TR-01-254

AD-720 252

HORIZONTAL STATIC FORCES EXERTED BY MEN STANDING IN COMMON WORKING POSITIONS ON SURFACES OF VARIOUS TRACTIONS-INCLUDING COEFFICIENTS OF FRICTION BETWEEN VARIOUS FLOOR AND SHOE MATERIALS

K. H. E. Kroemer, et al

Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base, Ohio

January 1971

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

AMRL-TR-70-114

HORIZONTAL STATIC FORCES EXERTED BY MEN STANDING IN COMMON WORKING POSITIONS ON SURFACES OF VARIOUS TRACTIONS

Including Coefficients of Friction Between Various Floor and Shoe Materials

K. H. EBERHARD KROEMER, DR. ING.
AEROSPACE MEDICAL RESEARCH LABORATORY

DANNY E. ROBINSON
ANTIOCH COLLEGE

JANUARY 1971

This document has been approved for public release and sale; its distribution is unlimited.

AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Federal Government agencies and their contractors registered with Defense Documentation Center (DDC) should direct requests for copies of this report to:

DDC
Cameron Station
Alexandria, Virginia 22314

Non-DDC users may purchase copies of this report from:

Chief, Storage and Dissemenation Section
Clearinghouse for Federal Scientific & Technical Information (CFSTI)
Sills Building
5285 Port Royal Road
Springfield, Virginia 22151

Organizations and individuals receiving announcements or reports via the Aerospace Medical Research Laboratory automatic mailing lists should submit the addressograph plate stamp on the report envelope or refer to the code number when corresponding about change of address or cancellation.

500 - MARCH 1971 - CO305 - 29-71-479

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP
N/A

3. REPORT TITLE
HORIZONTAL STATIC FORCES EXERTED BY MEN STANDING IN COMMON WORKING POSITIONS ON SURFACES OF VARIOUS TRACTIONS — Including Coefficients of Friction Between Various Floor and Shoe Materials

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
K. H. E. Kroemer and Danny E. Robinson*

6. REPORT DATE
January 1971

7a. TOTAL NO. OF PAGES
43

7b. NO. OF REFS
15

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 7184

c. Task No. 718408, Work Unit 718408007
Supported C5A System Program Office

d. Projec 410A

9a. ORIGINATOR'S REPORT NUMBER(S)
AMRL-TR-70-114

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES
*From Antioch College, Yellow Springs, Ohio

12. SPONSORING MILITARY ACTIVITY
Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, Oh

13. ABSTRACT

Experiments were conducted to measure maximal isometric horizontal push forces. Twenty-eight male subjects pushed forward with both hands, laterally with the preferred shoulder, and with their backs. Reaction force for body stabilization was provided by a vertical wall, a footrest, or by floor-shoe combinations with coefficients of static friction of approximately 1.0, 0.6, and 0.3. Means, standard deviations, and 5th percentiles of the exerted forces are reported. In comparing the experimental data with results previously published, it is concluded that body weight cannot serve as a reliable predictor for push force capability from floors of various tractions. Estimates for static horizontal push as well as pull force capabilities of one or several men are tabulated in relation to traction available to the operator. An appendix contains coefficients of static friction between nineteen floor materials and eight shoe materials.

DD FORM 1 NOV 65 1473

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Biomechanics						
Anthropology						
Push Forces						
Pull Forces						
Strength						
Muscle Strength						
Isometrics						
One-handed Push						
Two-handed Push						
Shoulder Push						
Back Push						
Body Support during Force Exertion						
Traction						
Coefficients of Friction						
Shoe Materials						
Floor Materials						

FOREWORD

This report was prepared by the Anthropology Branch, Human Engineering Division, of the Aerospace Medical Research Laboratory. The research was performed in support of Project 7184, "Human Engineering in Air Force Systems"; Task 718408, "Physical Anthropological Criteria for Air Force Systems Design"; Work Unit 718408007, "Biomechanics". The work supported the C5A System Program Office's Project 410A.

The authors are indebted to Mr. C. E. Clauser, Chief, Anthropology Branch; to their colleagues: Messrs. M. Alexander, J. W. Garrett, and K. W. Kennedy of the Anthropology Branch; and to Drs. J. T. McConville and L. L. Laubach of the Anthropology Research Project, Antioch College, Yellow Springs, Ohio, for sustained cooperation and helpful critique. Mr. J. L. Ferguson, Chief, Resources and Instrumentation Branch, Advanced Systems Support Division, Air Force Human Resources Laboratory, and his crew set up and maintained the recording system.

The authors gratefully acknowledge the continuous administrative support of the project and the constructive criticism of the final manuscript by Dr. M. J. Warrick, Associate Director, and Dr. J. M. Christensen, Director, Human Engineering Division of the Aerospace Medical Research Laboratory.

The technical report has been reviewed and is approved.

CLINTON L. HOLT, *Colonel, USAF, MC*
Commander
Aerospace Medical Research Laboratory

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

This report describes experiments designed to assess the horizontal push forces subjects can exert under various combinations of floor slipperiness and shoe-sole types.

This is a follow-up study of a previous series of experiments (Kroemer, 1969) concerned with push forces exerted in 65 common working positions. In these experiments, the subjects stood on nonslip floors or braced themselves against a rigid vertical surface while pushing. To allow comparisons of the force data, basically the same equipment was used and the subjects assumed some of the same body positions as in the "nonslip" experiments.

Previous experimental results (Fox, 1967; Kroemer, 1969; Snook, Irvine and Bass, 1969) are reviewed and combined to give an overview of the push forces exertable in common working positions by one or several operators, standing on various surfaces with different amounts of foot traction.

SECTION II

EQUIPMENT

The experimental equipment is shown in figure 1.

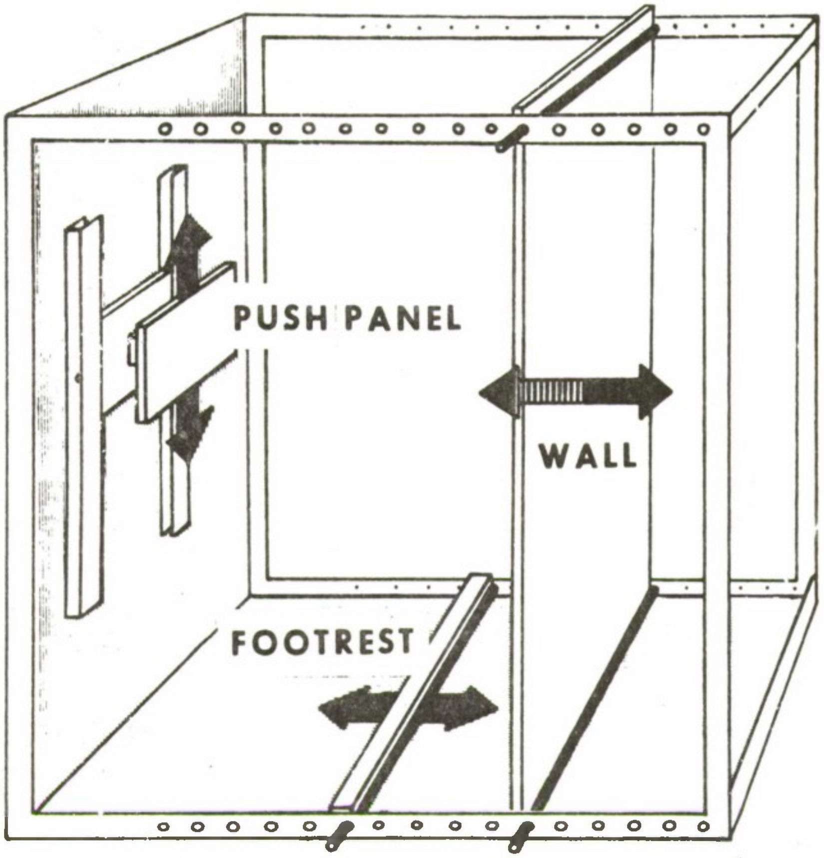


Figure 1. Experimental Equipment. Framework with push panel, footrest and wall. Arrows indicate adjustability.

1. The three-dimensional framework was constructed of 2.5 by 2.5 cm angle irons and was 230 cm long, 230 cm high, and 75 cm deep. The bottom and front were filled with plywood. Along the long sides of the framework, the horizontal angle irons at the bottom and at the top had holes 2 cm in diameter. Iron rods (1.5 cm diameter and 80 cm long) could be inserted in these holes horizontally and parallel to the front side of the frame. If only one rod was inserted into opposite holes of the bottom angles, a wooden footrest (61 by 6 by 6 cm) could be hooked to it; the footrest was designed to lie on the plywood "floor". If one rod each was inserted horizontally into two bottom and two top holes, respectively, a removable wall could be hooked onto the top rod to rest against the bottom rod so that it would not give way if pressed against. This wall, 61 cm wide and 215 cm high, consisted of reinforced plywood.

By means of the holes in the frame and the rods inserted into them, either the footrest or the wall could be adjusted in steps of 5 cm to distances from 25 to 200 cm from the stationary vertical plywood front.

