USAARL REPORT NO. 86-10

IN-FLIGHT CONTROL FORCE INPUTS FOR THE US ARMY UH-1 HELICOPTER DURING "HYDRAULICS-ON" AND "HYDRAULICS-OFF" APPROACHES AND LANDINGS

By
Aaron W. Schopper
John H. Wells
Leon R. Kaylor

BIODYNAMICS RESEARCH DIVISION

May 1986

USAARL

NOTICE

QUALIFIED REQUESTERS

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Cameron Station, Alexandria, Virginia 22314. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the US Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Human Volunteer Use

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Reg 70-25 on Use of Volunteers in Research.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Disclaimer

Reviewed:

ARTHUR C. SIPPO
MAJ, MC
Director, Biodynamics Research Division

J. D. LaMOTHE
Colonel, MS
Chairman, Scientific Review Committee

Released for Publication:

DUDLEY R. PRICE
Colonel, MC
Commanding

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER USAARL REPORT NO. 86-	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) In-Flight Control Force Inputs for the US Army UH-1 Helicopter During "Hydraulics-On" and "Hydraulics-Off" Approaches and Landings		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Aaron W. Schopper John H. Wells Leon R. Kaylor		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Biodynamics Research Division, SGRD-UAD US Army Aeromedical Research Laboratory P.O. Box 577, Fort Rucker, AL 36362-5000		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62777A 3E162777A879 BH 166
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Aeromedical Research Laboratory P.O. Box 577, Fort Rucker, AL 36362-5000		12. REPORT DATE May 1986 13. NUMBER OF PAGES 64
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aircraft Controls, Helicopter Controls, Control Force Requirement, Aerospace Medicine, Human Factors, Strength, Male, Female

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

See Back of Page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT

There is little information available regarding the magnitude of force input to helicopter controls under emergency conditions. Accordingly, 12 male US Army aviators each flew six normal and six simulated emergency condition ("hydraulics-off") approaches and landings in an Army JUH-1H utility helicopter. Because there existed concern that forces applied might vary substantially with flight experience, the aviators who participated in the study were solicited from two groups differing widely in the number of hours flown. The six less-experienced aviators had between 170 and 200 hours of flight time (mean = 183), and the six more-experienced aviators had between 1300 and 2750 hours of flight time (mean = 2250). The three principal controls of the aircraft (cyclic, collective, and pedals) were strain-gage instrumented. The outputs recorded during the last 60 seconds of flight prior to each touchdown were studied. Analyses of variance undertaken on the means of the forces recorded during successive 5-second intervals revealed significant differences in the magnitude of the forces applied as a function of hydraulics condition and time-to-touchdown; i.e., forces differentially increased as touchdown neared during hydraulics-off approaches. Significant interactions involving level-of-experience were discovered; the nature of the effects differed among the various controls and directions-of-input. With the exception of inputs in the downward direction on the collective, the descriptive statistics showed the overall mean and median forces for both groups of aviators to be lower than previously reported helicopter-control-referenced maximal 4-second strength capabilities of small Army males and females.

Acknowledgments

On behalf of myself and my collaborators, I wish to express my sincere gratitude to those who labored so earnestly behind the scenes in the preparation of this report. Thanks are given to Dr. Heber Jones and Mr. Andy Higdon for their invaluable and untiring support in the development of key software support during the extensive data reduction/database development phases. Special thanks are due Mrs. Mary Gramling for the tremendous dedication, skill, and equanimity she evidenced throughout the preparation of the numerous drafts required to bring this portion of the project to fruition. My appreciation also is given to those in the reviewing chain who efforts contributed substantially to the interpretability of this final draft: Mr. Udo Volker Nowak, USAARL writer-editor; COL J. D. LaMothe, deputy commander for science, USAARL; and COL Dudley L. Price, Commander, USAARL. My thanks, too, are due MAJ Arthur Sippo, who (in my absence following reassignment) suffered the task of incorporating the reviewers' comments into the final draft.

A.W.S.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The Commanders of the US Army Aviation Center (ATZQ letter to The Surgeon General, Oct 1979) and the Military Personnel Center (DAPC letter to The Surgeon General, Nov 1979) expressed concern regarding the adequacy of existing aviator selection standards. In response to these concerns, The Surgeon General of the Army, through the US Army Medical Research and Development Command (USAMRDC) (DASG letter to USAMRDC, Nov 1979), tasked the US Army Aeromedical Research Laboratory (USAARL) (USAMRDC letter to USAARL, Jan 1980) to reevaluate the anthropometric criteria cited in Army Regulation (AR) 40-501, Standards of Medical Fitness (Department of Defense 1960), governing the selection of personnel for flying duty.

The initial response to this tasking (USAARL letter to USAMRDC, May 1980) resulted in the adoption of interim, revised minimum anthropometric criteria for reach-related dimensions. However, this brief study was not a comprehensive one. Among the issues not addressed was that pertaining to the potential need for the inclusion of strength criteria within AR 40-501. There presently exist no such criteria, although research recently completed (Cote and Schopper 1984, Schopper and Cote 1984) has indicated that for several of the Army's helicopters, individuals smaller than those previously eligible may be capable of attaining the static cockpit reaches necessary to operate those controls judged to be critical by instructor pilots. Given this circumstance and the widely researched findings that women possess less physical strength than men of comparable size (e.g., Laubach 1975), an effort was undertaken to examine the need for potential strength criteria more closely. Parallel efforts were, therefore, initiated to assess the helicopter-referenced control force exertion capabilities of samples of small males and females (Schopper and Mastroianni 1985) and the control forces actually encountered during flight.

This study was designed to determine forces exerted on the controls of a JUH-1H helicopter during standard maneuvers that are considered the most demanding in terms of strength requirements.* For this "worst case" condition, the "hydraulics off" maneuver (Task 4005, TC 135 [UH-1H], Department of the Army, 1981 [c1]) was chosen. Among the

---

* The letter J which precedes the UH-1H aircraft designation denotes that the aircraft is used for research purposes. The modifications made to this aircraft were principally instrument- related to permit the in-flight recording of sensor inputs to the aircraft cockpit instruments.

aircraft in the current active inventory, it was the opinion of all aviators spoken to that the "hydraulics off" forces associated with the UH-1 were larger than those encountered in other model Army helicopters for this type of training maneuver.

The present research also addressed another factor of relevance: the level of pilot experience. The concern was that aviators might, due to differences in flying techniques which accrue with increasing levels of experience, evidence substantially different magnitudes and patterns of control force inputs during the execution of normal and hydraulics-disabled approaches and landings. Although the authors know of no previous helicopter-flight-related research to suggest that this might be the case, there does exist considerable literature that documents that the performance of motor skills changes with increasing exposure to the task; i.e., practice (Newell 1981, Rabbitt 1981). While there does not exist relevant research literature known to the authors which has addressed the conjoint effects of force input requirements and operator experience level upon task performance, the belief was that in a force-loaded, time dependent dynamic performance environment (as exists during hydraulics-disabled approaches and landings) differences would be observed.

METHOD

SUBJECTS

Data was collected from 12 subjects, six with more than 1300 hours of flight time each ($\bar{X}$=2250 hours) in a UH-1H helicopter and six recent graduates of the Army Aviation Basic Flight Course, each with less than 200 hours of flight time (X=183 hours). The height, weight, and flight hours of experience are shown for each individual in Table 1.

TABLE 1

SUBJECT ANTHROPOMETRY AND FLIGHT EXPERIENCE

SUBJECT CATEGORY	HEIGHT (cm)	WEIGHT (kg)	FLIGHT HOURS (Hr)
More Experienced	173	73	2100
	183	84	3100
	178	86	2100
	175	75	1300
	183	92	2000
	180	80	2750
Mean:	178.7	81.7	2250
Less Experienced	170	72	175
	185	89	175
	168	66	175
	185	86	200
	175	80	175
	175	82	200
Mean:	176.3	79.2	183

PROCEDURE

To evaluate both force requirements and the possible role of experience in contributing to extent of force required, each aviator flew 12 approaches and landings in an instrumented UH-1H. Six of these were flown with full, normal hydraulic assist and six were flown with the hydraulics disabled in accordance with the procedures outlined for this training maneuver (Task 4005, TC-135 [UH-1H] Department of the Army, 1981 [cl]).

The data from strain-gage instrumented controls during the last 60 seconds prior to touchdown were recorded for each landing. These were then subjected to both descriptive and analytic statistical analysis to document the levels of force required and to determine if pilot experience differentially affected the forces measured.

To assure maximal familiarity with the aircraft prior to undertaking the more hazardous (hydraulics-off) maneuver, the six normally-assisted approaches and landings were flown first, followed by six approaches and landings with the hydraulics disabled. Although the adoption of this procedure inextricably confounds the statistical analysis (hydraulics condition is confounded with hydraulics on-off order effects), the decision was made knowingly in the interest of safety.

The aviator subject flew in the left hand, pilot's seat. Subsequent to approximately 15 minutes of normal flight enroute to the staging airfield where the research was to be performed, the safety pilot directed the volunteer to fly 12 consecutive running landing patterns (Task 4005), six with hydraulics on and six with hydraulics off. For each approach, as soon as the volunteer aviator was in the landing pattern so that the aircraft was parallel with the landing lane and traveling in the opposite direction to the planned approach, data collection started and, if the test conditions required, the hydraulic system was turned off. This point was identified on the recording tape with a marker voltage. As soon as the volunteer touched down on the landing lane, another reference voltage mark was entered onto the tape. Data pertaining to both magnitude and direction of applied force inputs and control position were recorded for the cyclic, collective, and pedals throughout the period of data collection through the use of the laboratory's Helicopter In-Flight Monitoring System (HIMS-II) (Jones, Lewis and Higdon 1983). Only the data recorded during the last 60 seconds prior to touchdown of the final leg were subjected to analysis.

The time required to execute these 12 approaches and landings was approximately 1 hour for each aviator. No flights were initiated unless the sustained wind conditions were less than 15 knots and the wind gust spread was less than 10 knots.

INSTRUMENTATION

To measure the control forces, the cyclic, the collective, and the pedals were instrumented with resistor-type strain gages that transduced the applied forces into voltage outputs. The pedals were instrumented to measure the force applied to the right or left pedal in the forward direction. The pedals are interconnected and control the angle of attack of tail rotor blades. The tail rotor blade controls the yawing of the helicopter and offsets the torque caused by the main rotor blade (e.g., during level flight, pedal inputs control the left-right movement of the tail of the helicopter).

The cyclic control is located directly in front of the pilot, between the legs. It controls the relative angle of attack of the plane of the helicopter rotor blades and horizontal stabilizer and, therefore, the pitch and roll of the helicopter. It is operated with the pilot's right hand. The cyclic control was instrumented to measure both fore-aft and left-right control input forces.

The collective is located adjacent to the left of the pilot's seat. It controls the angle of attack of the main rotor blade system. The collective control was instrumented to measure the downward (left-handed push) and upward (left-handed pull) control forces.

Four strain gages were applied to make up a four-arm Wheatstone bridge to measure force in each desired direction on each of the controls. Signal outputs from the bridge were conditioned by a Metraplex® 340-A strain gage conditioning card placed in a circuit with a Metraplex® model 304 conditioner/VCO card*. The voltage output from the conditioning card then was fed by coaxial cable to the HIMS-II analog-to-digital channels. In this project, four analog-to-digital channels were employed to record the four strain-gage channels used in the HIMS-II. A pre- and post-flight calibration of the Metraplex® signal conditioners and HIMS-II was conducted with the Metraplex® calibration card for each of the 12 flights. The data in each channel were sampled at 10 Hz. The digitized information from the HIMS-II system was transferred to a Systems Engineering Laboratories (SEL) 8500 hybrid computer* via a dedicated PDP 11/03 computer through a serial interface. For each flight profile, the computer was programmed to sort each set of data channels for each trial and isolate the final 60 seconds of data prior to touchdown for each approach and landing. The individual data points then were multiplied by proper calibration factors to convert the analog voltage signal levels into force values (Newtons) and position values (degrees). The final matrix of required data was transferred to the laboratory's VAX 11-780 for further reduction and statistical analysis.

