in strength. While not robust within the relatively constrained range of force levels addressed, the finding of a low-but-significant negative correlation between the FV and SDR measures indicates that strength plays a moderating role, tending to mitigate the degree of force variability or tremor evidenced as the force demands increase.

With the exception of Jenkins (1947), who reported no effect, no other force discrimination study has examined the potential effects that direction-of-force may have. In view of the marked impact that changes in direction and relative geometry are known to have on one's force exertion capabilities (e.g., Kroemer, Kroemer, and Kroemer-Elbert, 1986; Laubach, 1978; Chaffin and Andersson, 1984), it is surprising that this is the case. The only other study known to have acknowledged these factors is by Davis (1974) who reported differences in the perceived heaviness of a lifted object when the object was supported at different elbow angles.

Direction-related effects were found among the present force discrimination data. In general, the differences which existed are most readily understood in terms of the strength-related differences associated with the various directions. For the RE measure, the effect appeared in interaction with variation in force level. Significant differences associated with changes in force level were observed only in the direction associated with the least strength; i.e., to the right. Differences in direction-specific strength also relate to the significant effects encountered in the SRE data. The SRE value associated with the weakest direction was the only negative value, and it was significantly different from all others. Significant overestimations were associated with the longitudinal directions, those wherein subjects were the strongest.

The force variability measure was the only measure without a significant Force Direction effect. Why this is so is not known. As cited previously, Jenkins (1947), too, failed to find significant direction-related differences in his standard deviation measure.

Overall, it is observed that the magnitudes of the effects observed (particularly that for Force Direction) appear to have been modified by the nature and extent of their respective correlations with the strength-related measure, SDR. The measure, RE, which was not significantly correlated with individual differences in strength, yielded significant force-level-related differences only in the direction wherein the relative demand represented by the force level was the greatest. For the measure which had a positive correlation with the SDR measure, direction-related effects were enhanced and significant main effects were evidenced for both Force Level and Direction. The force variability measure, FV, which had negative correlation with SDR, yielded a significant effect for Force Level only.

In summary, the force discrimination findings are viewed as being consistent with those of previous investigations. The measures were all affected by variations in the levels and directions of force addressed. The role of strength-related differences was found to be rather minimal, albeit useful in understanding the differences which were evidenced among the measures employed.

Isometric Tracking

To avoid confusion during the subsequent discussion, the word "orthogonal" will be used in reference to axes of measurement. The word "perpendicular" will be used in reference to the line-of-action of force. In general, the tracking conditions of greatest interest and focus are those in which the measurement axis and the line-of-action of the applied force are coincident. The research hypotheses related to these conditions.

Linear tracking. Linear tracking performance during outward target movement was generally supportive of the experimental hypotheses. Highly significant Force Level effects ($F(2,40) = 48.25$, $p \ll 0.0001$) were evidenced in the predicted direction. Clearly, as the absolute level of force demand increased, performance worsened.

Direction-related significant effects were also obtained. They were supportive of hypothesized relationships to the extent that the greatest error was found in the right (out) direction, the direction of least strength. However, the relationship between tracking error and direction did not follow a strength-related pattern in the remaining directions. A strength-determined result would have yielded the best tracking performance in the aft direction. The post-hoc analyses revealed aft-directed performance to be not significantly different from tracking in the forward or right directions. The best performance was in the left (in) lateral direction, albeit it was nonsignificantly different from the forward or aft directions.

Among the literature reviewed, there were no studies which had adequately reported direction-related findings. That research which would have been most relevant to the present, Ribot, Roll, and Gauthier's (1986) examination of both isometric- and displacement-control compensatory tracking performance under vibration conditions, could have examined direction-specific performance. The reporting of their findings in this regard was minimal. They stated only that "... maximal amplitude errors occurred near the extreme right, left, up, and down positions of the target" (p. 794). The reliability of this finding is unknown, however, since the statement was based solely on their visual examination of the data.