2. The floor consisted of reinforced plywood, fitted loosely into the framework. It was supported at the front end (under the push panel) by one force transducer[1] and at the

[1] Alinco Load Cell Model 36-233-BAFB, max. load 300 pounds

rear by two transducers, one on each side. The transducer outputs, proportional to the force applied, were recorded separately on an 8-channel recorder[2]. The sum of the three transducers was recorded separately on a fourth channel.

3. The push panel consisted of two oval rings of stainless steel, mounted in parallel between two aluminum plates. These plates were 25 cm wide, 20 cm high, and 1 cm thick; the horizontal distance between the two outside surfaces was 14 cm. The subject pushed against one of the plates, which was covered with a rough, sturdy, linen cloth. The other plate slid between two U-shaped aluminum angles, bolted vertically to the rigid plywood which fills in the front side of the iron frame. By inserting pins into holes in one of the U-angles, the center of the protruding surface of the push panel could be adjusted in steps of 2 cm to heights between 35 and 160 cm above the floor.

Four strain gauges were glued to each steel ring. By means of the usual Wheatstone Bridge arrangement, deformation of the steel rings resulting from the force applied to the push panel was recorded on one channel of the recorder.

Due to design and arrangement of the measuring and recording systems, only horizontal forces perpendicular to the push panel and vertical forces perpendicular to the floor were recorded. After calibration of the recording system with lead weights, forces can be read in kiloponds[3] from the record. Readings are accurate to at least the nearest kilopond when the force is less than 100 kp; above 100 kp, readings are accurate to at least the nearest full 5 kp.

---

[2] Brush Mark 200, Model RF 1783-60

[3] Kilopond (kp, formerly called kilogram-force, kg_f) is the force which is exerted by a mass of 1 kg at standard gravity. One kp equals 2.205 pounds or 9.807 N (Newton).

SECTION III

EXPERIMENTAL CONDITIONS

BODY SUPPORT

In this study, two different conditions of support to the subject are distinguished:

(a) The subject stands on a flat horizontal floor. No vertical surfaces are provided against which he can anchor his body. Reaction to the push force he exerts is provided only by the friction between his shoes and the floor.

(b) In addition to the floor, vertical surfaces are provided against which he anchors his feet or braces his body, or both. Reaction to the push he exerts is partly, and sometimes only, provided by contact with the vertical surfaces perpendicular to the direction of push.

According to "action = reaction", the amount of reaction force available to the subject determines the amount of force he can exert; he cannot sustain any forces greater than the reaction forces available to him. If he stands on a flat floor—as in condition (a) —it is likely that the push force he exerts is not determined by his strength, but by his intention to prevent his feet from sliding on the floor so he won't fall. Under this condition, the exerted push force simply reflects the reaction force available to him at his shoes.

The horizontal reaction force, R, preventing the subject from sliding on the floor depends on the coefficient of friction, μ, between his shoes and the floor and also on the vertical force, F, pressing shoes and floor together (this force is partly generated by his weight): $R = \mu \cdot F$. Data for the coefficients of static friction μ between several floor and shoe sole materials are given in the appendix.

In this study, three different magnitudes of friction between the floor and the subject's shoes were investigated:

$\mu \backsim 1$: A soft rubber mat, about ¼-inch thick, on which it was virtually impossible to initiate sliding with any sole and heel materials used by the subject (see appendix).

$\mu \backsim 0.6$: Vinyl linoleum in combination with the smooth side of a 35 cm x 70 cm piece of sole leather[4]. The subject stood in his own shoes on the rough side of the leather. If sliding occurred, it happened between the linoleum and the leather, not between the leather and the subject's shoes.

$\mu \backsim 0.3$: Stainless steel in combination with the same 35 cm x 70 cm leather.

To compare the scores of the subjects in this experiment with those in the previous study (Kroemer, 1969), the wall and the footrest were used in some trials to provide unlimited reaction force as described below.

BODY POSTURE

Each subject exerted his push force in three basically different body postures and directions:

"Forward" The subject has both hands flat against the push panel. He stands on

[4] This was the same piece of leather from which the specimen had been cut to measure the coefficients of friction —see appendix.

one or both feet; if he uses both feet, they are at the same horizontal distance from the push panel.

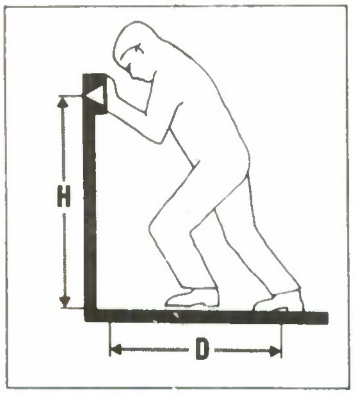


Figure 2. Forward push with both hands. Reaction force provided by friction. (D measured from the center of the shoe.)

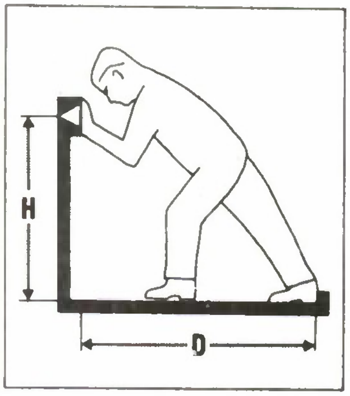


Figure 3. Forward push with both hands. Reaction force provided by a footrest. (D measured from the leading edge of the footrest.)

"Lateral" The subject has his preferred shoulder and upper half of his upper arm against the push panel. He stands on one foot, keeping the other off the floor.

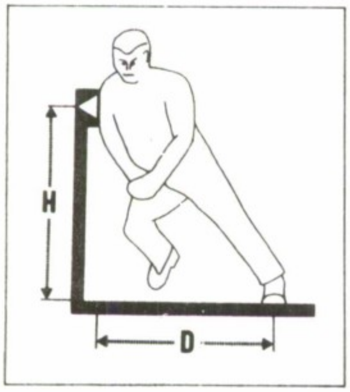


Figure 4. Lateral push with the preferred shoulder. Reaction force provided by friction. (D measured from the center of the shoe.)

Figure 5. Lateral push with the preferred shoulder. Reaction force provided by a footrest. (D measured from the leading edge of the footrest.)

"Backward" The subject exerts force against the push panel with any part of his back that he chooses. He braces himself with both feet which are at equal distance from the push panel.

Figure 6. Backward push with the feet flat on the floor. Reaction force provided by friction. (D measured from the center of the shoe.)

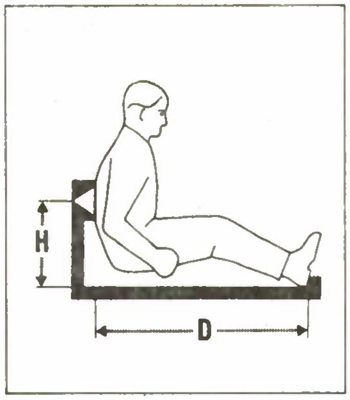


Figure 7. Backward push with the heels against a footrest. (D measured from the leading edge of the footrest.)

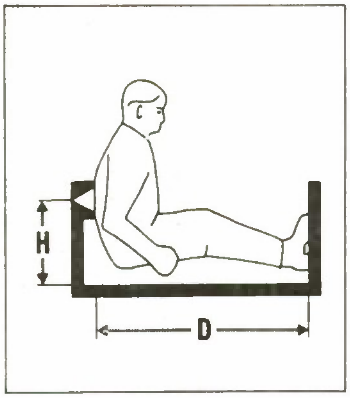


Figure 8. Backward push with the feet flat against a vertical wall. (D measured from the leading edge of the wall.)

In each of these positions, the subject exerted his push force using either the steel-leather ($\mu \backsim 0.3$) or the linoleum-leather combination ($\mu \backsim 0.6$), or standing on the rubber pad ($\mu \backsim 1$). When using any of the three shoe-floor combinations, he first tried out various heights (H) of the push panel until he found the height that was the most efficient and convenient for force exertion. Similarly, he also selected the preferred distance (D) between the push panel and his feet. The selected locations of the panel and the subject's foot or feet were recorded.

When the footrest or the wall was used as an anchor, the height (H) of the center of the push panel, and the horizontal distance (D) between the push panel and the front surface of the footrest or wall were set to predetermined values, which had been found most advantageous in the previous study (Kroemer, 1969). The particular value used was related to the individual's body dimensions as follows:

Forward Push (with footrest)
- H = 70% of Acromial Height[5]
- D = 80% of Acromial Height

Lateral Push (with footrest)
- H = 60% of Acromial Height
- D = 80% of Acromial Height

Backward Push (with footrest and wall)
- H = 40% of Acromial Height
- D = 100% of Thumb-Tip Reach[5]

These adjustments allowed direct comparisons of the subjects' performances in this and the previous study. The use of the footrest as well as the rubber pad, both assumed to exclude any sliding of the subjects while pushing, allowed the experimenter to check the effectiveness of either footing. Backward pushes were also performed with the subject braced against wall or footrest to check their effectiveness as anchoring surfaces. In all, each subject had to exert force under 13 experimental conditions.

---

[5] The anthropometric data are explained in detail by Kroemer (1969).

SECTION IV

PROCEDURE

The experiments were conducted in an air-conditioned room in which only the experimenters and one subject were present.