---

* See Appendix A.

DATA REDUCTION

The data were subjected to several types of analyses. To develop an overall appreciation of the force characteristics encountered, the data initially were divided into specific control/direction subsets to permit descriptive statistics to be generated for each of the four combinations of subject experience level and hydraulic condition. The data employed for developing these descriptive statistics were the 60 consecutive means for each 1-second interval of each approach and landing; i.e., the sign and magnitude of the mean of 10 data points recorded for each second were used as the input data from which the descriptive statistics were computed. For each of the four combinations of hydraulics condition and aviator experience, the distribution entailed 2160 data points (6 subjects x 6 trials/subject x 60 seconds/trial).

Due to the overly large number of cells which would result if 1-second intervals were employed in a 1-between, 3-within repeated measures analysis of variance, further reduction was required. The data from the final 60 seconds prior to touchdown for each channel of the tape were separated into direction-specific or (for pedals) control-specific voltages and then reduced to the mean force recorded during each of the 12 5-second time intervals. Because the direction of input could change during any 5-second interval, the number of data points available in successive 5-second intervals varied. Hence, the means computed for each interval were calculated on the basis of whatever number of direction- specific values were recorded during the interval. For example, if during one 5-second interval there were 20 positive voltages and 30 negative voltages, then the mean value for positive direction inputs would be based on the average of 20 data points and the mean value for the negative-direction inputs would be the average of 30 data points. If there were no inputs in one direction during a given 5-second period, the value zero was employed.

DATA ANALYSIS

The 2160 1-second means associated with all subjects' landings were employed to compute the descriptive statistics for each of the four combinations of experience and hydraulic condition. The 12 5-second means were employed in a 1-between, 3-within repeated measures analysis of variance to evaluate the between-group effects of aviator experience, and the within-group effects of hydraulics condition, trials, and intervals-within-trials on the magnitude of the forces exerted. (As cited previously, safety-related considerations deriving from the fixed sequence of hydraulics-on flights followed by hydraulics-off flights confounds the analysis of the hydraulics condition effects.)

In consonance with the manner in which currently existing helicopter force design standards are cited, the findings are described separately below for longitudinal cyclic forces, lateral cyclic forces, collective forces, and pedal forces. Descriptive statistics pertaining to the forces exerted during the 60-second period are provided initially. They have been analyzed in two ways:

The first table to appear in each section will provide the descriptive statistics which resulted from considering all 2160 data points collectively for each combination of experience and hydraulics condition. These are referred to as the "net" levels of force input. For example, the descriptive statistics for longitudinal inputs to the cyclic would combine all forward-directed (-) and rearward-directed (+) inputs as belonging to the same data set. Hence, these data reflect the algebraic sum of all inputs.

The data also are described in a direction-specific fashion to more closely appreciate the differences which exist but are not apparent when the positive- and negative-signed data are considered in combination. The second table which appears in each section, therefore, has been separated initially into positive or negative values before being subjected to statistical analysis. These tables reflect differences in both the frequency (i.e., number of 1-second means) and magnitude of direction-specific inputs.*

Descriptive statistics are provided separately for each of the four combinations resulting from the conjoint consideration of the two aviators' experience levels (more and less) and the two hydrualics conditions (on and off). The final portion of each control-specific section will be the citation of the significant findings which resulted from the repeated measures analysis of variance that was undertaken.

* While referred to as "frequency," it is clear that the use of this label is artificial. The measure is merely the number of 1-second means derived from arbitrarily segmenting the recorded 60-second periods into ones of 1-second duration. It is noted, however, that the term "duration" is not applicable for that suggests that the parameter pertains to a period of continuous time. The numbers appearing in the table do not relate to any period of sequentially connected time; they merely denote the total number of periods of 1-second duration when the algebraic mean of the 10 samples measured were of one sign (+) or the other (-).

RESULTS

LONGITUDINAL CYCLIC INPUTS

The descriptive statistics for the four possible combinations of pilot experience level and control hydraulics condition for the combined longitudinal inputs to the cyclic are provided in Table 2. Negative values reflect a mean force during the 1-second interval corresponding to a forward-directed input (push), positive values refer to a mean force in the aft direction (pull).

TABLE 2

DESCRIPTIVE STATISTICAL PARAMETERS OF THE NET LEVELS OF LONGITUDINAL DIRECTIONAL INPUT FORCES APPLIED TO THE CYCLIC CONTROL AS A FUNCTION OF HYDRAULIC CONDITION AND LEVEL OF AVIATORS' EXPERIENCE

Statistical Parameter	Hydraulics On		Hydraulics Off	
	More Exp	Less Exp	More Exp	Less Exp
Mean	-1.46	-4.62	2.18	-5.08
Median	0.06	-3.57	1.75	-3.77
Maximum Forward	9.14	11.59	78.23	16.55
Maximum Rearward	-28.12	-17.45	-81.43	-37.94
Range	37.26	29.04	159.66	54.49
Variance	49.02	55.57	285.14	72.67
Standard Deviation	7.00	7.45	16.89	8.52
Semi-Interquartile Range	2.90	6.54	6.83	6.83
Skewness	-1.05	0.14	-0.58	-0.08
Kurtosis	0.58	-0.81	3.32	-0.50

NOTE: Forces are expressed in Newtons. Distributions consist of 2160 means of inputs of 1-second duration.

The absolute magnitude of the mean and median forces applied were relatively small with substantial variability reflected in the magnitude of the range of forces and the relatively large standard deviations encountered. The magnitude of acute forward-directed input (pushes) were larger than the acute rearward-directed inputs (pulls) so that the minimum values (negative sign) were larger in absolute magnitude than the maximum values encountered.

The descriptive statistics for the direction-specific longitudinal cyclic force inputs are cited in Table 3. The effects of separating the data into direction-specific components is clearly evident. Most of the values of the measures of central tendency (means and medians) are several times larger in this table than they were in the preceding table in which the summing of values of opposite signs served to minimize the actual magnitudes of opposing types of force inputs. Also this table reveals the variation which exists among the frequencies of direction-specific values. Considerable disparity exists between the groupings cited. Whereas the number of rearward- and forward-directed control inputs for the more experienced group were nearly equal (1090 vs 1070) when the hydraulics were on, there was a marked difference between the number of directional inputs by the less experienced aviators (585 vs 1575) under the same conditions.

During hydraulics-off approaches, the differences were even greater. The ratio of duration of forward inputs in seconds to the duration of rearward inputs was .7:1 for the more experienced aviators. For the less experienced aviators, it was 3:1.

The results of the analyses of variance (ANOVA) undertaken on the forward-and rearward-directed cyclic inputs are provided in Tables 4 and 5, respectively. The main effect of experience was marginally significant for rearward-directed inputs, $F(1,10) = 3.83$, $\underline{p} = .079$, and nonsignificant for aft-directed inputs, $F(1,10) = 0.03$, $\underline{p} = .862$. There were only two other statistically significant effects involving level-of-experience. Both were interactions evidenced in the forward-directed results.

The simpler effect was a significant second-order interaction between aviator experience-level and time-to-touchdown (i.e., interval), $F(11,110) = 2.27$, $\underline{p} = .015$. This effect (as well as the comparable data for rearward-directed inputs) is depicted in Figure 1. There is little effect on the interval of rearward-directed forces related to the experience level of the aviators. Figure 1 shows that forward-directed forces became higher for the more-experienced group (relative to those of the less-experienced group) as time-to-touchdown neared.

TABLE 5

ANALYSIS OF VARIANCE SUMMARY TABLE FOR REARWARD-DIRECTED CYCLIC FORCE INPUTS

SOURCE	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	1,10	6955.7	3.83	0.079
Hydraulics Condition (H)	1,10	5744.0	4.76	0.054
H x E	1,10	3369.8	2.79	0.126
Trials (T)	5,50	65.3	0.90	0.486
T x E	5,50	57.5	0.80	0.558
T x H	5,50	52.7	0.78	0.567
T x H x E	5,50	87.6	1.30	0.279
Intervals (I)	11,110	47.6	2.35	0.012
I x E	11,110	19.3	0.95	0.494
I x H	11,110	20.7	1.31	0.227
I x H x E	11,110	7.9	0.47	0.917
I x T	55,550	4.3	0.91	0.665
I x T x E	55,550	4.0	0.86	0.758
I x T x H	55,550	3.5	0.82	0.817
I x T x H x E	55,550	3.5	0.83	0.808

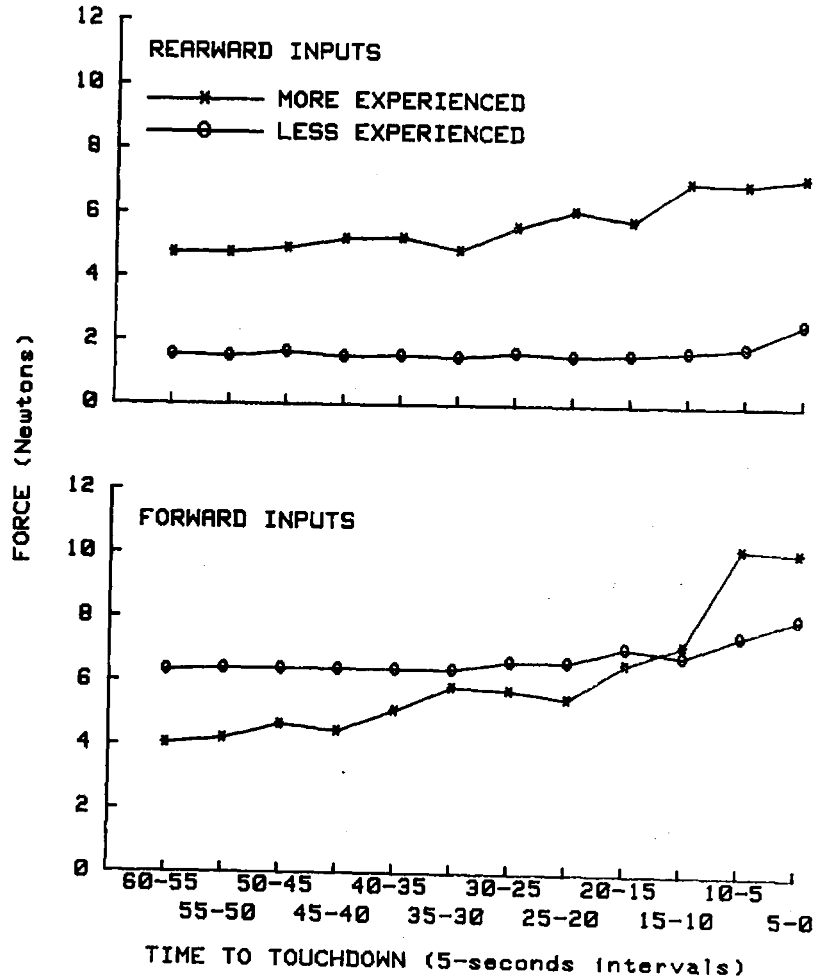

FIGURE 1. Mean Magnitude of Forward- and Rearward-Directed Cyclic Inputs as a Function of Time-to-Touchdown and Level of Aviator Experience. (Experience Level: * more, 0 less.)