While of lesser interest, the findings pertaining to error measured orthogonal to the path during outward linear tracking are viewed as being reasonably consistent with a biomechanical interpretation. The main effect of Force Direction was significant. Figure 9 depicted all errors to be to the right of the target path except that associated with target movement to the left. From a biomechanical perspective, the longitudinal findings are believed to reflect the fact that a major source of the force being applied derives from torque generated about (or at least transmitted through) the shoulder. The line-of-action from the shoulder through the control is at an angle which reflects the same orientation as that evidenced in the foreward- and aft-related errors. Forward pushes along this line of action would yield a force component to the right (outer side) of the path while rearward pulls along a similar line-of-action would yield a component that was to the left (inner side) of the control. The line of action for lateral exertions is not readily discerned, and no hypotheses are proposed regarding the pattern evidenced.

This hypothesized line-of-action explanation for the longitudinal findings is supported first by noting that the line-of-action was in the appropriate direction. The mean distance of the participants' shoulders from the centerline of the chair was estimated by dividing the mean biacromial breadth by two. The result, 18.7 cm, was less than the distance of the control from the centerline of the chair, 27.9 cm. That the explanation is plausible was further supported by examining the perpendicular components of the forward and aft force exertions rendered during the strength assessments. (The relevant positions of the handles used in the strength assessment and the tracking task were quite similar. The lateral positions differed by but 3 mm, and the forward displacements differed by only 6 mm.) It was found that the mean perpendicular components of both longitudinal strength-testing exertions were in the direction that is supportive of the hypothesized effect.

The second set of ANOVAs performed on the linear tracking was undertaken in an effort to assess the effects of the direction of target travel. For reasons discussed earlier, the data set was limited to the lower two force levels. The most striking finding was the very marked effect that direction-of- travel had upon the data: $\underline{F}(1,20) = 70.31$, $\underline{p} \ll 0.0001$. As also reflected in the statistical parameters, it strongly interacted with Force-Level: $\underline{F}(1,20) = 30.31$. $\underline{p} \ll 0.0001$. It is noted that during the inward tracking mode, the recentering effects of the force requirements act to "pull" the cursor toward the center, null position. This is in direct contrast to the oppositional force effects experienced during outward tracking. Hence, the nature of the subjects' task during inward linear tracking is very different from that present during outward tracking.

The conditions existing during inward tracking are unique among those addressed in the study. During inward tracking subjects had to act to prevent the cursor from overrunning the target by controlling the manner (rate) in which they relaxed the magnitude of force being applied to the control. In all other conditions, the subject is either faced with the task of exerting continuously increasing forces (outward linear tracking) or having to actively maintain a fixed level of outward-directed force (circular tracking).

The anticipated finding was that the error associated with inward tracking would be less than that evidenced during outward tracking--a result clearly supported by the results. Moreover, the means indicated that during inward tracking, the amount of error was inversely related to the magnitude of the force level--an outcome opposite to that encountered during outward tracking. Since the subject is attempting to follow the target closely, the findings suggest that the higher force level provides a significant degree of assistance. Alternatively, the result indicating a significantly smaller lag at the higher force level may merely indicate that he or she is less able to prevent overrun. Had the task been able to address the highest force level, 66.75 N (or even higher levels), there would be a better basis for interpreting the finding. Regardless, the data indicated that during inward movement the target was followed at a greater distance when the force requirements were lower.

The significant Force Direction x Force Level interaction evidenced in the analyses of the errors orthogonal to the path indicated that, averaged over the two directions of travel, errors associated with the higher force level appeared to be inversely related to the strength-related differences associated with direction. Conversely, orthogonal errors associated with the lower force level did not; they appeared to be independent of direction. All means reflected errors to the right of the path. While there is the temptation to generate an hypothesis predicated on the likely occurrence of differential prioritization of attentional resources coupled with assumptions regarding effective lines-of-action pertaining to the applied force vectors, there are no other empirical data from the present study which are relevant, and there are no previous studies which have addressed the issue. Hence, no explanation for this result is offered. The same applies to the significant Force Direction x Mode interaction. There existed no a priori hypotheses regarding linear tracking errors orthogonal to the path.

Circular Tracking

No hypotheses were rendered prior to the initiation of the study regarding the pattern of errors in the measurement axis along the path during circular movement of the target. The findings are presented principally for descriptive purposes.