When the subject first came to the laboratory, his body dimensions were measured. The purpose and procedure of the experiments were explained and the following text was read to him and, if necessary, explained:

"(a) If you have any disabilities such as hernia, damages to muscles, or any other disabilities that might have any bearing on the experiment, please tell me now." (The subjects had been prescreened; this was simply an added precaution.)

"(b) Although it is intended to measure maximal forces, and although you are encouraged to exert your maximal force, you are urged to take all precautions not to hurt yourself."

"(c) Push as hard as possible, but do not hurt yourself."

Using a table of random numbers, a sequence of 13 trials, one under each condition, was established.

On each trial, the experimenter told the subject which body posture to use and which parts of the body, if any, to brace against the wall or the footrest. He told the subject that the palms must be flat against the push panel when pushes were to be exerted with the hands. The experimenter made it clear to the subject that, within the given limits, he was free to choose any variation in body posture that seemed to be most appropriate.

In nine of the trials, the subject was free to choose the height of the push panel and the distance he stood from the panel so that he "felt comfortable and able to exert his strongest push." For the height adjustment, the experimenter first raised the push panel to positions obviously too high or too low, and then to a position somewhere in between these extremes, and in each condition, asked the subject to assume a push posture. Then, as the subject acquired an understanding for the effects of the panel height, the experimenter adjusted the panel as directed by the subject. For the experiments with footrest or wall, the experimenter set the distance from the push panel, and the height, to the predetermined values.

The subject was advised to push so hard that he "almost slipped" on the steel, linoleum, or rubber pad floor. During the period of adjusting the push panel and selecting the footing, the subject tried to get a feeling for when sliding would occur, if at all. For the lateral and backward pushes, a simple harness (weave belt) was loosely placed around the subject's chest, under his arms, and attached to a slack chain hanging from the ceiling. Without hindering him, this harness was designed to catch the subject should he slide or be in danger of falling.

The subject was not only encouraged to try as many positions of the panel and of this foot (feet) as he wished, but could even rerun a trial (immediately or later, at his discretion) if he felt that he could have "done better" with another arrangement of panel, foot position or body posture, or both. However, only two reruns were actually requested.

When the subject had assumed the appropriate body posture, he was given an oral countdown two seconds before the start signal, upon which he began to place force upon the push panel. During the actual push period, the experimenter counted aloud each second until the fifth, after which the subject held the position briefly without trying to push, and then relaxed. Every subject exerted his maximal push force once under each of the experimental conditions.

The subjects had been told that they should maintain a maximum push force steadily over the 5-second period; and that short-time peak forces were not desired. After a build-up of force during the first second, a rather constant force level was generally observed until the force dropped during the last second. The subject's score ("P" in table II, page 11) was obtained by reading the mean force applied during the third second (Kroemer and Howard, 1970). For the forces at panel and floor while the subject just maintained his position after the 5-second push period ("p" and "f" in table II, page 11), values were averaged over one second.

Each subject completed the 13 trials during a 2-hour session. Since force had to be exerted for only 5 seconds per trial and since ample time for rest and recovery was provided between trials, muscle fatigue (Caldwell, 1961, 1964; Rohmert, 1960, 1961) was averted.

Although the experimenter expressed his appreciation for the subject's cooperation, he did not encourage the subject to make any extreme efforts. After each experiment, the subjects were allowed to look at the force recording, but they did not get immediate feedback while exerting force. A friendly but businesslike atmosphere prevailed throughout the experimental session. There were no verbal exhortation, competition, rewards, spectators, danger of injuries, or other stimulating or restraining motivational factors (Kroemer and Howard, 1970).

The experimenter noted on the recorded strip chart the height (H) to which the push panel was actually set (either following the subject's directions or according to the preselected portion of his Acromial Height). He also noted the horizontal distance (D) between the vertical surfaces of the push panel and the subject's load-bearing foot, or, if used, the predetermined distance to the footrest or wall. The experimenter also recorded the horizontal distance (A) between the push panel and the center of mass of the subject's body in the push position. The location of the center of mass was estimated according to Santschi et al. (1963).

To test the significance of observed differences between experimental results, two-tailed t-tests were performed. The null hypothesis was rejected if the t-value was beyond the 5% limit.

SECTION V

SUBJECTS

Twenty-eight male students from the University of Dayton, Dayton, Ohio, served as subjects. They took part voluntarily and were paid by the hour. The experimenter did not attempt to select certain subjects, but none were admitted with a history of hernia, muscle rupture, or other factors that could have affected exertion of push force.

On each of the subjects, 12 body dimensions or characteristics were obtained; also noted were age, handedness, and shoe size.

In table I, the anthropometric data of the 28 subjects are listed together with the corresponding dimensions of the 45 male subjects used in the previous study and of 2420 rated officers of the United States Air Force.

TABLE I

ANTHROPOMETRIC DATA OF THE SUBJECTS AS COMPARED WITH USAF MALE OFFICER PERSONNEL

Items Measured	*Unit of Measurement*	*28 Male Subjects*		*45 Male Subjects (Kroemer, 1969)*		*2420 Male Rated USAF Officers**	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
1 Weight	kg	77.4	11.0	76.5	11.1	78.7	9.7
2 Grip Strength I	N†	487.4	100.2	538.4	74.5	553.1	74.5
3 Stature	cm	176.3	6.8	177.4	5.1	177.3	6.2
4 Acromial Height, Right	cm	144.3	6.3	145.8	4.6	145.2	5.8
5 Grip Strength II	N	490.3	86.3	543.3	79.4	—	—
6 Lateral Thumb-Tip Reach	cm	108.5	4.1	108.9	4.0	—	—
7 Thumb-Tip Reach	cm	82.1	4.3	82.2	4.4	80.3	4.0
8 Sitting Height	cm	92.0	3.1	91.8	3.2	93.2	3.2
9 Triceps Skinfold, Right	cm	1.6	0.7	1.4	0.5	1.3	0.5
10 Juxtanipple Skinfold, Right	cm	1.3	0.7	1.8	0.7	1.4	0.7
11 Subscapular Skinfold, Right	cm	1.6	0.7	1.5	0.6	1.4	0.5
12 Grip Strength III	N	475.6	96.1	545.2	78.5	—	—
13 Shoe Size	—	9.9	1.4	—	—	—	—
14 Age	years	20.6	1.7	20.7	1.7	30.0	6.3
15 Handedness: Right	%	85	—	84	—	89	—
Left	%	15	—	13	—	9	—

*Clauser, C. E., et al., Anthropometry of Air Force Rated Officers—1967, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio. unpublished data.

†Newton. 1 N equals 0.225 lb.

SECTION VI

RESULTS

The results of the experiments are presented in tables II, III, and IV.

In each of the tables, the experimental conditions and results are indicated in the same manner. Illustrated by sketches of the body postures used, it is indicated:

(a) In which direction (e.g., forward) and with which part of the body (e.g., with both hands) the subject applied force to the push panel

(b) Which specific requirements were imposed on the subject (e.g., keep both palms flat on the plate)

(c) Whether the subject stood on the floor (and which coefficient of friction prevailed) or whether reaction force was provided by footrest or wall.

For each experimental condition, the mean push force (P) is given as well as the number (n) of subjects participating, the standard deviation (SD), and the estimated 5th percentile force (mean − 1.65 SD). Also given are the height adjustments (H) of the push panel over the floor, and the horizontal distance (D) between the panel and the location of the subject's supporting foot (feet), or footrest, or wall. In addition, the tables contain the values of the force (F) transmitted vertically to the floor by the subject's feet while exerting his maximal push force, and the horizontal force (p) on the push panel and the simultaneous vertical force (f) transmitted to the floor while the subject briefly maintained his body posture after the active force exertion. Finally, the tables list the horizontal distance (A) between push panel and the center of mass of the subject's body during exertion of his maximal push force.

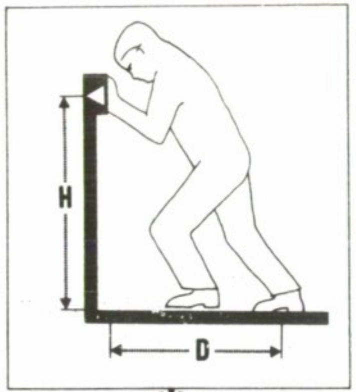
Brief commentaries follow tables II, III, and IV.

FORWARD PUSH

Comments

The mean horizontal push forces increase with increasing friction (reaction force) available to the subject: When standing on the slippery steel floor, the subjects could exert on the average about 210/Newton, on the nonslip rubber pad about 460 N, and when using the footrest almost 530 N. However, with the footrest, the variability of the force data increased so much that the 5th percentile force, calculated from the mean and standard deviation, was numerically lower than calculated for the nonslip rubber pad ($\mu \sim 1$) as a floor covering. Thus, at least in this experiment, free selection of foot positions on the rubber pad resulted in more uniform force data than the use of a footrest in a predetermined location.

The subjects selected lower adjustments of the push panel, and positioned their feet farther from the push panel when the traction was greater. The forces registered on push panel and floor while the subjects continued to maintain their body position following each trial, and the changes in location of the center of mass of the body, also indicate that the subjects leaned more forward with the less slippery conditions. This is certainly in accordance with common experience.