The marginally significant forward-input-related third-order interaction among experience-level, hydraulics condition, and trials, $F(5,50) = 2.12$, $p = .078$ is depicted in Figure 2 along with the corresponding rearward-directed data. The forward-directed forces for more-experienced aviators decrease more sharply during the initial exposures (trials) to the hydraulics-off condition than they do for the less-experienced aviators. In contrast, there is little change in

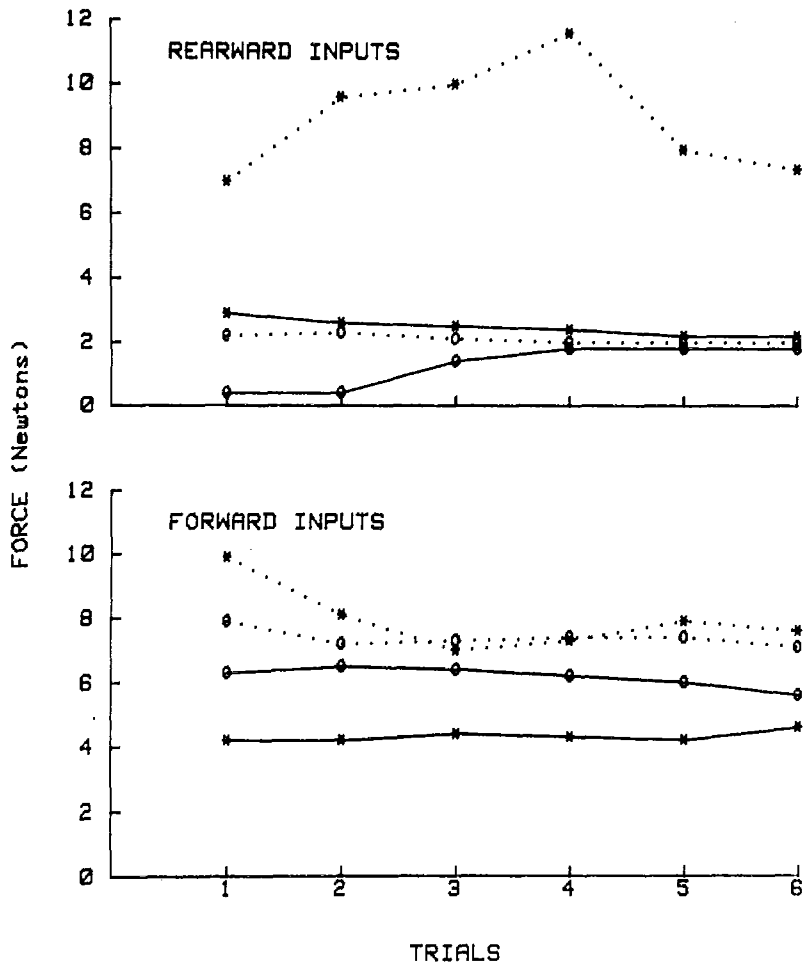

FIGURE 2. Mean Magnitude of Forward- and Rearward-Directed Cyclic Inputs as a Function of Hydraulics-Assist Condition, Aviators' Experience, and Trials. (Hydraulics Conditions: --- On, ... Off; Experience Levels: * More, 0 Less.)

the magnitude of forces applied by either group during successive exposures to the task during the fully-assisted trials. The fact that the overall decrease in applied forward force during the first two trials by the more- experienced group was less than that of the less-experienced group resulted in a significant interaction, $F(5,50) = 3.63$, $\underline{p} = .007$, between hydraulics condition and trials. The gradual decrease in the initial trials along with the small increase in the final trials which results from averaging the data over both hydraulics conditions and experience levels reflects a reliable main effect of trials, $F(550) = 3.02$, $p = .018$. More obvious is the significant main effect of hydraulics condition for both forward- ($F(1,10) = 4.97$, $p = .050$) and rearward-directed ($F(1,10) = 4.76$, $p = .054$) input forces.

Figure 3 depicts forward- and rearward-directed cyclic input forces as a function of both hydraulics condition and time-to-touchdown. This two-way interaction is statistically significant for forward-directed inputs, $F(11,110) = 4.14$, $p < .001$. The rise in forces applied is greater during hydraulics-off approaches than it is during hydraulics-on approaches as time-to-touchdown decreases. The overall main effect of time-to-touchdown was significant for both forward-directed inputs, $F(11,110) = 6.06$, $p < .001$, and rearward-directed inputs, $F(11,110) = 2.35$, $p = .012$.

LATERAL CYCLIC INPUTS

Table 6 provides the net, 1-second-based descriptive statistics for force magnitudes associated with lateral cyclic inputs. Negative values reflect inputs to the left, positive values reflect inputs to the right. The magnitudes of the mean and median values are comparable to those associated with longitudinal inputs (Table 2). The variability, however, is generally less than that encountered in the fore-aft data.

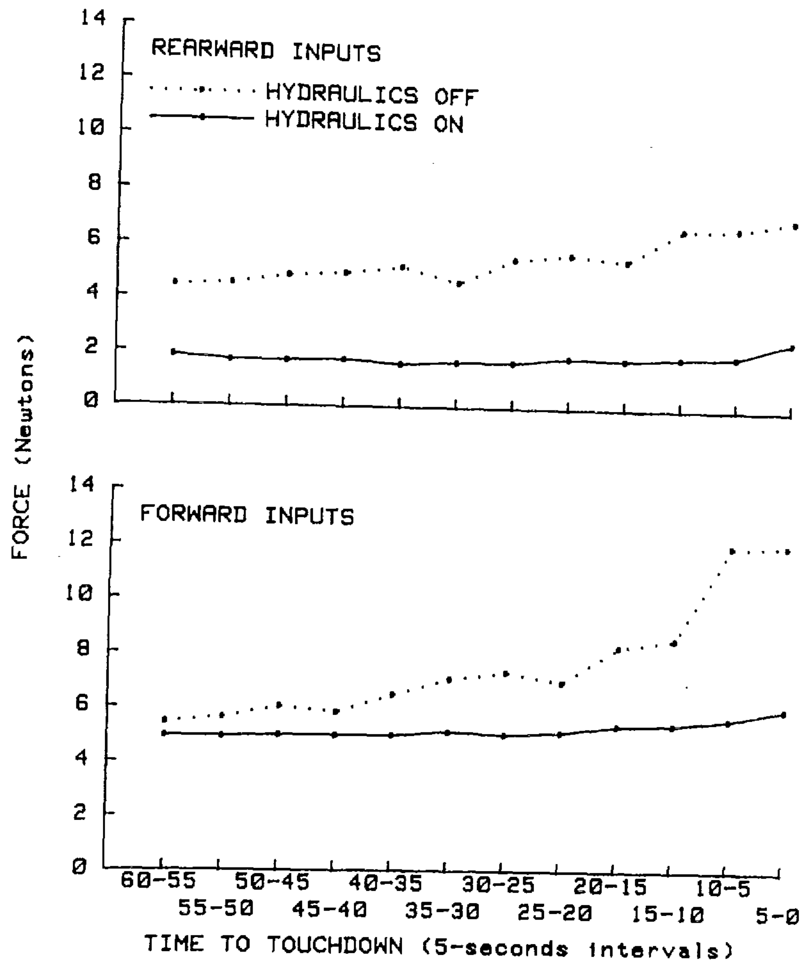

FIGURE 3. Mean Magnitude of Cyclic Inputs in the Forward and Rearward Directions as a Function of Hydraulics-Assist Condition and Time-to-Touchdown.

TABLE 6

DESCRIPTIVE STATISTICAL PARAMETERS OF THE NET LEVELS OF LEFT-RIGHT DIRECTIONAL INPUT FORCES APPLIED TO THE CYCLIC CONTROL AS A FUNCTION OF HYDRAULIC CONDITION AND AVIATORS' LEVEL OF EXPERIENCE

Statistical Parameter	Hydraulics On		Hydraulics Off	
	More Exp	Less Exp	More Exp	Less Exp
Mean	3.74	-0.55	8.66	-0.13
Median	2.97	1.19	4.71	1.19
Maximum Right	10.66	15.70	56.90	17.44
Maximum Left	0.33	0.01	0.01	-44.09
Range	10.33	28.71	78.85	61.53
Variance	6.06	48.03	66.11	64.30
Standard Deviation	2.46	6.93	8.13	8.02
Semi-Interquartile Range	0.93	5.41	4.27	5.34
Skewness	1.36	0.30	1.34	-0.18
Kurtosis	0.62	-0.43	1.31	0.91

NOTE: Forces are expressed in Newtons. Distributions each consist of 2160 means of 1-second duration.

Descriptive statistics derived from the separate distributions of right- and left-directed inputs are provided in Table 7. The most striking finding is the marked difference between the more- and less-experienced aviators in the number of seconds of force input in the left and right directions. Regardless of the hydraulics condition, more-experienced aviators tended to employ right-directed inputs almost exclusively. In contrast, less-experienced aviators employed right and left inputs at about the ratio of 1.5 to 1.0 (right:left) during both hydraulics-on and hydraulics-off landings.

The results of the ANOVA accomplished for the right- and left-directed forces input to the cyclic are provided in Tables 8 and 9. With the exception of significantly higher forces during the hydraulics-off condition than during the hydraulics-on condition, $F(1,10) = 5.64$, $p = .039$, there were no statistically significant effects encountered among the right-directed force data.

TABLE 7

DESCRIPTIVE STATISTICAL PARAMETERS OF LEFT- AND RIGHT-DIRECTED INPUT FORCES TO THE CYCLIC AS A FUNCTION OF HYDRAULIC CONDITION AND LEVEL OF AVIATOR'S EXPERIENCE

	DIRECTION OF INPUT							
	RIGHT				LEFT			
	HYDRAULICS ON		HYDRAULICS OFF		HYDRAULICS ON		HYDRAULICS OFF	
STATISTIC	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED
Mean	3.7	3.9	8.7	5.2	---	7.9	5.0	8.0
Median	3.0	2.2	4.7	2.8	---	8.8	1.9	7.9
Maximum	10.7	15.7	56.9	17.4	---	13.0	22.0	44.1
Variance	6.1	19.4	65.2	24.6	---	8.8	50.2	19.1
Standard Deviation	2.5	4.4	8.1	5.0	---	3.0	7.1	4.4
Skewness	1.4	1.6	1.4	0.9	---	1.8	1.4	-3.2
Kurtosis	0.6	1.0	1.3	1.0	---	2.2	0.4	19.5
Frequency	2160	1341	2148	1285	0	819	12	875

Note: Forces are expressed in Newtons

TABLE 8

ANALYSIS OF VARIANCE SUMMARY TABLE FOR RIGHT-DIRECTED CYCLIC FORCE INPUTS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	4749.46875	1,10	4749.7	1.97	0.191
Hydraulics Condition (H)	4599.47314	1,10	4599.5	5.64	0.039
H x E	1817.53076	1,10	1817.5	2.23	0.166
Trials (T)	412.58911	5,50	82.5	1.65	0.163
T x E	120.53345	5,50	24.1	0.48	0.787
T x H	98.65454	5,50	19.7	0.37	0.869
T x H x E	341.97559	5,50	68.4	1.27	0.291
Intervals (I)	20.83502	11,110	1.9	0.52	0.886
I x E	20.94818	11,110	1.9	0.52	0.884
I x H	54.94443	11,110	5.0	1.47	0.154
I x H x E	26.36044	11,110	2.4	0.70	0.732
I x T	58.20776	55,550	1.1	1.07	0.345
I x T x E	62.76208	55,550	1.1	1.15	0.216
I x T x H	58.04120	55,550	1.1	1.09	0.320
I x T x H x E	57.46423	55,550	1.0	1.07	0.338

TABLE 9

ANALYSIS OF VARIANCE SUMMARY TABLE FOR LEFT-DIRECTED CYCLIC FORCE INPUTS BY LESS-EXPERIENCED AVIATORS

SOURCE	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Hydraulics Conditions (H)	1,5	230.0	2.11	0.206
Trials (T)	5,25	6.1	1.00	0.437
T x H	5,25	3.4	0.58	0.713
Intervals (I)	11,55	49.8	5.77	0.000
I x H	11,55	28.2	3.37	0.001
I x T	55,275	2.7	1.10	0.305
I x T x H	55,275	2.64	1.12	0.272

The ANOVA undertaken on the left-directed data was confined to the less-experienced subjects as there were insufficient data for the more-experienced subjects. Figure 4 depicts the nature of significant main effect of interval (i.e., time-to-touchdown), $F(11,55) = 5.77$, $p < .001$, and the significant interaction of interval with hydraulics condition, $F(11,55) = 3.37$, $p = .001$. Increases in the magnitude of left-directed cyclic inputs as touchdown neared were larger during hydraulics-off landings than they were during hydraulics-on landings.