The analyses of the along-the-path errors associated with circular target tracking yielded two significant interactions, both involving the differences in the direction of target travel. The interaction of direction-of-travel (Mode) with Force Direction indicated that in the forward and aft force directions the errors were smaller when the target was traveling in the clockwise (CW) direction than when traveling counter clockwise (CCW) Errors along the path in the CCW direction appeared virtually unaffected by the direction of force. The interaction of direction-of-travel with Force Level yielded results similar to those just cited. CCW errors along the path were nearly unaffected by change in the force level. CW errors were slightly smaller at the higher force level. In all instances the errors were lagging errors.

As regards the circular-tracking performance measure of principal interest, errors measured orthogonal to the path, only main effects were evidenced in the data. All were robust ($\underline{p} < 0.0001$). Those pertaining to both Force Level and Force Direction were consistent with hypothesized relationships. The means asssociated with the highly significant Force-Level effect ($\underline{F}(1,20) = 74.56$, $\underline{p} < 0.0001$) showed that the larger error at the higher force level. The direction-related mean errors yielded a pattern which was consistent with the strength capabilities encountered in each direction. Errors were largest in the direction (right) associated with the least strength and were smallest in the direction (aft) associated with the greatest strength.

The remaining main effect is that pertaining to direction-of-travel, Mode. In contrast to the findings associated with errors measured along the circular path, the degree of error measured orthogonal to the path (radial error) was largest during CW movement of the target.

While there were no CW-CCW effects anticipated, it is readily apparent that the direction-of-travel effects are reliable. They were found to exist at significant levels for error measured both along the path and perpendicular to it. There appears to be no relevant findings in the literature with which either to explain the phenomenon or to form the basis for a viable post hoc hypothesis which might account for its existence. Efforts to locate relevant literature included a computerized bibliographic search. Among the 166 abstracts identified, only one indicated that direction-of-travel had been addressed. Unfortunately, that very brief article (Spatz and Irion, 1969), published 18 years ago, referenced no previously performed CW-CCW research, and employed the CCW task as a non-primary task that was not addressed in the findings.

To this point the discussion has focused on the effects of the experimental factors under the control of the researcher. There had been hypothesized, however, relationships between tracking performance (measured along the axis coincident with the force direction required for successful tracking) and the SDR measure which transformed fixed levels of force requirements into individualized expressions of relative force demand that reflected both intersubject and intrasubject (direction-related) variation in the strength.

The results appear to support the hypothesized relationships. Statistically significant correlations were obtained between the SDR measure and each measure of tracking performance aligned with the line-of-action of the direction-of-force; however, the magnitude of these correlations ranged from small to modest, none exceeding r = 0.50. (One of the correlations that was significant was also negative. However, this pertained to the linear, inward tracking condition. As previously discussed, this condition was unique among those investigated and yielded Force-Level findings which, although significant, were in the opposite direction to those encountered for all other conditions of interest. Hence, the small, significant correlation observed for this condition is consistent with the nature of the effect of the SDR findings evidenced elsewhere; i.e., greater strength is associated with smaller errors.)

There exist several possible reasons why the correlations were not larger. One reason may be that the low-but-significant values reflect the status of the "real world". There can be little further discussion regarding this possibility.

More plausible reasons, perhaps, relate to the procedures employed. One factor which limits the magnitude of any effort to ascertain the extent of correlation between any two measures is the reliability of the measures themselves. The procedures which have been developed to date for the assessment of strength do not yield very reliable measures. Both intra- and interexertion variation can be substantial with a wide variety of factors having the capability to influence the outcome (Astrand and Rodahl, 1977; Kroemer, Kroemer, and Kroemer-Elbert, 1986). Individuals subjected to repeated testing within the same day typically show a standard deviation equal to 10 percent or more of their mean (Astrand and Rodahl, 1977).

One index which describes the quality of the measurement process is the coefficient of variation (Churchill, 1978; Stobbe, Plummer, and Shreves, 1983), obtained by dividing the standard deviation by the mean. In the present research, substantial efforts were made to assure that the temporal factors pertaining to strength assessment were closely controlled by "computerizing" them. Computer-generated, CRT-displayed cues and instructions governed the sequencing and timing of the exertions. As a result, the mean intraexertion COVs obtained for each direction ranged between 0.040 and 0.057, clearly within acceptable limits. It is emphasized, however, that this measure does not assure that the mean values obtained represent the "actual" strengths of the individuals tested. While one could have tried to obtain a more reliable estimate of each subject's strength by measuring it several times during each assessment period, there is yet no agreement on the number of times that one should measure to determine strength "correctly" (Stobbe and Plummer, 1984). Hence, to have attempted to attain an asymptotic level of measured strength for each of the eight exertions would have required the addition of an extensive and variable time requirement to an experimental session that was already demanding. To do so was not feasible because of an externally imposed time limit for the completion of the research.