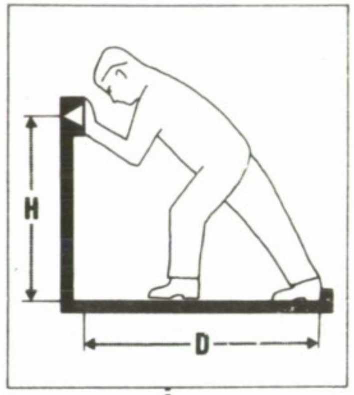


TABLE II—FORWARD PUSH

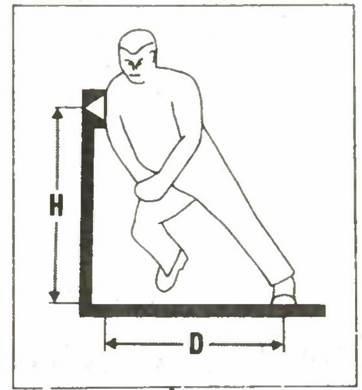
Both hands are flat against the push panel. Supporting foot must be flat on the floor. If the subject stands on both feet, they must be at the same distance from the panel.

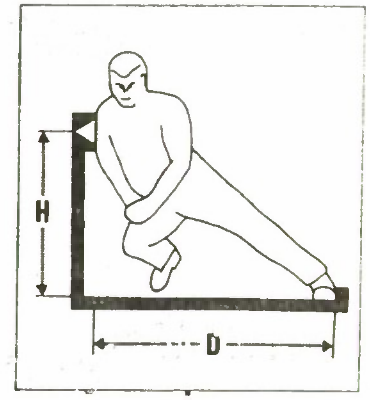
		$\mu \approx 0.3$	$\mu \approx 0.6$	$\mu \approx 1$	*Footrest*
MAXIMUM STATIC PUSH FORCE exerted horizontally at the panel; P in Newton (and kp)	Mean	211.8 (21.6)	297.1 (30.3)	462.9 (47.2)	527.6 (53.8)
	n	27	28	27	26
	SD	46.78 (4.77)	65.12 (6.64)	119.15 (12.15)	178.68 (18.22)
	5th %	134.4 (13.7)	189.3 (19.3)	265.8 (27.1)	232.4 (23.7)
HEIGHT of the center of the push panel; H in cm	Mean	129.6*	125.7*	120.6*	101.0†
	SD	9.20	10.44	13.68	4.38
Horizontal DISTANCE push panel—footing; D in cm	Mean	61.5*	70.4*	94.4*	115.3‡
	SD	14.45	16.76	23.79	25.11
Vertical force on the floor while exerting P; F in Newton	Mean	896.3	901.2	948.3	903.2
	SD	114.35	122.86	139.84	268.80
Horizontal force on the push panel while maintaining position; p in N	Mean	147.4	185.3	282.9	302.9
	SD	46.84	47.86	75.61	92.97
Vertical force on the floor while maintaining position; f in Newton	Mean	821.9	782.1	788.9	731.7
	SD	102.19	108.36	119.35	111.60
Horizontal distance push panel—center of body mass; A in cm	Mean	44.6	46.8	58.4	61.0
	SD	13.03	13.52	18.53	12.26

* As selected by each subject.
† Predetermined: 70% of each subject's acromial height.
‡ Predetermined: 80% of each subject's acromial height.

TABLE III—LATERAL PUSH

The subject pushes with his shoulder/upper arm against the push panel. Supporting foot must be flat on the floor, the other lifted off the floor.



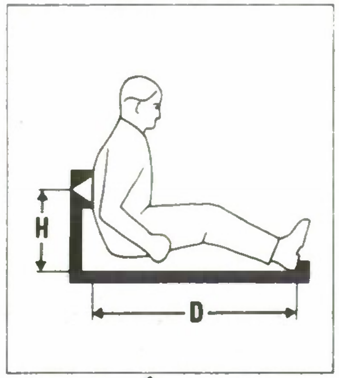


		$\mu \sim 0.3$	$\mu \sim 0.6$	$\mu \sim 1$	*Footrest*
MAXIMUM STATIC PUSH FORCE exerted horizontally at the panel; P in Newton (and kp)	Mean	201.0 (20.5)	303.0 (30.9)	459.9 (36.9)	813.0 (82.9)
	n	27	27	28	26
	SD	40.60 (4.14)	63.55 (6.48)	157.59 (16.06)	209.07 (21.32)
	5th%	134.4 (13.7)	198.1 (20.2)	200.1 (20.4)	468.8 (47.8)
HEIGHT of the center of the push panel; H in cm	Mean	125.5*	122.5*	118.5*	86.4†
	SD	9.26	8.76	11.87	4.00
Horizontal DISTANCE push panel—footing; D in cm	Mean	53.6*	61.4*	73.0*	115.3‡
	SD	10.10	8.93	13.25	5.11
Vertical force on the floor while exerting P; F in Newton	Mean	864.0	911.0	987.5	916.9
	SD	112.29	132.88	166.71	166.42
Horizontal force on the push panel while maintaining position; p in N	Mean	171.4	241.8	320.8	571.3
	SD	39.81	51.29	98.07	95.12
Vertical force on the floor while maintaining position; f in Newton	Mean	824.5	816.4	823.8	781.1
	SD	105.52	115.33	122.88	116.01
Horizontal distance push panel—center of body mass; A in cm	Mean	30.5	28.7	31.0	43.6
	SD	7.05	5.59	6.38	5.28

* As selected by each subject.
† Predetermined: 60% of each subject's Acromial Height.
‡ Predetermined: 80% of each subject's Acromial Height.

TABLE IV—BACKWARD PUSH

The subject decides with which part of his back to push. Supporting feet must be flat on the floor or propped against footrest or wall.



		$\mu \infty 0.3$	$\mu \infty 0.6$	$\mu \infty 1$	*Footrest*	*Wall*
MAXIMUM STATIC PUSH FORCE exerted horizontally at the panel; P in Newton (and kp)	Mean	188.3 (19.2)	309.9 (31.6)	587.4 (59.9)	1380.8 (140.8)	2363.4 (241.0)
	n	27	28	27	28	27
	SD	36.87 (3.76)	58.15 (5.93)	154.65 (15.77)	391.09 (39.88)	869.26 (88.64)
	5th%	127.5 (13.0)	213.8 (21.8)	332.5 (33.0)	735.5 (75.0)	929.7 (94.8)
HEIGHT of the center of the push panel; H in cm	Mean	110.0*	104.8*	94.5*	57.8†	57.8†
	SD	13.08	13.88	13.56	2.64	2.64
Horizontal DISTANCE push panel—footing; D in cm	Mean	43.1*	53.0*	69.1*	90.3‡	90.3‡
	SD	9.27	7.47	10.54	4.90	4.90
Vertical force on the floor while exerting P; F in Newton	Mean	875.7	886.5	1030.7	NA	NA
	SD	111.80	133.17	149.55		
Horizontal force on the push panel while maintaining position; p in N	Mean	160.8	250.1	398.1	870.0	NA
	SD	41.58	57.37	97.18	188.19	
Vertical force on the floor while maintaining position; f in Newton	Mean	827.7	804.8	834.6	NA	NA
	SD	104.24	119.64	103.46		
Horizontal distance push panel—center of body mass; A in cm	Mean	18.2	20.25	21.8	21.6	NA
	SD	3.27	3.44	3.13	3.97	

* As selected by each subject.
† Predetermined: 40% of each subject's Acromial Height.
‡ Predetermined: 110% of each subject's Thumb-Tip Reach.

LATERAL PUSH

Comments

The mean horizontal forces exerted at the push panel increase consistently from about 200 to more than 800 N with increasing friction (resistance) available to the subject. Accordingly, the 5th percentile forces are also lowest when the subject stands on the very slippery steel floor, increase to about the same level with the less slippery linoleum and rubber floor materials, and reach a peak value when the footrest is used for anchoring the feet. Several subjects complained about the rather awkward position of the foot in transmitting force to the floor. Lateral bending at the ankle joint, necessary to keep the sole flat on the floor, was uncomfortable, almost painful. This may explain the rather large standard deviation and small mean force exerted while standing on the rubber pad.

Lower push panel adjustments and foot positions farther from the panel were selected with increasing friction available on the different floor coverings. This trend is also apparent through the forces recorded at the panel and the floor when the subjects just maintained their positions without actively exerting a force. The footrest provided the most secure anchor for the subjects' feet, thus allowing a pronounced leaning posture, and exertion of the strongest push.

BACKWARD PUSH

Comments

The mean push force increases significantly from about 190 N with the steel floor to about 310 N with the less slippery linoleum to almost 590 N with the skid-resistant rubber pad. Anchoring the feet at the footrest more than doubles the force capability, while another large increase to about 2360 N occurs when the feet are propped against the vertical wall. The 5th percentile forces follow that pattern.

On the slippery steel floor, the subjects selected rather high adjustments of the push panel and stood close to it. With more skid-resistant floor materials, the subjects selected lower panels and placed the feet farther away. The forces recorded while the subjects just maintained their body posture also clearly reflect the changes in adjustments and posture according to the frictional resistance (reaction force) offered.