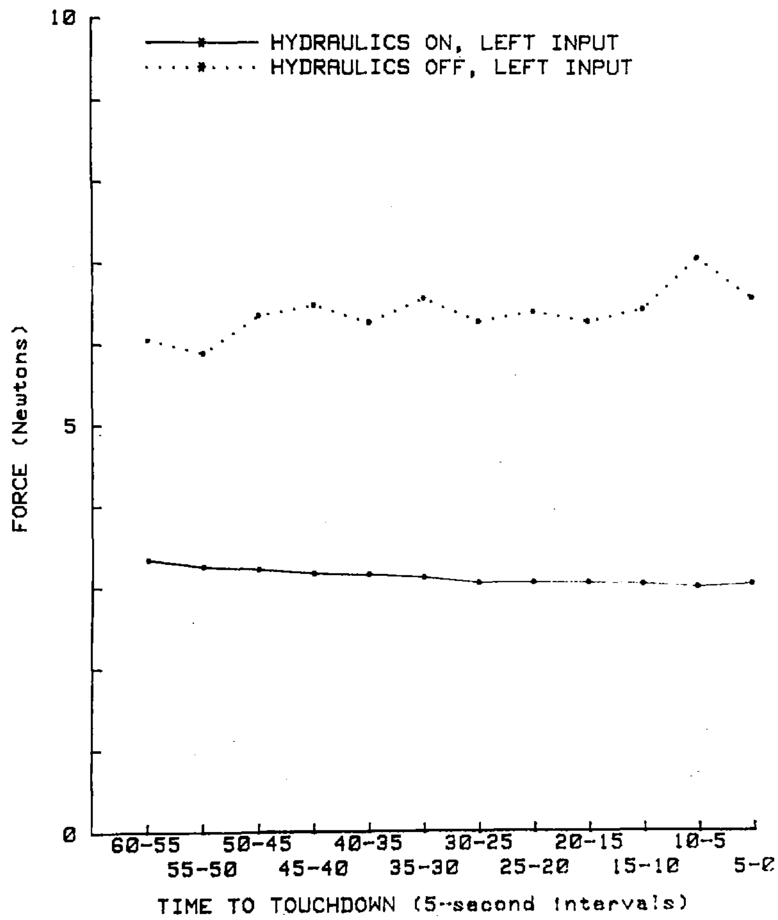

FIGURE 4. Left-Directed Cyclic Input Forces by Less Experienced Aviators as a Function of Hydraulics-Assist Condition and Time-to-Touchdown.

CYCLIC RESULTANT VECTOR MAGNITUDE

Table 10 cites the descriptive statistics pertaining to the magnitude of the resultant force vector obtained from the vector sum of the longitudinal and lateral force inputs to the cyclic. Each of the 1-second data points comprising the distribution is the mean of the absolute values of the 10 resultant vectors computed for each pair of data points resulting from the 10 Hz sampling of the fore-aft and left-right recording channels.

TABLE 10

DESCRIPTIVE STATISTICAL PARAMETERS OF THE MAGNITUDES OF RESULTANT FORCE VECTOR INPUTS APPLIED TO THE CYCLIC CONTROL AS A FUNCTION OF HYDRAULIC CONDITION AND AVIATORS' LEVEL OF EXPERIENCE

Statistical Parameter	Hydraulics On		Hydraulics Off	
	More Exp	Less Exp	More Exp	Less Exp
Mean	7.14	9.21	16.95	11.21
Median	4.95	4.63	13.60	14.16
Maximum	28.28	21.21	81.70	56.24
Minimum	1.17	1.59	2.63	1.71
Range	27.10	19.63	79.07	54.53
Variance	23.90	41.23	165.64	45.66
Standard Deviation	4.89	6.42	12.87	6.76
Semi-Interquartile Range	3.99	6.41	9.83	5.82
Skewness	1.01	0.28	1.32	0.99
Kurtosis	0.24	-1.79	2.02	3.92

NOTE: Forces are expressed in Newtons. Distributions each consist of 2160 means of 1-second duration.

A comparison of the data in Table 10 with those pertaining to the fore-aft and left-right inputs clearly illustrates the inadequacy of either of these tables to describe the measures of central tendency of the actual cyclic force inputs involved in piloting the helicopter, particularly during hydraulically-unassisted approaches. However, they have been retained because of their relevance to existing control design force limit specifications as cited in MIL-H-8501A (Department of Defense 1961). Both mean and median values appearing in Table 10 for hydraulics disabled approaches are considerably larger than those appearing in Tables 3 and 7. The magnitude of the resultant mean vector for more experienced pilots (17.0 N) is 45-49 percent larger than the means (11.7 N and 11.4 N) for the largest directional inputs (those for the rearward- and forward-directed inputs, respectively). It is 3.4 times as large as that for the mean left-directed input which was the smallest directional mean input. The largest directional mean input appearing in Tables 3 and 7 for less experienced aviators is for forward-directed inputs, 8.7 N. The mean resultant vector magnitude for these aviators 11.2 N was approximately 30-40 percent larger than the values for mean forward- (8.7 N) and left- (8.0 N) directed inputs. It was nearly twice as large as the means for the rearward- (5.8 N) and right- (5.2 N) directed inputs.

The results of the ANOVA undertaken on the mean resultant vector magnitude data are shown in Table 11. The overall mean resultant vector during hydraulics-off approaches (12.1 N) was significantly greater than that during hydraulics-on approaches (10.2 N), $F(1,10) = 12.90$, $p = .005$. This was also seen in the overall increase in the applied force vector as the time-to-touchdown decreased, $F(11,110) = 4.70$, $p < .001$. The interaction of these two factors (Figure 5) also was highly significant, $F(11,110) = 4.09$, $p < .001$. As depicted in Figure 6, the increase in magnitude began to occur somewhat earlier and was much larger during hydraulics-off approaches than it was during hydraulics-on approaches.

TABLE 11

ANALYSIS OF VARIANCE SUMMARY TABLE FOR THE MAGNITUDE OF RESULTANT FORCE VECTORS FOR CYCLIC INPUTS

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	PROBLEMS
Experience (E)	1451.43171	1,10	1451.43171	0.30	0.595
Hydraulics Condition (H)	15062.53308	1,10	15062.53308	12.90	0.005
H x E	6580.04426	1,10	6580.04426	5.63	0.039
Trials (T)	512.46282	5,50	102.49256	0.95	0.457
T x E	185.73919	5,50	37.14784	0.34	0.883
T x H	174.58780	5,50	34.91756	0.31	0.907
T x H x E	674.75761	5,50	134.95152	1.18	0.332
Intervals (I)	1920.69599	11,110	174.60873	4.70	0.000
I x E	528.06735	11,110	48.00612	1.29	0.239
I x H	1395.88156	11,110	126.89832	4.09	0.000
I x H x E	528.22348	11,110	48.02032	1.55	0.124
I x T	505.72746	55,550	9.19504	1.24	0.126
I x T x E	343.03451	55,550	6.23699	0.84	0.789
I x H x T	373.27977	55,550	6.78690	0.99	0.499
I x H x T x E	334.35653	55,550	6.07921	0.89	0.705

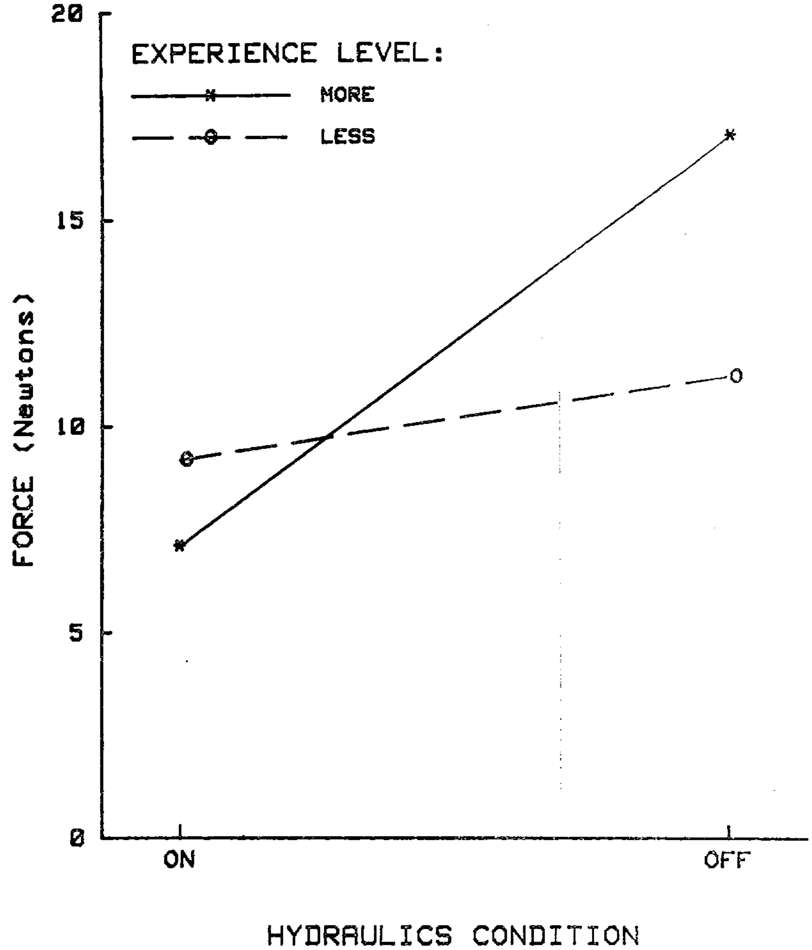

FIGURE 5. Mean Magnitudes of Resultant Force Vectors Applied to the Cyclic Control as a Function of Hydraulics-Assist Condition and Level of Aviator Experience.