Again, from the perspective of the replicability of the measures obtained, it is also possible that the individuals' proficiencies were still improving over the course of the period during which the criterion tracking measures were obtained. There is no easy or entirely satisfactory solution to the question of how much practice an individual should be permitted. Notterman and Page (1962) have reported continued improvement in related types of tracking tasks through as many as 3000 trials. In most instances, therefore, one either chooses a performance criterion and allows the number of practice trials to vary as necessary to achieve the designated level of proficiency, or, as in this instance, one controls the amount of practice and allows the level of proficiency achieved to vary. Because of existing time constraints, the second alternative was selected.

Correlations were also anticipated between force discrimination capabilities and tracking performance. With the exception of one force discrimination measure, the hypothesis was generally confirmed among the measurement and tracking conditions of principal interest (those related to the experimental hypotheses; i.e., wherein the measurement axis coincided with the direction of force required to successfully perform the task). The exception was the RE measure, which evidenced only one significant correlation, that associated with linear tracking in the outward direction. The previous discussion (regarding the manner in which this measure is calculated and the consequent reduced opportunity for the expression of potential strength-related variance) is relevant here. It is possible that the reduced variance may have contributed to the generally lower correlations demonstrated between this measure and tracking performance.

The circular tracking data yielded more consistent support for the hypothesized correlations between tracking performance and force discrimination measures than did the linear tracking results. Significant correlations existed between circular tracking performance measured perpendicular to the path and both the SRE measure and the FV measures during target movement in both the CW and CCW directions. Significant correlations for the linear tracking conditions were found only between the SRE measure and the inward linear tracking condition and between the FV measure and the outward linear tracking condition.

Relative to those associated with linear tracking data, the greater frequency and larger magnitude of the significant correlations between force discrimination measures and circular tracking performance (measured both orthogonal to and along the path) suggest that, within the present context, requirements for change in the directional component of requisite input force vectors are more reliably accomplished than are requirements for change in magnitudes of the required input force vectors. Clearly, however, the caveat constraining the conclusion to the present findings is necessary in that the findings of this research (or of any future related research) are closely related to the range of force inputs used. It is easy to envision that the outcome of a subsequent replication that addressed a much narrower range of force levels would yield the opposite result.

While of lesser importance, it is interesting to observe that the signs of the circular path correlations between the SRE and FV variables with tracking errors measured along the path are opposite in sign to those measured perpendicular to the path. These correlations indicate that, in contrast to the positive effects of higher SRE and lower FV scores in tracking performed along the force-relevant directions, smaller SRE scores and larger FV scores are associated with better performance along the path perpendicular to the force axis. It may be that these results reflect efforts on the part of the subjects to minimize their total error (direct-line distance). The FV variable has, as previously discussed, a plausible physical analog: tremor. The term "tremor" is used, therefore, in lieu of the symbols FV in the following discussion in the hope that it is easier to understand. It is hypothesized that those subjects who show a lesser degree of tremor approach the target more closely along the axis coincident with the line of force than do those who demonstrate more tremor. Conversely, those who evidence greater tremor as they approach the target along the line of force do not approach as close as their "less-tremor" peers, but choose, instead, to attempt to minimize their total error by focusing on getting closer along the direction having no force requirements, the axis along the path of movement.

In general, the correlational findings supported the hypothesized relationships. However, the correlations were small in magnitude. Albeit there were no previous studies which have addressed the issue, larger correlations were anticipated. From one's experience with everyday life demands, it appeared logical to assert that stronger individuals should be able to perform a physically demanding task better than weaker individuals. Clearly, in other areas, where demands are such that an injury potential exists (e.g., as in lifting), there is considerable attention given to assuring that individuals have the strength needed to perform the job adequately and safely. Many research efforts pertain to back injuries, as evidenced by the appearance in January, 1985, of an entire, oversized issue of Ergonomics (volume 28, issue number 1) devoted to that topic. Hence, not only did "common sense" suggest that strength would be a relevant variable, but research emphasis in another related field indicated that such was so. The curiosity, then, is why the present correlations, albeit significant and consistent in direction with the hypothesized effects, are so much smaller than anticipated.