SECTION VII

DISCUSSION OF THE RESULTS

In the following, the experimental results are discussed in the light of previously published findings as well as with respect to the effectiveness of body support and body posture employed. The relationship between exerted force and body weight is investigated in some detail.

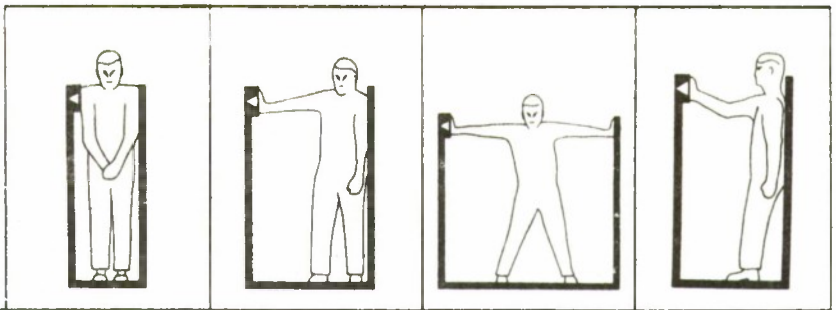
General Comparison with Other Experiments

The experiments reported here were designed to be comparable with those conducted previously (Kroemer, 1969) with subjects exerting their maximal forces while anchoring their body at a footrest or wall (see figures 9, 10, and 11). Origin and physical dimensions of the subjects in both studies are comparable. The experiments were conducted in the same laboratory, using essentially the same equipment and about the same techniques. The main differences lay in the use of some shoe/floor combinations with small coefficients of friction in this study. Hence, the experimenter and subjects were cautious to avoid accidents on the slippery floors.

		
HEIGHT ADJUSTMENTS **of the push panel**	**70*, 80, 90%**	**60*, 70, 80%**
	of the individual Shoulder Height (Acromial Height) of the subjects	
DISTANCE ADJUSTMENTS **between the push panel** **and the footrest**	**70, 80*, 90%**	**60, 70, 80*, 90%**
	of the individual Acromial Height of the subjects	

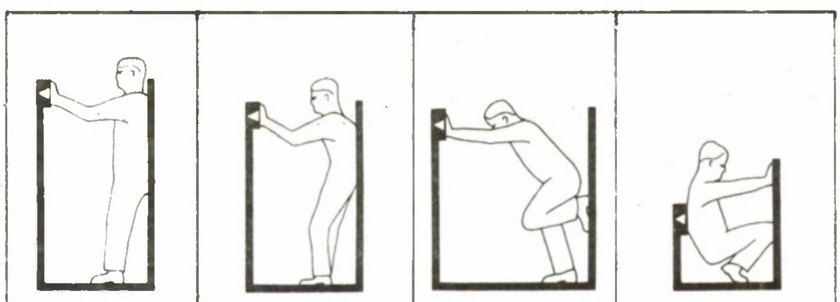
* Similar to the experimental conditions in this study.

Figure 9. Push force exertion with hands or shoulder while anchoring the feet at a footrest (Kroemer, 1969).



HEIGHT ADJUSTMENT of the push panel	100%	100%	100%	100%
	of the individual Shoulder Height (Acromial Height) of the subjects			
DISTANCE ADJUSTMENTS between the push panel and the wall	80, 90, 100% of Shoulder (Bideltoid) Breadth	50, 60, 70, 80, 90, 100% of Lateral Thumb-tip Reach	50, 60 70, 80, 90% of Span	50, 60, 70, 80, 90, 100% of Thumb-tip Reach

Figure 10. Push force exertion with one shoulder or one hand while braced against a vertical wall (Kroemer, 1969).



HEIGHT ADJUSTMENTS of the push panel	100%	90%	50, 70, 90%	40%*
	of the individual Shoulder Height (Acromial Height) of the subjects			
DISTANCE ADJUSTMENTS between the push panel and the wall	50, 60, 70, 80, 90, 100%	70, 80, 90, 100 110, 120%	80, 100, 120% of Acromial Height	80, 90, 100, 110*, 120, 130% of Thump-tip Reach
	of Thumb-tip Reach			

* Similar to the experimental conditions in this study.

Figure 11. Push force exertion forward and backward while braced against a vertical wall (Kroemer, 1969).

When comparing the mean forces exerted by the subjects while bracing themselves against wall or footrest, no statistically significant differences are apparent between the scores of the experiments in either the backward or the lateral exertion. In the forward leaning position, however, the subjects in the present study exerted significantly less force (530 versus 690N) although the height adjustments for the push panel and the distance adjustment for the footrest were principally the same as in the previous experiments. The difference may be due, at least in part, to the requirement in this study either to stand only on one foot (which most of the subjects did) or to have both feet flat on the floor at the same distance from the push panel. Neither posture may be assumed naturally when the subject tries hard to exert a maximal push force. Generally, however, the present study indicates the same trends in body posture/force capability relationship as the previous experiment.

In an elaborate experiment, Fox (1967) had 100 male subjects (age 16 to 20 years) exert maximal isometric push forces of about 5 seconds against a vertical plywood board. The subjects placed either both hands against the board (forward push) or pushed laterally with one shoulder against the board, or pushed backwards. They stood on an aluminum floor, with the coefficients of static friction μ between their shoe soles and the floor between 0.26 and 0.50. In another part of the experiment, 52 of the subjects could brace their shoes against the rungs of a wooden ladder lying flat on and anchored to the floor. (The rungs were about 1 inch in diameter, and spaced 13 inches apart.) The subjects, free to assume the most appropriate body position, exerted the scores listed in table V. Also listed are the comparable results obtained in this study.

All of Fox's and our mean scores are significantly different from each other. When standing on the metal floors, Fox's subjects exerted substantially larger forces than our subjects in either forward, lateral, or backward pushes. Since, on slippery floors, the existing

TABLE V

MEAN AND 5TH PERCENTILE FORCES (IN NEWTON) EXERTED IN FOX'S (1967) AND THIS STUDY

Direction of Force Exertion		*Subjects Standing on Metal Floors*		*Subjects Anchoring Their Feet*	
		$0.26 < \mu < 0.50$ Fox (1967)	*$\mu \backsim 0.3$ This Study*	*At Rungs Fox (1967)*	*At Footrest This Study*
FORWARD	Mean	500.1	211.8	954.5	527.6
	5th %	341.9	134.4	469.2	232.4
	N	100	27	52	26
	SD	95.9	46.8	294.1	178.7
LATERAL	Mean	463.7	201.0	1004.0	813.0
	5th %	287.0	134.4	395.7	468.8
	N	100	27	52	26
	SD	107.1	40.6	368.9	209.1
BACKWARD	Mean	460.1	188.3	1213.5	1380.8
	5th %	251.2	122.5	719.3	735.5
	N	100	27	52	28
	SD	126.6	36.9	299.5	391.1

friction between shoe and floor limits the applicable force, it is rather obvious that in Fox's study a larger coefficient of friction prevailed than in our experiment. Inherent muscular strength of the subject samples does not seem to differ: When anchoring their feet at the ladder rungs, Fox's subjects applied more force in lateral pushes but less force in backward pushes than our subjects braced against the footrest.

Fox's comprehensive study also contains data on the forces exerted by several operators pushing at the same time. His data indicated that the forces exerted by each operator can simply be added for the combined push capability of up to three people pushing simultaneously. However, with a fourth or fifth operator increasingly less force is added. According to Fox, interactions among more than three pushers seem to negate some of the expected advantage of adding more men.

Effectiveness of Body Support and Body Posture

The steel-leather combination ($\mu \backsim 0.3$) allowed exertion of only very weak push forces, with the average at about 200 N for each body position. The linoleum-leather combination ($\mu \backsim 0.6$) increased the mean force to a rather uniform 300 N with no significant differences among the body positions employed. When the rubber pad ($\mu \backsim 1$) was used, the force output of about 460 N in the lateral and forward exertion was significantly larger than on the more slippery floors. The mean back push of about 590 N is significantly different from the other results.

The rubber pad prevented sliding of the leather sole only as long as the force (F) normal to the surface multiplied by the coefficient of friction μ, was definitely and continuously larger than the force (P) parallel to the surface. The subjects seemed to keep $F \cdot \mu$ above P by a rather large margin. The footrest, in contrast, prevented sliding of a shoe braced against it under any circumstances. Anchoring their feet at the footrest, which is physically and psychologically "safer" than the rubber pad, enabled the subjects to exert significantly larger forces.

In accordance with previous findings (Kroemer, 1969), the forward exertion from a footrest yielded the lowest mean scores of almost 530 N; the lateral exertion was significantly more effective resulting in about 810 N; while the back push allowed a significantly more forceful exertion of almost 1400 N. "Wedging" the body between the vertical surfaces of push plate and wall increased the effectiveness of the back push to an average of almost 2400 N.

The results indicate that with very low reaction force available to the subject (here: $\mu \leqslant 0.6$), differences among the force effectiveness of body postures employed become insignificant. With little traction available, any body posture allows application of only very weak pushes. With high friction, however, as with the rubber pad, and even more with virtually unlimited reaction force available at the footrest or wall, the effectiveness of the three body postures employed proves to depend on biomechanical principles described previously (Kroemer, 1969): In the forward leaning position, the bent arms constitute weak links in the flow of force vectors between push plate and floor through the operator's body. Elimination of the weak components in the laterally inclined posture significantly increases the force capability. Utilization of the strong leg extensors in the back push is even more effective. The maximal force is exerted when the flow of force vectors is about horizontal between the push panel and the opposite wall.