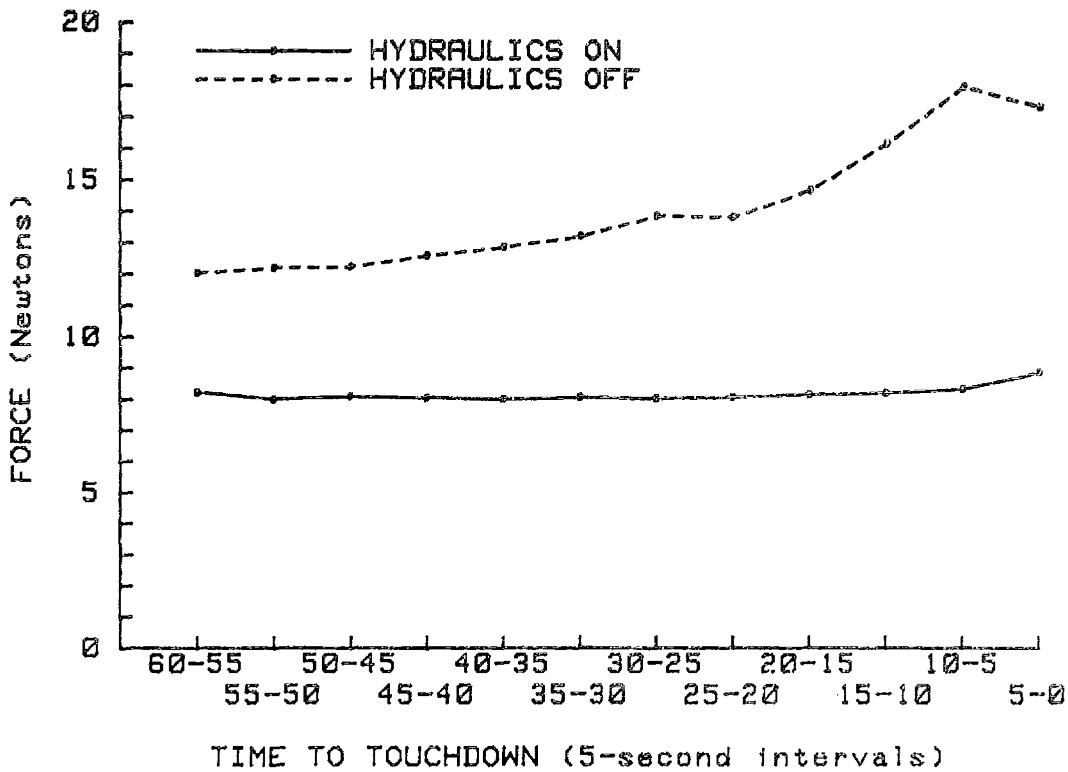

FIGURE 6. Mean Magnitudes of Resultant Force Vectors Applied to the Cyclic Control as a Function of Hydraulics Condition and Time Remaining to Touchdown. (Data are averaged over both groups of aviators.)

COLLECTIVE INPUTS

Descriptive statistics for net collective input forces are shown in Table 12. Negative values in this table refer to upward pulls on the collective. The table reflects the shift from upward pulls to downward pushes as the hydraulics conditions change from on to off. Too, with this change in hydraulics assist, the relative magnitudes of the forces applied by the two groups of aviators also changed. During hydraulics-on approaches, the larger net mean force was input by the less-experienced aviators. However, during hydraulics-off approaches, the more-experienced aviators applied the larger mean net force. In comparison to the level of forces applied to the cyclic (Tables 2, 6, and 10), the peak forces applied to the collective are markedly larger.

TABLE 12

DESCRIPTIVE STATISTICAL PARAMETERS OF THE NET LEVELS OF INPUT FORCES APPLIED TO THE COLLECTIVE CONTROL AS A FUNCTION OF HYDRAULIC CONDITION AND AVIATORS' LEVEL OF EXPERIENCE

Statistical Parameter	Hydraulics On		Hydraulics Off	
	More Exp	Less Exp	More Exp	Less Exp
Mean	-3.88	-16.17	42.62	18.45
Median	-1.15	-14.76	20.76	9.95
Maximum Down	53.01	54.21	391.10	256.62
Maximum Up	-73.25	-85.48	-71.06	-128.11
Range	126.26	139.69	462.17	384.73
Variance	567.76	848.46	6108.47	3732.43
Standard Deviation	23.83	29.15	78.16	61.09
Semi-Interquartile Range	15.93	20.68	50.52	41.06
Skewness	0.21	-0.16	1.02	0.63
Kurtosis	-0.31	-0.48	0.48	0.21

NOTE: Forces are expressed in Newtons. Distributions each consist of 2160 means of inputs of 1-second duration.

The descriptions of the direction-specific collective input force distributions (Table 13) reflect the substantial differences in the measures of central tendency between downward and upward inputs. The mean magnitudes of downward-directed inputs during hydraulics-off approaches were 5 times larger than during hydraulics-on approaches for more-experienced aviators and 3.4 times larger for less-experienced aviators. In contrast, the mean upward-directed inputs during hydraulics-off approaches exceeded those during hydraulics-on approaches by only a relatively small amount (10-20 percent) for both groups of aviators. During hydraulics-on approaches, the number of seconds of

TABLE 13

DESCRIPTIVE STATISTICAL PARAMETERS OF DOWNWARD- AND UPWARD-DIRECTED INPUT FORCES TO THE COLLECTIVE AS A FUNCTION OF HYDRAULIC CONDITION AND LEVEL OF AVIATORS' EXPERIENCE

	DIRECTION OF INPUT							
	DOWNWARD				UPWARD			
	HYDRAULICS ON		HYDRAULICS OFF		HYDRAULICS ON		HYDRAULICS OFF	
STATISTIC	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED
Mean	16.2	17.1	83.9	58.3	21.2	30.7	23.4	36.0
Median	13.4	14.2	65.3	46.8	18.5	28.0	20.9	32.7
Maximum	53.0	54.2	391.1	256.6	73.3	85.5	71.1	128.0
Variance	165.3	158.2	5190.2	2270.7	267.0	455.0	308.1	597.3
Standard Deviation	12.9	12.6	72.0	47.7	16.3	21.3	17.6	24.4
Skewness	0.7	0.7	0.9	1.0	0.7	0.7	0.6	0.6
Kurtosis	-0.5	-0.5	0.2	0.7	0.3	0.4	0.7	0.4
Frequency	1002	658	1408	1247	1158	1502	752	913

Note: Forces are expressed in Newtons.

recorded direction-specific force input differed substantially between the two groups. Whereas the recorded seconds of upward-directed inputs exceeded downward inputs by only a small amount for the more-experienced aviators (1.16:1.00), this bias was twice as large among those in the less-experienced group (2.28:1.00).

Tables 14 and 15 provide the results of the ANOVA undertaken on the downward- and upward-directed collective input forces, respectively. The direction-specific force inputs were affected in substantially different ways by the factors investigated. As reflected in Table 14, the only factor to have attained the conventional $p \leq .05$ level of statistical confidence in downward-directed inputs (pushes) was the main effect of hydraulic condition, $F(1,10) = 90.7$, $p < .001$. As shown in Figure 7, when the hydraulics were disabled, the collective was pushed down with an overall mean force that was nearly six times that employed during fully-assisted approaches.

TABLE 14

ANALYSIS OF VARIANCE SUMMARY TABLE FOR DOWNWARD-DIRECTED COLLECTIVE FORCE INPUTS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	57191.89063	1,10	57191.9	2.68	0.133
Hydraulic Condition (H)	1033335.21250	1,10	1033335.3	90.72	0.000
H x E	41059.24219	1,10	41059.2	3.60	0.087
Trials (T)	1695.49219	5,50	339.1	0.28	0.924
T x E	1959.28906	5,50	391.9	0.32	0.899
T x H	620.87891	5,50	124.2	0.11	0.991
T x H x E	1473.58203	5,50	294.7	0.24	0.943
Intervals (I)	23818.45313	11,110	2165.3	1.48	0.150
I x E	11889.82813	11,110	1080.9	0.74	0.701
I x H	15568.70313	11,110	1415.3	1.04	0.419
I x H x E	10924.00000	11,110	993.1	0.73	0.709
I x T	37634.34375	55,550	684.3	0.79	0.856
I x T x E	42565.81250	55,550	773.9	0.90	0.682
I x T x H	40158.75000	55,550	730.2	0.86	0.750
I x T x H x E	46714.53125	55,550	849.4	1.00	0.474

TABLE 15

ANALYSIS OF VARIANCE SUMMARY TABLE FOR UPWARD-DIRECTED COLLECTIVE FORCE INPUTS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	37178.82813	1,10	37178.8	2.58	0.139
Hydraulics Condition (H)	46.05371	1,10	46.1	0.04	0.847
H x E	1.45215	1,10	1.5	0.00	0.973
Trials (T)	309.58594	5,50	61.9	0.24	0.941
T x E	515.37988	5,50	103.1	0.40	0.843
T x H	2860.07617	5,50	572.0	4.37	0.002
T x H x E	3695.35254	5,50	739.1	5.65	0.000
Intervals (I)	49467.32031	11,110	4497.1	15.48	0.000
I x E	2353.59961	11,110	214.0	0.74	0.702
I x H	7876.61719	11,110	716.1	3.27	0.001
I x H x E	1584.24609	11,110	114.0	0.66	0.775
I x T	9139.57813	55,550	166.2	1.09	0.316
I x T x E	9589.70313	55,550	174.4	1.14	0.234
I x T x H	7016.50000	55,550	127.6	0.99	0.497
I x T x H x E	5383.78125	55,550	97.9	0.76	0.897

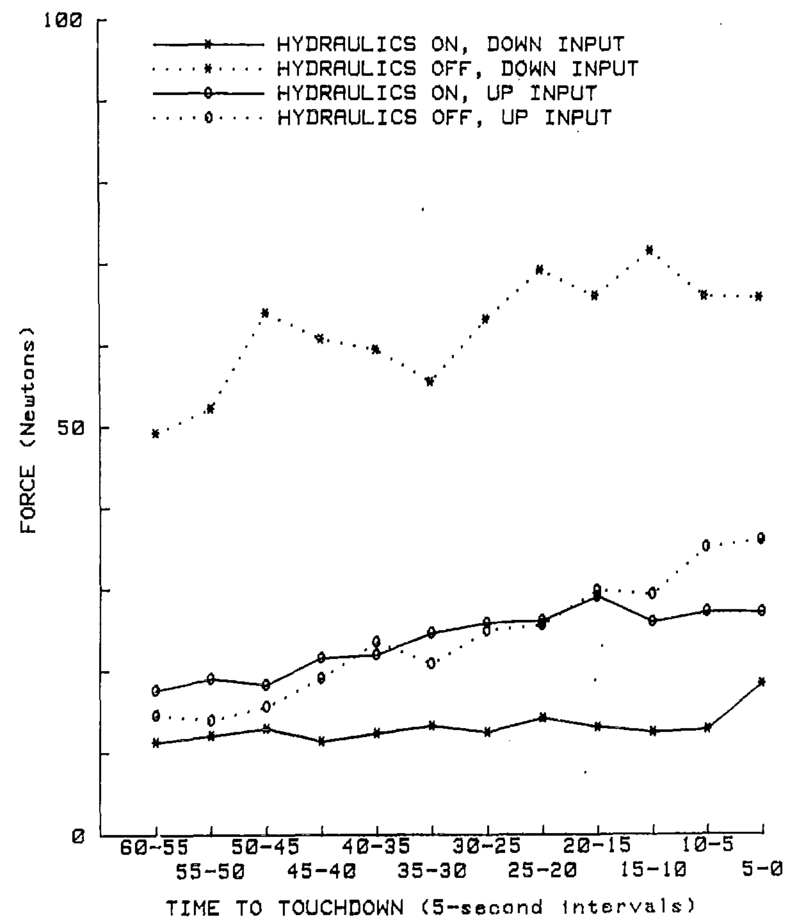

FIGURE 7. Mean Magnitude of Collective Inputs in the Up and Down Directions as a Function of Hydraulics-Assist Condition and Time-to-Touchdown. (Data are averaged over both groups of aviators.)

In contrast to the robust hydraulics condition effects cited for downward-directed inputs, Figure 8 also clearly illustrates that upward-directed collective inputs (pulls) were not affected in an overall sense by the status of the hydraulics system, $F(1,10) = 46.1$, $p = 0.847$. The overall increase in the upward-directed inputs evidenced as time-to-

touchdown decreased during both hydraulics-assisted and hydraulics-disabled approaches was, however, significant, $F(1,10) = 15.5$, $p < .001$.