In previously provided discusssion, the possibility was cited that either inadequacies in the state-of-the-art (regarding strength assessment techniques) and/or inadequately stabilized measures (insufficient practice) may have constrained the magnitude of the correlations which were possible. While it may be that the use of a greater number of trials (for both the strength testing and the tracking task) might have resulted in improved correlations, it is pointed out that previous research has indicated that correlations between various measures of ability and actual task performance change with practice (e.g., Fleishman, 1960; Fleishman and Rich, 1963; Kleinman, 1977; Marteniuk, 1974). Fleishman and Rich's (1963) data indicated that between the ninth and the 24th trials there was little correlation between their measure of weight discrimination and performance of a two-handed tracking task. However, correlations did increase to significant levels over succeeding blocks of trials. The inference, therefore, is that in the present study larger correlations may have developed if the task had been continued.

That these factors are relevant is not dismissed. However, factors related to procedural issues are also believed pertinent.

A correlation reflects the relationship between the variation observed in two measures. Hence, any factor affecting either measure will have an impact upon the correlation that results. As concerns force discrimination measurements, it has been pointed out already that temporal factors are relevant. It may be, therefore, that the specific time parameters employed in the present research have introduced some as-yet-unknown bias or variation in the results. Allowing subjects more time to stabilize their referent exertions prior to undertaking the matching exertion might produce more accurate discriminations. Similarly, increasing the duration of the time allotted for the subject to perform the matching exertion might result in greater accuracy. It is emphasized, however, that the potential for fatigue-related effects become more potent as the duration-of-exertion increases, particularly when higher levels of force are employed. Hence, while providing more time to execute each exertion might provide enhanced test-retest reliability and larger correlations, the associated fatigue-related factors might counteract these potential gains and induce greater discrepancies between the referent and matching exertions as well.

There is also the issue of individual differences. The writer's initial thought regarding this factor was that the procedure should be self-paced (at least the referent-exertion and matching-exertion components thereof). Permitting each subject the opportunity to attain the referent level and execute the matching exertion at one's own pace results in the greatest degree of accommodation to individual differences. Some degree of experimental control is sacrificed in this case, however.

Another factor believed to be of marked importance (to both the force discrimination and tracking experiments) is that pertaining to the role of feedback. The substantial decrement in referent force magnitude which is thought to have occurred during the force matching interval is believed to be due to the absence of visual feedback. The reason for not employing visual feedback relates to the writer's previous dual-task-related research findings (Mastroianni and Schopper, 1986) which demonstrated the existence of force-exertion-related interference in an ongoing mental task.

The focus of the subjects' efforts during the simultaneous-exertion portion of each trial as it was performed in the present research was to equate the perceived levels of force being applied by each hand. To accomplish this implies a dual-task requirement; i.e., the subject must monitor the level of force being applied to each handle. To have continued the visual feedback for the referent exertion would have added another dimension to the task. Not only would the participant have to attempt to equate levels of perceived force (a task predicated on some internal process of monitoring muscle sense or muscle tension), but he or she also would have the added task of continuing to visually monitor the external feedback display and adjust the magnitude of the referent exertion to maintain it at the prescribed level. Further comparative research would be required to determine how and to what extent force matching performance would be affected as a result of using such a procedure.

As regards the tracking task, the role of visual feedback is believed to be a major (if not the major) reason that higher correlations were not evidenced between tracking performance and either the strength or the force discrimination measures.