Fox (1967) had observed that his subjects, free to choose the subjectively appropriate body posture, selected different foot positions when either standing on a low-friction floor or anchoring the feet at a rigid surface. The results of this study confirm Fox's observation. With the coefficient of friction increasing from 0.3 to 0.6 to 1, our subjects monotonously increased the distance of the footing from the push panel. With increasing horizontal distance between panel and supporting feet, the subjects also consistently selected lower adjustments of the push panel. In other words, the higher the skid resistance, the more steeply the subjects leaned towards the push panel. However, even with the nonskid rubber pad they did not reach the low adjustment and the distant spacing of the panel previously found (Kroemer, 1969) to allow the largest force exertion with the (absolutely skid-proof) footrest or wall as anchor grounds.

The forces exerted by the subjects standing on the steel floor ($\mu \backsim 0.3$) are remarkably consistent in all three body positions: The means are about 200 N, the fifth percentiles about 140 N. The same uniformity exists among the forces exerted while standing on the linoleum ($\mu \backsim 0.6$). The means are at 300 N for any body position, the fifth percentiles stand at 200 N.

Considerable scattering of the force data occurs in the forward and lateral pushes executed when standing on the rubber pad ($\mu \backsim 1$) or when using the footrest. Some rather low scores may be due to an unusual and uncomfortable leg and foot positioning, as discussed before, or to a fear of possible sliding and falling. During the back pushes, which are uniformly strong and change consistently with the reaction force available, the subjects were secured by the safety harness when using the rubber pad, and had their feet in a more natural position when braced against the footrest.

Obviously, there are two distinct conditions under which the exertable forces are rather well defined: Slippery floors, with $\mu \leq 0.6$, constitute one condition. Here the force exertable is limited by the frictional resistance available to the subject, and not by his inherent muscular strength. Consequently, the forces measured stay below a certain level. Rigid surfaces (like footrest and wall), against which the subject can brace himself, constitute the other condition. In this case, the exertable force depends primarily on his muscle strength and his skill to exert the inherent strength. Thus, the forces measured in this study and in the previous ones (Fox, 1967; Kroemer, 1969) are in agreement—obviously, because the subject populations were similar in skill and strength. Between these extreme conditions lies a "gray area" of high-traction floor where the coefficient of friction approximates unity. Here, the force exertable depends on the actual friction (which may change easily), on the subject's skill and willingness to use the existing friction completely, and on his strength.

Evaluation of relations between push force capability (in several body positions) and the amount of reaction force available to the subject, therefore, should be based primarily on the data obtained when he is standing either on the slippery floors or when braced against footrest and wall.

In terms of 5th percentile values, the following minimum push forces, rounded to convenient numbers, should be exertable by one operator:

In any of the employed body positions and with low traction

($0.2 < \mu < 0.3$) : 100 N or 25 lb.

If the operator can anchor his feet securely at a suitable immobile obstacle (like a footrest), or if he can brace himself against a wall:

500 N (110 lb) in lateral or two-handed forward pushes,
750 N (165 lb) in backward pushes.

For medium traction ($\mu \backsim 0.6$), 200 N (or 45 lb) appears to be a reasonable estimate, while for high traction ($\mu \backsim 0.9$) about 300 N (or 70 lb) may be assumed.

Body Weight and Exerted Force

Among anthropometric dimensions, body weight is commonly considered to be rather closely correlated to muscular capabilities. Laubach (1969) conducted a study on body composition and muscle strength. He found that weight (also stature and lean body mass) yielded positive zero-order correlations to measures of strength. However, the highest correlation coefficient was only 0.52. When using this value to predict strength from weight, it would account for only about $0.52^2 \backsim 1/4$ of the variance in strength. In a related paper by Laubach and McConville (1969), weight was found to yield simple correlations of not more than 0.53 between weight and measures of strength. The authors conclude that, for most practical purposes, weight (and the sixteen other anthropometric variables used in their study) do not appear to be effective predictors of static strength.

TABLE VI

CORRELATION COEFFICIENTS BETWEEN WEIGHT AND PUSH FORCE EXERTED

Type of force exertion		*Reaction force provided by*		*Pearson's Correlation Coefficients*
FORWARD PUSH	n = 27	Friction:	$\mu \backsim 0.3$	0.70
	n = 28		$\mu \backsim 0.6$	0.76
	n = 27		$\mu \backsim 1.0$	0.51
	n = 26	Footrest		0.34
LATERAL PUSH	n = 27	Friction:	$\mu \backsim 0.3$	0.62
	n = 27		$\mu \backsim 0.6$	0.67
	n = 28		$\mu \backsim 1.0$	0.43
	n = 26	Footrest		0.43
BACKWARD PUSH	n = 27	Friction:	$\mu \backsim 0.3$	0.62
	n = 28		$\mu \backsim 0.6$	0.58
	n = 27		$\mu \backsim 1.0$	0.49
	n = 28	Footrest		0.51
	n = 27	Wall		0.57

In our study, the correlation coefficients between the subjects' body weight and the forces they exerted at the push panel vary with the body position employed and with the amount and kind of reaction force provided. Table VI lists the correlation coefficients. The highest coefficients appear when the subject leaned towards the push panel while standing on the more slippery floors. The correlations are smaller when a nonskid floor material (rubber pad, $\mu \backsim 1$) was used or when the feet were anchored at a rigid surface. Body weight helps to increase the resistance to sliding on the flat floors. If the feet are anchored at a wall or footrest, however, body weight pressing the feet onto the ground is much less important for body stabilization.

In most studies on muscle strength and body dimensions, body weight is not the critical source of the reaction force counteracting the force actively exerted. In Fox (1967) and this study, however, body weight does greatly contribute to the reaction force available to the subject at his feet when standing on the more or less slippery floor materials. In fact, Fox initially tried to relate the push forces exertable to body weight and the prevailing coefficient of friction. He states, however, "Relating body weight and friction alone does not produce results which are indicative of actual [push force] capability" (Fox 1967, p. 23)

In our study, we measured the vertical force transmitted to the floor with the feet in addition to the horizontal push force exerted. Tables II, III, and IV show that this vertical force was in every case larger than the subject's body weight. This held true during the period of active muscle contraction and also when the subjects just maintained their body positions. Obviously, while exerting horizontal force at the push panel, the subjects also applied an upward force component to the panel and, as a result, pressed down with their feet.

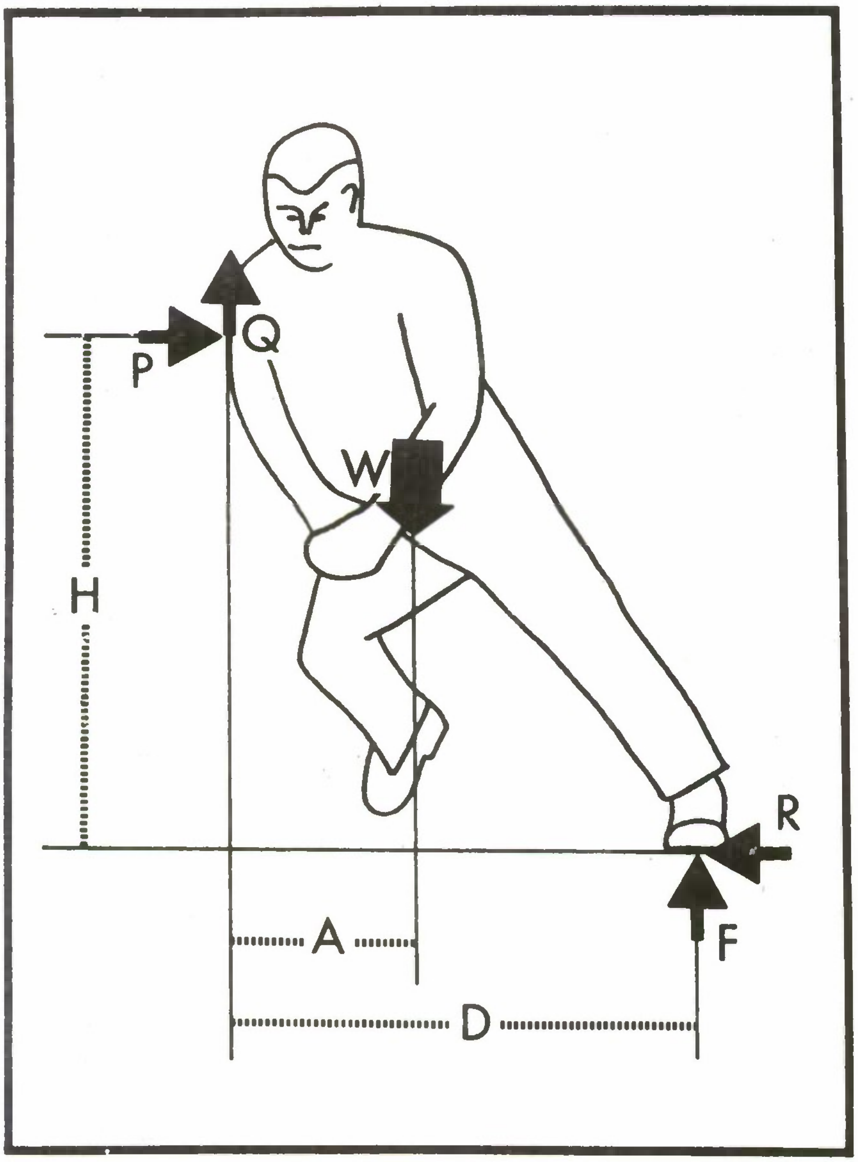


Figure 12. Force vectors and their relative locations.