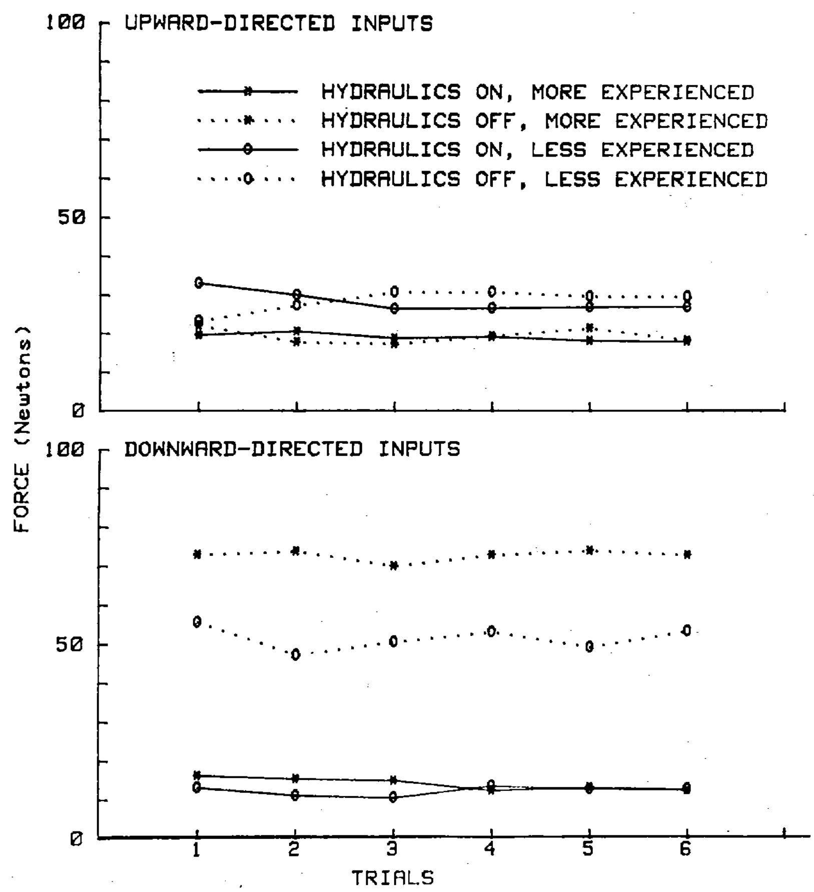

FIGURE 8. Mean Magnitude of Collective Inputs in the Up and Down Directions as a Function of Hydraulics-Assist Condition, Aviators' Experience, and Trials.

The interaction of aviator experience with hydraulics condition and trials is shown in Figure 8 for upward- and downward-directed inputs on the collective. This third-order interaction was highly significant for upward-directed input forces, $F(5,50) = 565$, $p < .001$, and not significant for downward-directed input forces, $F(5,50) = 0.23$, $p = .943$. The significant upward-related effect was most strongly evidenced during the first three trials. During the hydraulics-off approaches, forces increased sharply for more-experienced aviators and decreased substantially for less-experienced subjects. During hydraulics-on approaches, there was a substantial decrease in the magnitude of force applied for more-experienced aviators, but relatively little change among their less-experienced counterparts.

PEDALS

The descriptive statistics of the net force applied to the pedals are shown in Table 16 for the 1-second-based data. The overall mean and median values reflect a substantial shift from predominantly right pedal inputs during hydraulics-on approaches to larger, left pedal inputs during hydraulics-off approaches. In general, the characteristics of this distribution of forces is much closer to those in the distribution of collective-related inputs than they are to those encountered for the cyclic.

The pedal-specific distribution of the force during the final 60 seconds of the approaches (Table 17) reveals larger inputs by the less-experienced aviators. The relative frequency (duration) of inputs to the pedals show a substantial reversal when the hydraulics are off. During hydraulics-on approaches, the ratio of left-to-right pedal inputs was 2.6:1 for less-experienced subjects and 7.0:1 for more-experienced subjects. However, these relationships were reversed for hydraulics-off approaches. Under these conditions, the ratio of left-to-right pedal inputs was 0.5:1 for both the less-experienced and more-experienced groups.

The results of the ANOVA for left and right pedal inputs are cited in Tables 18 and 19. These analyses revealed a difference in sensitivity between the two pedals. While the only significant effect for right pedal inputs was related to the hydraulics condition, $F(1,10) = 23.00$, $p = .001$, left pedal inputs were significantly affected by several factors and their interactions.

TABLE 16

DESCRIPTIVE STATISTICAL PARAMETERS OF NET LEVEL OF INPUT FORCES APPLIED TO THE PEDALS AS A FUNCTION OF HYDRAULIC CONDITION AND LEVEL OF AVIATORS' EXPERIENCE

Statistical Parameter	Hydraulics On		Hydraulics Off	
	More Exp	Less Exp	More Exp	Less Exp
Mean	-9.36	-24.81	38.86	37.70
Median	-11.20	-24.92	24.10	34.06
Maximum Right	38.90	47.78	327.53	295.74
Maximum Left	-53.43	-81.78	-221.17	-270.97
Range	92.33	129.56	548.09	566.71
Variance	288.98	488.30	5589.09	6626.67
Standard Deviation	15.13	22.10	74.76	81.40
Semi-Interquartile Range	11.76	14.96	47.97	55.22
Skewness	0.41	0.17	0.74	-0.10
Kurtosis	-0.24	-0.12	0.69	0.25

NOTE: Forces are expressed in Newtons. Distributions each consist of 2160 means of inputs of 1-second duration.

TABLE 17

DESCRIPTIVE STATISTICAL PARAMETERS OF INPUT FORCES TO THE LEFT AND RIGHT PEDALS AS A FUNCTION OF HYDRAULIC CONDITION AND LEVEL OF AVIATORS' EXPERIENCE

	PEDAL							
	RIGHT				LEFT			
	HYDRAULICS ON		HYDRAULICS OFF		HYDRAULICS ON		HYDRAULICS OFF	
STATISTIC	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED	MORE EXPERIENCED	LESS EXPERIENCED
Mean	10.2	12.8	73.9	82.0	16.9	30.2	32.3	48.5
Median	8.4	10.1	52.4	74.4	16.6	29.4	24.2	35.6
Maximum	38.9	47.8	327.5	295.7	53.4	81.8	221.2	271.0
Variance	66.1	109.5	4176.2	3151.7	88.3	311.1	904.8	2117.1
Standard Deviation	8.1	10.5	64.6	56.1	9.4	17.6	30.1	46.0
Skewness	1.2	0.9	1.1	0.7	-0.3	-0.4	-2.7	-1.9
Kurtosis	0.9	0.1	0.3	-0.1	-0.2	-0.6	8.8	4.3
Frequency	600	270	1447	1425	1560	1890	713	735

Note: Forces are expressed in Newtons.

TABLE 18

ANALYSIS OF VARIANCE SUMMARY TABLE FOR RIGHT PEDAL FORCE INPUTS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	1259.18750	1,10	1259.2	0.02	0.891
Hydraulics Condition (H)	1362092.37500	1,10	1362092.4	23.00	0.001
H x E	63715.81250	1,10	63715.8	1.08	0.324
Trials (T)	7317.99219	5,50	1463.6	0.68	0.638
T x E	16582.30469	5,50	3316.5	1.55	0.192
T x H	16109.90625	5,50	3222.0	1.60	0.179
T x H x E	15191.54688	5,50	3038.3	1.50	0.205
Intervals (I)	3840.77344	11,110	349.2	0.36	0.968
I x E	5553.02344	11,110	504.8	0.52	0.885
I x H	1949.83594	11,110	177.3	0.17	0.999
I x H x E	2899.16406	11,110	263.6	0.26	0.992
I x T	21073.50000	55,550	383.2	0.86	0.756
I x T x E	26105.34375	55,550	474.6	1.06	0.358
I x T x H	22959.60938	55,550	417.4	0.91	0.658
I x T x H x E	26947.29688	55,550	490.0	1.07	0.348

TABLE 19

ANALYSIS OF VARIANCE SUMMARY TABLE
FOR LEFT PEDAL FORCE INPUTS

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	P
Experience (E)	85311.61719	1,10	85311.6	6.81	0.026
Hydraulics Condition (H)	4158.34375	1,10	4158.3	0.57	0.469
H x E	233.89063	1,10	223.9	0.03	0.865
Trials (T)	296.54297	5,50	59.3	0.12	0.987
T x E	3042.38086	5,50	608.5	1.24	0.306
T x H	1392.63086	5,50	278.5	0.61	0.691
T x H x E	2872.97656	5,50	574.6	1.26	0.295
Intervals (I)	126705.89063	11,110	11518.7	15.42	0.000
I x E	9647.82813	11,110	877.1	1.17	0.313
I x H	60373.64063	11,110	5488.5	9.08	0.000
I x H x E	12483.60156	11,110	1134.9	1.88	0.050
I x T	7101.61719	55,550	129.1	0.89	0.695
I x T x E	8971.67969	55,550	163.1	1.13	0.256
I x T x H	9211.50781	55,550	167.5	1.18	0.180
I x T x H x E	8106.55469	55,550	147.4	1.04	0.397

The effects of hydraulics condition, level of aviator experience, and time-to-touchdown for both left and right pedal inputs are shown in Figure 9. The most significant effect of hydraulics condition on the right pedal, $F(1,10) = 23.0$, $p = .001$, was that forces input during the hydraulics-off approaches were consistently three to six times greater than those during hydraulics-on approaches. The most significant effect of forces input to the left pedal was time-to-touchdown $F(11,110) = 15.42$, $p < .001$. This was largely due to the sharp rise in inputs during the last 10-15 seconds of the hydraulics-off trials. This differential increase was not evident in the hydraulics-on trials. This resulted in a highly significant interaction, $F(11,110) = 9.07$, $p < .001$, between hydraulics condition and time-to-touchdown for left pedal input forces.

The statistical analysis of left pedal force inputs also yielded a significant main effect for pilot experience, $F(1,10) = 6.80$, $p = .026$, as well as a significant interaction, $F(11,110) = 1.88$, $p = .050$, of this factor upon the hydraulics-condition/time-to-touchdown interaction described in the preceding paragraph. Overall, it was found that more-experienced pilots input smaller left-pedal forces than did less-experienced pilots. The significant third order interaction (lower portion of Figure 9) was shown in the earlier and more pronounced increase in force levels for the less-experienced pilots relative to those shown by the more-experienced aviators during approaches executed with the hydraulics off. This difference was not evident during hydraulics-on approaches.

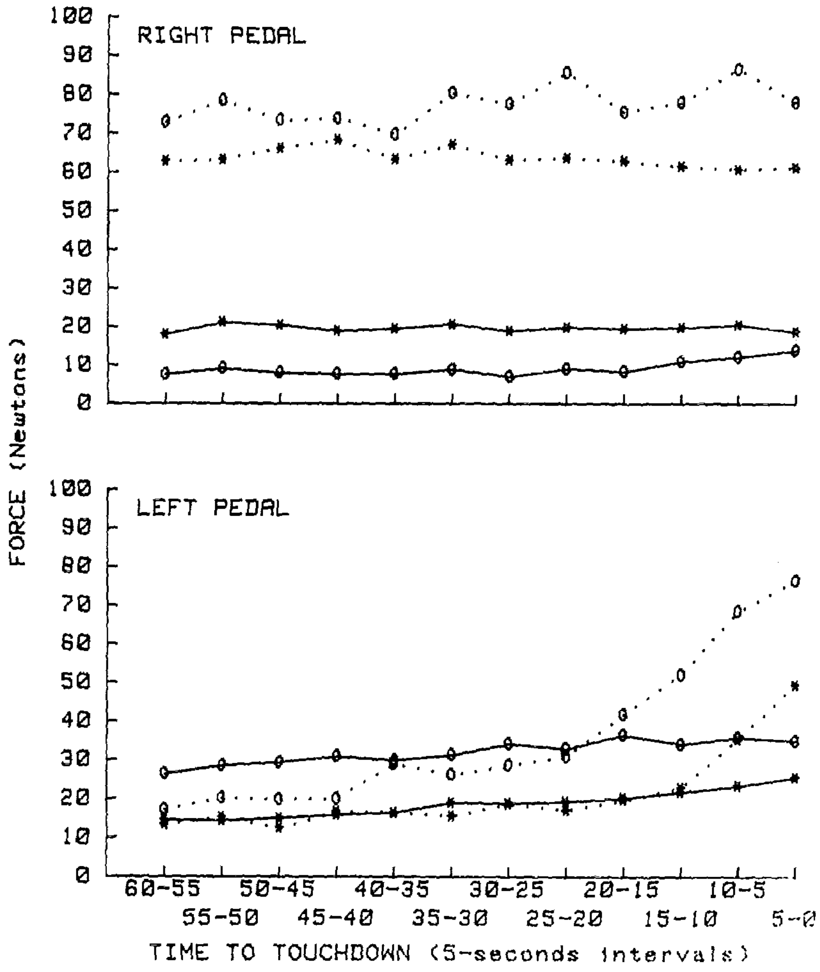

FIGURE 9. Mean Magnitude of Left and Right Pedal Inputs as a Function of Hydraulics-Assist Condition (On: ---, Off: ...), Aviators' Experience (More: *, Less: 0), and Time-to-Touchdown.