The potency of visual information is marked. The capacity for visual cues to overrule kinesthetic and proprioceptive information has been dramatically demonstrated in weight-discrimination studies (Jones, 1986). Judgements of individuals attempting to estimate the heavinesss of weights enclosed in containers of various sizes have been rather profoundly altered through the manipulation of pertinent visual cues. The importance of visual feedback to the assessment of force and the discrimination of weight has been demonstrated in reverse fashion by the fact that investigators have undertaken substantial efforts to assure that the participants could not see the apparatus involved (e.g., Bahrick, Bennett, and Fitts. 1955; Bahrick, Fitts, and Schneider, 1955; Henry, 1953; Fleishman and Rich, 1963). The role of visual feedback in motor learning has been the subject of previous research with results showing that visual feedback markedly facilitates learning and is more powerful than proprioceptive feedback (Adams, Gopher, and Lintern, 1977; Battig, 1954; Posner,1967). Even in tasks (e.g., flying) wherein visual feedback is not so blatantly tied to motor behavior as it is in the performance of a laboratory tracking task, the visual information derived from changes in the relative locations of objects in the field of view provides substantial feedback regarding the effects of physical control inputs. It is likely that substantially greater correlations would have been found had strength- and force-discrimination capabilities been investigated using a task which provided no visual feedback. However, the practical utility of such findings would be minimal.

CONCLUSIONS

Force discrimination capabilities, as assessed by the contralateral-arm force-matching technique, are significantly affected by variation in both the magnitude and the direction of the referent force. The magnitude of the referent force level is (a) positively correlated with the degree of intraexertion variability evidenced in the force-matching exertions and (b) negatively correlated with the degree of overestimation encountered in the force-matching exertions. (Significant underestimation occurred at the highest referent force level employed, 66.75 N.) Regardless of the magnitude of the referent force levels, the referent force levels are significantly overestimated in both the forward and aft directions--those directions associated with greater strength.

The accuracy of linear and circular tracking performance is significantly affected by variation in both the magnitude and direction of the force demand. With the exception of linear tracking during inward target movement, larger lagging errors are associated with higher levels of force demand. The magnitudes of the errors occurring in each force direction are inversely related to the level of strength associated with each direction. Within the reduced range of force levels examined, inward linear tracking (associated with decreasing force demands) yields smaller lagging errors at higher force levels than at lower force levels. Direction-of-travel (CW-CCW) effects observed during circular target movement are substantial: CW performance is significantly better than CCW performance.

Variation in strength affects both force discrimination and tracking performance. Intraindividual strength differences are reflected in the direction-related findings cited above. Interindividual differences in strength are correlated in a small-but-significant manner with both force discrimination capabilities and isometric tracking performance. The ratio of strength to force demand (SDR) is inversely correlated with intraexertion force-matching variability. Higher SDRs are associated with smaller tracking errors.

Future research is needed to ascertain the effects of variation in procedural timing factors which the writer believes to be contributing to the over- and underestimation phenomenon which has been encountered in the present and previous force discrimination studies. Additional research addressing a wider range of force levels than those used in the present study is also required to more fully understand the pattern of tracking errors occurring in the present study during inward linear target movement. Further research, too, is needed to understand the basis for the significant direction-of-travel (CW-CCW) effects found during the tracking of circular portions of the path.

SUMMARY

A contralateral force-matching task and a two-dimensional isometric pursuit tracking task of zero order and lag were used to investigate the effects of variation of both magnitude (22.25, 44.50, and 66.75 N) and direction (0, 90, 180, and 270 degrees) of force demands upon force discrimination capabilities and force-related visuomotor performance. The interrelationships among force discrimination capabilities, tracking performance, and a direction-sensitive, strength-normalized measure of force demand (strength:demand ratio, SDR) were also examined. The tracking task incorporated inward and outward linear target movement and clockwise and counterclockwise circular target movement.

Hypotheses

The hypotheses pertained only to measurement axes that coincided with the force direction required to perform the task successfully.
The principal hypothesis was that increases in the magnitude of force demand would degrade both force discrimination capabilities and tracking performance. Strength was also hypothesized to be relevant. Because force exertion capabilities vary markedly with direction, it was hypothesized that degradation would be inversely related to the levels of strength evidenced in each direction. SDR and force discrimination measures were hypothesized to correlate with tracking performance and

with each other. As reflected below, there also existed additional hypotheses pertaining to specific combinations of tasks and measures.