Figure 12 illustrates some dimensions necessary for a discussion of the mechanical aspects of the experiments. The nomenclature is the same as before:

A the horizontal distance between panel and the subject's center of mass
D the horizontal distance between panel and footing
F the foot force transmitted vertically to the floor
H the height of the push panel
μ coefficient of static friction
P the push force exerted horizontally at the panel,
and Q the vertical force between the panel and the subject's body
R the reaction force preventing the subject from sliding on the floor
W the subject's weight, concentrated in his center of mass

R and Q depend on the friction prevailing at the floor or panel, respectively, according to $R \leq F \cdot \mu_{floor}$ and $Q \leq P \cdot \mu_{panel}$. With the rough linen at the panel, the coefficient of friction was so high that the panel and the subject's body virtually interlocked; thus $\mu_{panel} \geq 1$ and $Q \leq P$.

Assuming that F, P, Q, R and W represent all the forces active in this system, and that the system is in balance, the following equations exist:

Sum of vertical forces: $W - Q - F = 0$ (1)

Sum of horizontal forces: $P - R = 0$ (2)

Sum of moments: $PH + QD - W(D - A) = 0$ (3)

With $F = W - Q$ (1a)

and $Q = W(1 - A/D) - PH/D$ (3a)

it is easily shown that

$$\boxed{F = PH/D + WA/D} \qquad (4)$$

Formula (4) contains only dimensions measured in this study. The recorded values should, for each condition and subject, fulfill this equation.

In testing this assumption, the accuracy must be taken into account with which the variables are measured. The mean measuring errors s_{x_i} of this study do not exceed:

$s_P = \pm 1$ kp if $P \leq 100$ kp
($s_P = \pm 5$ kp if $P > 100$ kp)
$s_W = \pm 1$ kg
$s_H = \pm 3.0$ cm
$s_D = \pm 4.0$ cm
$s_A = \pm 4.0$ cm

The mean square error s_f^2 (the variance) of a function of n variables $f(x_1, x_2, \ldots x_n)$ may be approximated by the first terms of a Taylor series:

$$s_f^2 = (\delta_f/\delta_{x_1})^2 s_{x_1}^2 + (\delta_f/\delta_{x_2})^2 s_{x_2}^2 + \ldots + (\delta_f/\delta_{x_n})^2 s_{x_n}^2$$
$$+ 2(\delta_f/\delta_{x_1})(\delta_f/\delta_{x_2}) s_{x_1} s_{x_2} r_{x_1x_2} + 2(\delta_f/\delta_{x_1})(\delta_f/\delta_{x_3}) s_{x_1} s_{x_3} r_{x_1x_3} + \ldots \qquad (5)$$

where the δ_f/δ_{x_i} is the first partial derivative of f with respect to x_i; the $s_{x_i}^2$ is the mean square error of the x_i; and $r_{x_{i,j}}$ is the coefficient of correlation between the errors. With little or no relation between the errors, the linear terms of equation (5) can be neglected. No other assumptions are made concerning the distribution of the errors (Deming, 1946).

The function f is, in our case, $f(x_i) = F = PH/D + WA/D$. (4)

Consequently, five partial derivatives exist:

$$\delta F/\delta P = H/D \tag{6a}$$

$$\delta F/\delta H = P/D \tag{6b}$$

$$\delta F/\delta D = -(PH + WA)/D^2 \tag{6c}$$

$$\delta F/\delta W = A/D \tag{6d}$$

$$\delta F/\delta A = W/D \tag{6e}$$

With these derivatives, and with the s_{x_i}, equation (5) becomes:

$$s_F = 1/D \sqrt{H^2 s_P^2 + P^2 s_H^2 + A^2 s_W^2 + W^2 s_A^2 + (PH + WA)^2 s_D^2/D^2} \tag{7}$$

Using the values recorded for each subject under each condition, equations (4) and (7) were computed. The computed results were compared with the values listed in tables II, III, and IV under "F", i.e., the force normal to the floor while the subject exerted his maximal push force (P). Of those forces recorded to be transmitted to the floor, only 58% lay within the computed range of $F_{comp} \pm S_F$.

Likewise, values were computed for each subject under each experimental condition and compared with the values listed under "f", i.e., when the force "p" was registered at the panel while the subject just maintained his position, but did not try to exert his maximal push force. Of the forces "f" actually transmitted to the floor, 68% lay within the range of $f_{comp} \pm S_f$.

Despite generous allowances for the mean errors of the variables to be entered into equation (4), the values entered into this formula obviously do not sufficiently reflect the actual conditions. Hence, additional forces must act within the closed system depicted in figure 6. By contracting muscles (by "wedging" himself "in"), the subject is obviously able to increase simultaneously the forces exerted at the push panel (P and Q) and at the footing (F and R) above the value set by his weight alone. This complies with common experience.

This result, based on simple mechanical considerations, is in remarkable agreement with the statistical considerations of the predictive value of weight for strength, and with Fox's actual findings, as discussed above. Weight, then, may be, statistically, significantly related to some muscular force capabilities, but is of little value in predicting exertable strength.

SECTION VIII

SUMMARY AND CONCLUSIONS

Twenty-eight male subjects assumed 13 different body positions to exert their largest possible forces in pushing isometrically and horizontally either forward with both hands, laterally with the preferred shoulder, or backwards.

Simplified, the experimental results may be summarized as follows:

- Body weight of the subject is not a practical predictor of force capability.
- Very slippery floors and shoe soles ($\mu \sim 0.3$) and medium-traction conditions ($\mu \sim 0.6$) limit the exertable push forces to very low values. Among body postures employed, very little differences in effectiveness exist.
- With high-traction floors and shoes (μ approximating unity), the push force capability depends rather unpredictably on: a) the actual coefficient of friction, b) the subject's skill just to avoid sliding, and c) the subject's muscular strength. Backward force exertion may be somewhat more effective than lateral or forward pushes.
- When the feet can be anchored (as at a footrest), substantially larger push forces can be exerted than attained when standing on any of the flat floor materials. Interlocking is least effective for forward pushes with both hands, more beneficial in lateral pushes with the shoulder, and decidedly increases backward push capabilities.

Combining the results of this study with the findings previously published (Fox, 1967; Kroemer, 1969) provides an overall picture of static horizontal push force capabilities of adult males.

The data concern only *horizontal* forces. They do not apply directly to the weight of objects to be pushed, lifted, or carried.

The force data apply to the static condition, in which muscles are contracted isometrically, without changing in length. In this case, no motion takes place between the operator and the object against which he pushes. Kroemer (1970) previously cautioned against the indiscriminate use of data on static muscle strength for dynamic work. However, static strength data may be used for conservative estimates on the "break-away force" to be applied initially to an object to set it in motion (Kroemer and Howard, 1970). They are also of value if a force must be sustained over a period of time, and may (with caution) be applied to very slow motions (Kroemer, 1970).

Snook, Irvine, and Bass (1969) reported on a study that included dynamic pushing and pulling with the subjects walking on high-traction floors. This experiment showed that 90% of male workers should be able to exert initial two-handed pushes of about 50[6] lb (220 N), to set heavy objects into motion, "without strain or unusual tiredness." Likewise, they should be able to sustain a continuous force of about 25 lb (110 N) to maintain the motion over distances of up to 100 feet. The study by Shook et al. also allows the conclusion that—under suitable conditions—horizontal pull force capabilities are comparable to push force capacities.

---

[6]All the following figures are rounded to convenient numbers.

A suitable panel is necessary for force exertion. It should be vertical and have a rough surface. To allow force application either with the hands, the shoulder, or the back, it should be about 40 cm (16 inches) wide, start not higher than 50 cm (20 inches) and end at about 125 cm (50 inches) above the floor.

At such a panel or other suitable device, healthy male US adults (comparable to the subjects in the studies cited), under common working conditions, should be able to exert, intermittently and for short periods of time, at least the following horizontal static forces (table VII) :

TABLE VII

HORIZONTAL PUSH AND PULL FORCES EXERTABLE

Horizontal force: at least*	*Applied with*	*Condition (μ: coefficient of friction)*
100 N (25 lb) push or pull	both hands or one shoulder or the back	with low traction $0.2 < \mu < 0.3$
200 N (45 lb) push or pull	both hands or one shoulder or the back	with medium traction $\mu \infty 0.6$
250 N (55 lb) push	one hand	if braced against a vertical wall 50-150 cm (20-60 in) from and parallel to the push panel
300 N (70 lb) push or pull	both hands or one shoulder or the back	with high traction $\mu > 0.9$
500 N (110 lb) push or pull	both hands or one shoulder or the back	if braced against a vertical wall 50-175 cm (20-70 in) from and parallel to the panel; or if anchoring the feet on a perfectly nonslip ground (like a footrest).
750 N (165 lb) push	the back	if braced against a vertical wall 60-110 cm (23-43 in) from and parallel to the push panel; or if anchoring the feet on a perfectly nonslip ground (like a footrest).