DISCUSSION

The present findings are discussed within several contexts. The descriptive statistics are compared to both existing military standards (MIL-H-8501A, Department of Defense 1961) for the upper design limits of helicopter control forces and the results of a recently completed study of helicopter control force exertion capabilities of small Army personnel (Schopper and Mastroianni 1985). The ANOVA-related findings are discussed in comparison with other research pertaining to the role of experience in the conduct of psychomotor tasks.

DESIGN STANDARDS COMPARISON

The upper design limits for input forces to the controls of Army helicopters are stipulated in MIL-H-8501A, Military Specification: "Helicopter flying and ground handling qualities" (Department of Defense 1961). Two sets of limits are cited; one applicable to hydraulics-on horizontal, straight flight (MIL-H-8501A, page 2, Table II), and one applicable to ". . . abrupt power-operated control system failure . . ."or hydraulics-off flight (MIL-H-8501A, page 9, paragraph 3.5.8). The values associated with these two sets of limits are cited in Table 20. The calculated value of the force which would result from the simultaneous application of maximal longitudinal and lateral cyclic inputs also is included although this value is not cited in the specification.

The discussion which follows for each of the controls will include a comparison of the descriptive statistics for the hydraulics-on approaches and landings executed during this study with those limits pertaining to "normal" flight in Table 20. The authors recognize that the flight conditions cited in MIL-H-8501A (straight and level flight) are not consistent with the flight conditions (descent) under which the present hydraulics-on data were collected; however, for purposes of exposition, they do provide a reasonable referent.

Cyclic inputs. Comparisons of the data cited in Table 3 with those appearing in Table 20 reveal that regardless of experience level, the measures of central tendency (means and medians) and peak values recorded for both forward- and rearward-directed control inputs during hydraulics-on and hydraulics-off approaches were all substantially less than their respective limits; i.e., 36 N for normal flight and 112.5 N for flight during hydraulics system failure. The results of a similar comparison between the data pertaining to lateral cyclic inputs appearing in Table 7 and the relevant limits cited in Table 20 were similar; i.e., none of the limits were exceeded. The same applies to similar comparisons of the magnitude of the resultant cyclic force vector (Tables 10 and 20).

TABLE 20

CONTROL FORCE DESIGN CRITERIA
(MIL-H-8501A, DOD 1961)

Flight Condition	Cyclic			Collective	Pedals
	Longitudinal	Lateral	Resultant*		
Normal	112.5 N (25 lb)	31.5 N (7 lb)	47.8 N* (10.6 lb)	31.5 N (7 lb)	67.5 N (15 lb)
Hydraulics Off	360.0 N (80 lb)	67.5 N (15 lb)	131.2 N* (29.2 lb)	112.5 N (25 lb)	360.0 N (80 lb)

* These values are not cited in MIL-H-8501A; it is the magnitude of the resultant force vector input which would occur as the result of maximum simultaneous longitudinal and lateral inputs to the cyclic.

Collective inputs. The design limit specification for collective force inputs does not address direction-of-input; i.e., the limits are applicable to both upward- and downward-directed inputs. In consonance with the cyclic-related findings regarding measures of central tendency, none of the means or medians cited in Table 13 exceeded their respective limits for either "normal" hydraulics-on flight (31.5 N) or hydraulics-off flight (112.5 N). However, the mean (30.7 N) and median (28.0 N) values for upward-directed inputs by the more experienced aviators during hydraulics-on flights came reasonably close to the limit.

The comparison between the maximum recorded values and the design limits yields a much different result. With the exception of upward-directed force inputs during hydraulics-off approaches and landings, the maximum values cited in Table 13 all exceed their respective limits by a considerable degree. In fact, the maximum upward-directed force input by the more experienced group also exceeded the limit by a small amount--14 percent. Maximum downward force inputs by both groups of aviators exceeded the 31.5 N normal flight limit by 70 percent. Approximately 17 percent of the data exceeded the limit. Downward-directed inputs during hydraulics-off conditions exceeded the 112.5 N limit by 250 percent for the less-experienced group (42 percent of the data) and by 130 percent for the more-experienced group (19 percent of the data). The hydraulics-on upward-directed inputs by the less- and more-experienced aviators also exceeded the 31.5 N limit by 130 percent (31 percent of the data) and 170 percent (45 percent of the data), respectively.

Pedal inputs. A comparison was made between the limits for pedal inputs (Table 20) and the values for the means, medians, and maximums derived from the force inputs on the left and right pedals by groups of aviators during both hydraulics-on and hydraulics-off conditions. It revealed no instance where the recorded forces exceeded their respective limits.

FORCE EXERTION CAPABILITY COMPARISON

A study of helicopter control exertion capabilities has been completed and reported (Schopper and Mastroianni 1985). This research focused on the strength capabilities of small Army males and females; i.e., those whose stature was just above or below the minimum standard for entrance into the US Army's aviator training program. This criterion, 162.6 cm (64 inches), corresponded to the 5th-percentile male. Descriptive statistics for males and females whose stature was equal-to-or-less-than 167 cm are cited in Table 21. They are dependent upon the mean force exerted during maximal exertions of 4-seconds duration.

To make a meaningful comparison, it was necessary to develop statistics from the in-flight data which were compatible with the 4-second period of exertion employed in the strength-related study. Accordingly, the data from the 1-second-based file were used in conjunction with a 4-second, moving average technique to estimate the mean force required for the successive 4-second periods of time. By employing a "moving window" of 4-seconds duration throughout the 60-second period, a total of 57 data points were generated for each approach and landing. Descriptive statistics then were calculated for each direction of input for each control for both experience-related groups of subjects. The results are provided in Table 22.

TABLE 21

DESCRIPTIVE STATISTICS FOR HELICOPTER-CONTROL-REFERENCED FORCE EXERTIONS BY MALES AND FEMALES OF STATURE ≤167 cm*

Gender	Statistic	Cyclic				Collective		Pedals	
		Forward	Rearward	Left	Right	Upward	Downward	Left	Right
Males									
(N#=39)	Min	136.4	172.4	68.4	53.6	260.1	155.7**	338.0	315.5
	Mdn	307.8	351.9	182.7	115.7	555.3	321.8	722.7	777.6
	Max	575.1	473.0	376.2	235.8	977.9	738.5	1434.2	1652.9
Females									
(N#=56)	Min	100.8	155.7	58.1	40.5	219.6	76.1	264.2	256.1
	Mdn	223.0	263.0	120.5	85.5	394.5	177.0	524.0	528.5
	Max	446.4	482.9	189.9***	177.8	604.4	424.8	1000.8	1227.2

* All force values given in Newtons.
** One value at 88.2 N also was recorded.
*** One value at 296.6 N also was recorded.

Note: Forces are expressed in Newtons. Data are from Schopper and Mastroianni (1985).

A comparison of the minimum values recorded during strength testing (Table 21) with the maximum values recorded during hydraulics-off approaches reveals that in only two instances did the minimum strength capability fail to exceed the maximum force input recorded during hydraulics-off approaches. For all directional control inputs, except those associated with downward-directed collective inputs and right pedal inputs, the strength capabilities of all males and females tested (Schopper and Mastroianni 1985) exceeded the maximum force demands recorded.

An examination of the strength data from Schopper and Mastroianni's study showed that less than 4 percent of the right pedal inputs during the hydraulics-off approaches exceeded the right-pedal exertion capabilities of the shorter (<167 cm) subjects tested. Because the values recorded by these researchers were labeled as conservative estimates of the force-exertion capabilities likely to be evidenced among aviators, there is little reason for concern regarding pedal inputs.

TABLE 22

SELECTED VALUES FOR COMPARISON OF THE DISTRIBUTIONS OF DOWNWARD-DIRECTED COLLECTIVE FORCE INPUTS FOR MORE- AND LESS-EXPERIENCED AVIATORS DURING HYDRAULICALLY UNASSISTED LANDINGS WITH THE DISTRIBUTIONS OF SIMILARLY DIRECTED INPUTS OF SMALL MALES AND FEMALES DURING STRENGTH ASSESSMENTS

	Force Distributions (in Newtons)				
	In-Flight Control Inputs			Force Exertion Capabilities	
Reference Values	More Experienced	Less Experienced	All	Males* (N#=38)	Females (N#=56)
80	50.9	35.6	44.0	0.0	3.6
100	37.7	27.1	32.9	0.0	7.1
120	28.8	20.3	25.0	0.0	17.9
140	20.4	15.3	18.1	0.0	30.4
160	15.6	11.9	13.9	5.3	46.4
180	9.6	8.5	9.1	10.5	53.6
200	7.2	5.1	6.2	23.7	60.7
220	4.8	3.4	4.3	28.9	67.9
240	2.4	---	1.3	31.6	75.0

* Distribution excludes one value of 88.2 N; the next three higher values were 155.7 N, 157.5 N, and 168.3 N.

Note: The values appearing in the table are those percentages of their respective distributions which exceed the reference values cited.

The discrepancy between force demands and exertion capabilities for downward-directed collective inputs was more substantial. The minimum collective-downward exertion capability cited in Table 21 for small males was 155.7 N. This value was exceeded by approximately 17 percent of the successive 4-second interval inputs of more-experienced aviators and by 13 percent of the inputs of less-experienced aviators during their hydraulics-off approaches.

The results of a similar comparison with the distribution of force-exertions for females were considerably worse. The minimum force exertion by females who were less than 167 cm tall was 76.1 N. This was exceeded by more than 55 percent of the more-experienced pilots and 38 percent of the less experienced pilots for the 4-second time-averaged force inputs during their hydraulics-off approaches. From the opposite perspective, 18 percent of the females who were less than 167 cm in height could not attain an exertion of 120 N during strength testing. This was exceeded by approximately 25 percent of the 4-second in-flight force inputs. With the exception of one suspect data point, all males tested could achieve this level of exertion. Table 22 provides a more comprehensive appreciation of how much the downward-directed collective force demands (force inputs during hydraulics-off approaches) exceeded force exertion capabilities.

ANOVA-RELATED FINDINGS

To simplify the discussion of ANOVA-related findings, the significant effects for each variable have been summarized in Table 23.

As anticipated, flying with hydraulics off had a robust and reproducible effect on the amount of force required for flight control tasks. Upward-directed inputs on the collective (mean "on" = 23.7 N, mean "off" = 24.1 N) and left pedal inputs (mean "on" = 25.4 N, mean "off" = 28.5 N) were not very different with hydraulics on or off. For all other control inputs the hydraulics-off landings required much higher force inputs. Forward-directed cyclic inputs nearly tripled and downward-directed collective inputs were nearly five times the magnitude of corresponding inputs during hydraulics-on landings. Right-directed cyclic inputs more than doubled in overall magnitude. Left- and rearward-directed cyclic inputs each increased by approximately 50 percent. Inputs to the right pedal increased by 70 percent.