Findings

Force discrimination. The degree of force variability evidenced in the force-matching exertions was correlated with the magnitude of the referent force levels. The means of the force-matching exertions associated with each force level differed significantly from one another. Referent force level values were significantly overestimated at the lowest (22.25 N) level and significantly underestimated at the highest force level (66.75 N). Independent of force level, force-matching exertions in both forward and aft directions--those associated with greater strength--significantly overestimated referent force levels. Force-matching exertions exceeded referent force levels in all but the forward direction. The largest difference between force-matching exertions and referent exertions occurred in the weakest (90-degree, "out") direction at the highest force level.

Tracking performance. Significant force-level effects were found while tracking both linear and circular target movement. During outward linear target movement, larger lagging errors were associated with higher force demands. Albeit examined over a lesser range of force levels (22.25 N and 44.50 N--for reasons associated with the path geometry), the specific hypothesis that inward (force-decreasing) linear tracking performance would be superior to outward (force-increasing) linear tracking performance was also supported. Additionally, during inward linear tracking over this smaller force-level range, the previously-cited relationship between magnitude of force level and error was reversed; i.e., significantly smaller errors were associated with the larger level of force demand. The hypothesized effects of force direction were generally supported among both the linear and circular tracking data. Larger errors generally occurred in directions associated with less strength. These effects were evidenced somewhat more consistently among the circular tracking data than the linear tracking data.

No hypotheses had been rendered regarding the effect of direction of target movement during circular tracking. However, clockwise tracking errors were significantly smaller than counterclockwise tracking errors when measured along the path and vice versa when measured orthogonal to the path.

Although there were no experimental hypotheses formulated, significant differences also were found in the tracking data along measurement axes orthogonal to the axes-of-interest. Significantly larger errors generally occurred at higher levels of force demand. Significant force direction effects occurred among the fore-aft linear tracking data and are interpreted as being related to the direction of the line-of-action from the shoulder to the control.

<u>Correlations</u>. Correlations among the SDR measure, force discrimination measures, and tracking performance were generally supportive of hypothesized relationships. Albeit significant and in the

anticipated directions, the correlations were small, ranging from 0.21 to 0.50 in magnitude.

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APPENDIX A

PHYSICAL FITNESS QUESTIONNAIRE

PHYSICAL FITNESS QUESTIONNAIRE

Name: ______________________________ No.: ______

Address: ______________________________

Telephone No: ______________

Which best describes your present physical condition (circle one):

Poor Fair Good Excellent

Describe the level of current involvement in sports/physical activities:

Activity	Amount of time per week
______________________	______________
______________________	______________
______________________	______________

(Add any additional on the reverse side of this form.)

Have you ever had a hernia? ____________ (yes or no)

Have you ever had a back injury? ________ (yes or no)

Have you ever had an arm injury? ________ (yes or no)

Have you ever had a shoulder injury? ________ (yes or no)

Have you ever had an elbow injury? ________ (yes or no)

Have you ever had a broken bone? ________ (yes or no)

Have you ever had a heart condition or disease (to include abnormal blood pressure and heart murmurs)? ________ (yes or no)

Do you now have, or have you ever had in the past, any physical impairment, injury, illness, or medical condition which might be aggravated by physical activity or participation in this experiment? ________ (yes or no)

Are you now taking any drugs/medication? ________ (yes or no)

Remarks:

____

Subject's signature and date

APPENDIX B

INFORMED CONSENT FORMS

PARTICIPANT'S INFORMED CONSENT

The purpose of this document is to obtain your consent to participate in this research and to inform you of your rights as a participant. This research is being conducted in the Department of Industrial Engineering and Operations Research by Dr. Aaron W. Schopper. The research is to be Dr. Schopper's Ph.D. dissertation in this area. The Chairman of Dr. Schopper's research committee is Karl H. E. Kroemer, Dr. Ing., Professor and Director Ergonomics Laboratory.

The research is directed toward achieving a better understanding of the physical factors which relate to manual performance. Accordingly, you must be in good physical health to participate. For reasons relating to appropriate research design considerations, you must be right-handed and have 20/20 (corrected or uncorrected) vision.

As a participant in this research you will be involved in a number of activities. Initially, you will have a number of anthropometric (body size and weight) measurements taken: height, weight, arm lengths and circumferences, shoulder width, shoulder height, and sitting height.