The interaction between hydraulic condition and time-to-touchdown was both reproducible and consistent. The interaction and the main effect of interval (i.e., time-to-touchdown) were both highly significant ($p \leq .001$) in forward- and left-directed cyclic inputs, upward-directed collective inputs, and inputs to the left pedal. For all the controls and directions cited, there was an increase in input forces as time-to-touchdown decreased, particularly during the hydraulics-off trials.

As reflected in Table 23, the effects of level of experience are not nearly as robust as those associated with hydraulics conditions and time-to-touchdown. If a more conservative, experimental criterion were employed (Kirk 1968), the significance would be even more doubtful. However, the existence of any experience-related effects is somewhat surprising given (a) that even the less-experienced group has

TABLE 23

SUMMARY OF STATISTICALLY SIGNIFICANT AND MARGINALLY SIGNIFICANT FINDINGS FOR ALL CONTROLS AND DIRECTIONS-OF-INPUT

	CONTROL AND DIRECTION OF INPUT								
	Cyclic					Collective		Pedals	
SOURCE	Forward	Rearward	Right	Left*	Resultant	Down	Up	Right	Left
Experience (E)		.079							.026
Hydraulics Condition (H)	.050	.054	.039		.005	.000		.001	
H x E					.039	.087			
Trials (T)									
T x E									
T x H	.007						.002		
T x H x E	.078						.000		
Intervals (I)	.000	.012		.000	.000		.000		.000
I x E	.015								
I x H	.000			.001	.000		.000		.000
I x H x E									.050
I x T									
I x T x E									
I x T x H									
I x T x H x E									

* Findings are for less-experienced aviators only; see relevant text in Results section.

had at least 175 hours of flight experience, (b) the training process involved in becoming an Army aviator is not one which tolerates substantial interindividual variability, and (c) the demands posed by the aircraft itself and those inherent in the successful execution of simulated emergency flight maneuvers are rigorous in themselves. This presents little opportunity for an aviator to demonstrate nonstandard flying techniques without placing himself and his copilot at risk.

The patterns of force inputs seen during the experiment were not uniform in relation to the aviator's level-of-experience. Overall, the mean magnitude of the resultant force applied to the cyclic and the mean downward force applied to the collective were larger for the more experienced aviators. In contrast, larger force inputs were made by the less experienced aviators in the upward direction on the collective, to the left on the cyclic, and to the left pedal. (There were no right-directed inputs by the more experienced aviators.) To some extent, these results suggest that the more experienced aviators were more "aggressive" in bringing down their aircraft for landing; however, the absence of information regarding control position during these maneuvers precludes further examination of this issue and makes any conclusion tentative.

Issues affecting the performance of more- and less-experienced aviators include proficiency and recentness of training. If one assumes that continued exposure to a task yields greater skill and efficiency in flight performance, one would expect the less experienced aviator to input greater force to the flight controls than his more experienced counterpart. This would compensate for the less experienced aviator's large deviations from optimum flight control.

While not entirely independent of proficiency, recentness of training also may contribute to the outcome. The more experienced aviator is more distant in time from the closely supervised flight-school environment, and has had a greater opportunity to develop an empirical appreciation of safe flight envelopes. He may have adopted flying techniques which differ from those taught in flight school. If one assumes the criteria employed by instructor pilots is more cautious or conservative than is required, the recentness of training factor might suggest more experienced aviators would input greater forces than less experienced aviators. This could be supported by earlier researchers (Simmons, Lees, and Kimball 1978, p.23) who performed in-flight monitoring of more and less experienced aviators during specified instrument flight maneuvers. They observed that the less-experienced group (mean = 209 hours of flight time) ". . . demonstrated a trend of less (frequent) control inputs and more time in control steady state . . . (and) better aircraft performance."

The present research was not designed to determine or quantify those factors which might account for observed differences between more and less experienced aviators. The citing of the above factors was included merely to illustrate some concerns which developed during the formulation of the project. The lack of relevant data on required control forces and the absence of any prior research pertinent to the effects of experience on control force inputs were the principal reasons for including the experience factor. The study was undertaken as part of a larger project addressing the potential need for overall revision of US Army aviator strength and anthropometric selection criteria. Consequently, to assure the safety of all new student aviators, it was particularly important to determine if newly graduating (less experienced) aviators typically employed higher control force inputs during the execution of this simulated emergency condition than did more experienced aviators.

The strength capabilities of small males and females (Schopper and Mastroianni, 1985) exceeded the force inputs recorded in the present study for all controls except those in the downward direction on the collective. In this one exception inputs by less experienced aviators were lower than those of their more experienced counterparts. As a result the issue of experience is not considered of major importance in addressing strength related initial selection criteria.

The present findings offer little opportunity for comparison to other research because of the paucity of work which has been done in this field. The role of previous exposure to the task, i.e., practice effects, has been well documented. Textbooks on motor-behavior (e.g., Sage 1977) cite the early work of Snoddy (1926) and Crossman (1959) as examples of the performance enhancing effects of large amounts of exposure to a task. Snoddy's work demonstrated nearly linear increases in performance of a mirror tracing task over a period of 100 days. Crossman recorded decreases in machine cycle time for workers engaged in cigar making over a period of more than 7 years. Relatively long term practice effects on a motor task have also been demonstrated by Baddeley and Longman (1978) in their study of training schedule effects for typewriter keyboard inputs to a letter sorting machine. Practice entailed as much as 80 hours for some participants. Continuing improvement in performance was linearly related to the number of hours practice under all conditions.

While the research cited above demonstrates the improvement in performance that occurs with practice, the dependent variables employed did not address force requirements. Reviews of strength-related literature (e.g., Ayoub *et al.* 1981) cite literature which demonstrates the effectiveness of structured practice (weight training) in achieving greater force exertion capabilities. Continued improvement in force-related athletic events has also been demonstrated to increase over prolonged periods of time (e.g., Singer 1975, pp. 126-127). There is also research which examined the effect of training on the performance of gross motor tasks entailing some significant strength requirement; e.g., load-handling tasks (Shannon 1982). However, there is no relevant psychomotor task related literature known to the authors which has focused on the subject's adjustment to escalated force requirement as a function of continued performance of the task.

The findings of the present study reflect data collected from only one aircraft, the USAARL JUH-1H. We don't know if the hydraulics-off forces recorded were representative of other UH-1 aircraft since there are no previously published studies. However, it is the opinion of the laboratory's aviators that the forces which they experienced during these maneuvers with the USAARL aircraft were typical of those they have encountered in other UH-1s. To determine if the present JUH-1H findings are consistent with those from other Army UH-1Hs will require that data be obtained from a representative sample of these aircraft.

CONCLUSIONS

The findings of this study of the effects of aviator experience and hydraulic assist condition on the forces recorded during the last 60 seconds of normal, fully-assisted and hydraulics-off approaches and landings support the following conclusions:

1. During hydraulics-on approaches and landings the input forces were all less than the control force design limits cited in MIL-H-8501A with the exception of collective-related input forces. Forces exerted on the collective in both the up and down directions exceeded the relevant limits.

2. During hydraulics-on approaches and landings, the required input forces for controlled flight were all within the exertion capabilities of the 5th percentile Army male. These results correlate with those from an experiment involving small Army males and females (Schopper and Mastroianni, 1985).

3. During hydraulics-off approaches and landings, the mean, median, and peak input forces recorded were all within the upper limits cited in MIL-H-8501A for all controls except the collective. Mean and median collective input parameters were all within design limits. All peak 1 second values exceeded their respective MIL-H-8501A limits except the maximum upward input performed by more experienced aviators. The upper portion of the distribution of downward forces, in particular, exceeded both the design limits and force exertion capabilities of some Army females and small males (females more so than males).

4. While statistically significant main effects and interactions were encountered between more experienced and less experienced aviators, the differences were of little practical significance when compared with present MIL-H-8501A design limits and helicopter control force exertion capabilities of Army personnel.

5. Because no other relevant literature exists, it is not known how the hydraulics-off forces recorded with this laboratory's aircraft compare with those of other Army UH-1 aircraft. However, the aviator's who participated in our experiment indicated that the forces encountered during the experiment were not atypical of the other UH-1s which they have flown.

REFERENCES CITED

Ayoub, M. M., Gidcumb, C. F., Reeder, M. J., Beshir, M. Y., Hafez, H. A., Aghazadeh, F., and Bethea, N. J. 1981. Development of an atlas of strengths and establishment of an appropriate model structure. Lubbock, TX: Texas Tech University.

Baddeley, A. D., and Longman, D. J. A. 1978. The influence of length and frequency of training session on the rate of learning to type. Ergonomics, 21:627-635.

Cote, D. O., and Schopper, A. W. 1984. Anthropometric cockpit compatibility assessment of U.S. Army aircraft for large and small personnel wearing a cold weather, armored vest, chemical defense protective clothing configuration. Fort Rucker, AL: US Army Aeromedical Research Laboratory. USAARL Report No. 84-11.

Crossman, E. R. F. 1959. A theory of the acquisition of speed skill. Ergonomics, 2:153-166.

Department of Defense. 1961. Military specification: "Helicopter flying and ground handling qualities: general requirement for." Washington, DC: Department of Defense. MIL-H-8501A.

Department of the Army. 1981. Aircrew Training Manual: "Utility Helicopter." Washington, DC: Department of the Army. TC 1-135 *C1.

Department of the Army. 1960. Medical Services: "Standards of Medical Fitness." Washington, DC: Department of the Army. AR 40-501.

Jones, H. D., Lewis, J. A., and Higdon, A. A. 1983. Helicopter In-Flight Monitoring System Second Generation (HIMS II). Fort Rucker, AL: US Army Aeromedical Research Laboratory. USAARL Report No. 83-13.

Kirk, R. E. 1968. Experimental Design: Procedures for the Behavioral Sciences. Belmont, CA: Brooks/Cole Publishing Company, Inc.

Laubach, L. L. 1975. Muscular strength of men and women: a comparative study. Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory. AMRL-TR-75-32.

Newell, K. M. 1981. Skill learning. In D. H. Holding (Ed.), Human Skills (pp. 203-225). New York: John Wiley and Sons.

Rabbitt, P. M. A. 1981. Sequential reactions. In D. H. Holding (Ed.), Human Skills (pp. 153-174). New York: John Wiley and Sons.

Sage, G. H. 1977. Introduction to motor behavior: a neuropsychological approach. (2d Ed). Reading, MA: Addison-Wesley Publishing Company.

Schopper, A. W., and Cote, D. O. 1984. Anthropometric cockpit compatibility assessment of U.S. Army aircraft for large and small personnel wearing a training, warm-weather clothing configuration. Fort Rucker, AL: US Army Aeromedical Research Laboratory. USAARL Report No. 84-10.

Schopper, A. W., and Mastroianni, G. R. 1985. Helicopter-referenced single control, center-position force exertion capabilities of males and females. Fort Rucker, AL: US Army Aeromedical Research Laboratory. (In preparation)

Shannon, R. H. 1982. Biomechanical analysis of tasks involving materials handling. New Orleans, LA: US Naval Biodynamics Laboratory. NBDL 82R001.

Simmons, R. R., Lees, M. A., and Kimball, K. A. 1978. Visual performance/workload assessment of helicopter pilots during instrument flight. Fort Rucker, AL: US Army Aeromedical Research Laboratory. USAARL Report No. 78-6.

Singer, R. N. 1975. Motor learning and human performance. (2d Ed). New York: Macmillan Publishing Company.

Snoddy, G. S. 1926. Learning and stability. Journal of applied psychology, 10:1-36.

APPENDIX A

Equipment Manufacturers

Metraplex Corporation
590 Danbury Road
Ridgefield, CT 06877

Gould Industries
(formerly Systems Engineering Laboratories)
6901 West Sunrise Boulevard
Fort Lauderdale, FL 33313