During the succeeding portion of the research, you will perform a 'force-matching' task wherein you simultaneously attempt to exert the same force level with both hands. This will be attempted at a number of force levels and in a number of directions. In the next phase of the research, you will perform a simple 'target tracking' task. During this task you will push and pull on a control to make one symbol follow another symbol on the screen of a computer monitor. (This is like a simple video game.) Both prior to and after the tracking task, you will be requested to push and pull as hard as you can on a vertical handle.

You will receive $ 4.00 per hour for the time you participate. The session is expected to last approximately 2 1/2 to 3 hours. If you complete the session, you will receive a total of $15.00.

It is hoped that you will find your participation to be an interesting experience. It is possible that you may feel stressed or frustrated at times during the session. This reflects the difficulty of the tasks involved, not your personal abilities or talents. Additionally, if you do not routinely use strong muscle exertions in your daily life, you may experience muscle fatigue during the session, and you may feel some muscle soreness after your participation.

Please note:

1. You have the right to stop participating in the research at any time. If you choose to stop prior to the end of the session, you will receive pay only for the time you participated.

2. You have the right to see your data and to withdraw them from the research. If you decide to withdraw your data, please notify the researcher immediately. Otherwise, identification of your data will not be possible because the data will be separated from your name.

3. You have the right to be informed of the overall results of the research. If, after participation, you wish to receive information regarding this research, please include your address (three months hence) with your signature below.

Your participation is greatly appreciated. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. Should you have any additional questions or problems, contact Dr. Schopper at 961-5951, or Mr. Charles D. Waring. Chairman of the Institutional Review Board for Research Involving Human Research Subjects at 961-5284.

Your signature below indicates you have read the above rights and you consent to participate. If you include your printed name and address below, a summary of the research results will be sent to you.

Signature: ______________________

Printed name: ______________________

Address: ______________________

City, State, ZIP ______________________

ATTACHMENT TO CONSENT FORM

You are invited to participate as a subject in research which examines the relationships between physical strength, force-matching capabilities, and visuomotor coordination under nonresisted and force-demanding conditions. The data gathered in this study will be statistically analyzed and reported. The findings will be used by those who are concerned with the proper design and employment of manual control systems; i. e., those who are interested in force-related aspects of manually operated controls.

At the beginning of the research session, several anthropometric measurements will be obtained (e.g., height and weight—without shoes, shoulder width, and arm lengths). During the remainder of the session, you will be asked to exert forces on various controls and handles and perform various tracking tasks.

During one portion of the research you will be involved in performing simultaneous force-matching exertions with both hands and arms. The exertions indicated to be made during this task may prove to be very demanding in some directions. You should attempt to do them as best you can without risking injury. The force you exert will be entirely under your control.

For those exertions which are intended to assess your strength, you will be asked to make a maximal voluntary exertion. As in the force-matching' phase, the force you exert will be entirely under your control. It should be representative of your maximal strength capability, but it should not be a force of such magnitude that it results in injury. There is a mandatory rest after each maximum exertion. You may have additional rest whenever you desire. The strength-related exertions will be required both before and after the performance of the tracking task briefly described below.

The target tracking task you will perform is somewhat like a video game displayed on a computer monitor. In contrast to the moveable joystick used with most video games, however, the control used in this task is rigid and responds to the amount of force you apply to it. Your task will be to follow one dot about the screen with another somewhat brighter dot whose position is controlled by the forces you apply to the control. Physically demanding levels of force will also be encountered in the performance of this task as well.

You should be aware that overexertion can result in muscle strain. If you have a history of hernia or previous muscle or bone injury to your back, shoulders, or arms, the maximal exertions requested during one portion of this study might increase the likelihood of re-injury, and you are advised not to participate. It is noted that if you do not make strong muscle exertions as part of your routine lifestyle, it is likely that you may experience some temporary muscle soreness following your participation in the present study.

Your signature indicates consent to be photographed, filmed, or videotaped to document the research. The research is designed to be completed in a single session. However, should there be a reason that you are involved in a subsequent session, you must inform research personnel of any change to your physical status. This information will include any medication taken and any medical or dental treatment you may have received since your last participation.

If you have any questions, we expect you to ask us. If you have additional questions later, we will be happy to answer them. Dr. Schopper can be called at 961-4882 during business hours to answer questions.

YOU WILL BE GIVEN A COPY OF THIS FORM TO KEEP.

Subject's initials:__________