* May be doubled for two and tripled for three operators pushing simultaneously. For the fourth and each additional operator, not more than 75% of his push capability should be added.

APPENDIX

COEFFICIENTS OF FRICTION BETWEEN VARIOUS FLOOR AND SHOE MATERIALS

The research reported here was conducted by Dr. Tung Liu in 1968, then with the Fluid and Lubricant Materials Branch of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. In 1969, Mr. R. J. Benzing, Technical Area Manager in this branch, completed a preliminary report based on Dr. Liu's notes, who, in the meantime, had accepted another position. This appendix relies heavily on Mr. Benzing's report, condensed and edited by one of the authors (Kroemer), who is responsible for omissions or reporting errors while Dr. Liu and Mr. Benzing should receive all credit.

INTRODUCTION

Experiments were conducted to provide a general comparison of the coefficient of friction between eight shoe sole materials and nineteen floor materials. The conditions used in this work were designed to simulate actual working environments. The materials, particularly the flooring materials, are not homogeneous and probably their properties change significantly due to varied atmospheric conditions, such as temperature and humidity. Thus, even with a large number of tests, the data must be treated with caution as indicated by the experience in the testing of abrasion resistance of flooring materials (International Study Committee, 1961; Military Standard MIL-S-22777B, 1967).

EXPERIMENTAL METHOD

Coefficients of friction between eight shoe sole materials and nineteen floor materials were to be measured. During preliminary studies, it was found that dynamic friction in most cases was very close to the static friction; hence, only the latter was pursued. Pressure of 4.7 psi between sole and floor materials was used in the main part of the study to approximate the load due to the weight of a standing man. In some tests, a dry surface was used. For other experiments, an oil-water mixture was prepared. To each cc of oil, one drop of a surface-active agent was added together with 3 cc of water and mixed in a blender. This mixture was brushed on the flooring material until the surface appeared barely wet.

The experimental apparatus used was of a slider type. Three one-inch diameter disks of the sole material to be tested were attached to a sled or rider being pulled over the floor surface selected. Static friction was determined by the horizontal force required to initiate sliding of the sled on the horizontal floor material. The sled, loaded so that it had a total weight of 5 kg was pulled by a horizontal cord. After passing a pulley, the cord was attached to a hanging container. Into this container lead shots (average weight 0.17 grams) were poured until the sled began to move. At this moment, the can was weighed and the load (R) recorded to the next lower 10 grams. Five measurements at each condition were made to minimize the errors caused by local irregularities of the floor materials.

Eight sole materials were used in this work, four of which had a contoured surface for improved traction:

a) rubber overshoe,
b) neoprene heel,
c) soft nylon heel, and
d) standard shoe sole for USAF and US Army (Mil. Spec. S-22777B, 1967).

The flat materials are standard materials used for manufacturing soles:

e) neoprene,
f) rubber - crepe,
g) rubber - cork, and
h) leather.

Nineteen floor materials were used in this work. They may be graded in three categories:

Working floors—where appearance is of no importance:

CODE
1 smooth concrete—finished with a steel trowel
2 painted concrete—three coats of floor enamel applied to smooth concrete
3 rough concrete—finished with a wooden float
4 synthetic stone
5 soft wood blocks (end grain)

Working floors—decorative:

6 hardwood—oak with two coats of varnish
7 vinyl tile—smooth
8 vinyl tile with random decorative grain
9 linoleum (sheet)
10 vinyl asbestos tile—smooth
11 asphalt tile
12 vinyl asbestos tile with grains parallel to the direction of motion
13 vinyl asbestos tile with grains perpendicular to the direction of motion
14 rubber tile

Special purpose floors:

15 rubber pad (about ¼ inch thick, ribbed)
16 steel—sanded with #240 grit sandpaper
17 steel grid—polished with #600 grit sandpaper
18 steel—polished with #600 grit sandpaper
19 aluminum—sanded with #240 grit sandpaper

All flooring specimens were cut to a shape 22 inches long by 4 inches wide. The nonrigid floor coverings such as asbestos tile were glued to a ⅜-inch particle board backing of the same size.

RESULTS AND DISCUSSIONS

A preliminary evaluation of all nineteen floor materials was made with the eight sole materials using a weight of 500 grams[7]. Twelve flooring materials were selected for a more intensive evaluation by running all eight soling specimens with 1500[7] and 5000 g. In addition, eleven of these twelve were run with 500[7] and 5000 g under simulated soiled (oil-water mixture) conditions. Using the formula $\mu = R/F$ (R is the force necessary to initiate movement; F is the normal force between the materials), μ was calculated from R and F (F = 500, 1500, 5000 g). Means and standard deviations for μ with F = 5 kg are compiled in table VIII.

Repeatability of the test data appeared to be adequate. An overall standard deviation of 6.53% of the measured value was obtained. For individual floor materials this ranged from a low of 3.91% to a high of 9.42%. The range for any one single test was from 0 to 28.1%.

Preliminary Comparison of Floors

Based on the data obtained with F = 500 g, the following floor specimens were excluded from further investigations for the reasons noted:

No. 2 Painted concrete—For precise data, the type of paint should be considered. Data on smooth concrete (No. 1) may be used for conservative estimates.

No. 4 Synthetic stone—This material behaved very much like rough concrete (No. 3) and, besides, is not very commonly used due to its high cost and low chip resistance.

No. 8 Vinyl tile, randomly grained—This material is not often used. The grain improves the friction over a smooth surface. The data on the smooth vinyl (No. 7) may be used conservatively.

No. 9 Linoleum—This material had coefficients of friction below those of vinyl tile with smooth surface (No. 7), which may be used for conservative estimates.

No. 11 Asphalt tile—The friction behavior appears to be between vinyl (No. 7) and vinyl asbestos tiles (No. 10, 12, and 13).

No. 12 Vinyl asbestos tile with grains parallel to the direction of motion—The results are similar to those with grains perpendicular to the direction of motion (No. 13).

No. 19 Aluminum—This is not a commonly used flooring material. This surface can be easily damaged by scratches and thus changes its traction.

Final Comparison of Floors and Soles

Twelve selected flooring specimens were run against all eight soling specimens under clean and simulated soiled conditions (except the rubber pad where a soiled condition could not be maintained); see table VIII. Performance of the twelve flooring materials is compared in figure 13 in terms of the average coefficient of friction.

---

[7] The results of these tests are omitted from this report.

TABLE VIII

COEFFICIENTS OF FRICTION BETWEEN FLOOR AND SHOE MATERIALS [MEANS AND STANDARD DEVIATIONS (SD)]

	a Rubber Overshoe		*b* Neoprene Heel		*c* Soft Nylon Heel		*d* USA - USAF Standard Sole		*e* Neoprene Sole, Flat		*f* Rubber-Crepe Sole, Flat		*g* Rubber-Cork Sole, Flat		*h* Leather Sole, Flat		*Average*		*APPLICABLE ALSO TO*
	Dry	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	*Dry*	*Soiled*	
1. Concrete,	.72	.47	.64	.56	.80	.47	.81	.83	.70	.62	.65	.59	.65	.70	.44	.37	.68	.65	2. Concrete, painted
smooth	.022	.031	.049	.063	.013	.045	.035	.044	.012	.015	.052	.038	.018	.030	.012	.077			
3. Concrete,	.84	.65	.85	.88	.73	.55	.76	.82	.85	.80	.76	.68	.73	.66	.56	.90	.76	.74	4. Synthetic stone
rough	0.15	.023	.043	.027	.015	.058	.043	.022	.044	.034	.047	.076	.027	.040	.052	.033			
5. Wood, soft	.83	.71	.94	.96	.76	.75	.97	.86	.74	.78	.81	.75	.83	.85	.60	.71	.81	.80	
end grain	.024	.029	.023	.054	.040	.037	.026	.025	.010	.014	.030	.050	.067	.024	.035	.076			
6. Hardwood	.48	.44	.69	.48	.41	.34	.78	.57	.35	.35	.75	.30	.92	.52	.53	.67	.61	.46	
(oak), varnished	.021	.027	.013	.011	.020	.028	.022	.014	.016	.012	.028	.077	.006	.039	.021	.044			
7. Vinyl tile,	.77	.42	.66	.51	.79	.49	.68	.58	.73	.41	.81	.52	.87	.53	.65	.60	.75	.51	8. Vinyl tile, grained
smooth	.021	.019	.012	.024	.009	.007	.051	.032	.028	.014	.052	.050	.059	.015	.041	.048			and 9. Linoleum
10. Vinyl asbestos	.68	.45	.77	.53	.55	.43	1.04	.58	.49	.43	.88	.49	1.01	.40	.57	.66	.75	.50	11. Asphalt tile
tile, smooth	.046	.036	.043	.046	.050	.022	.039	.009	.014	.043	.054	.024	.060	.078	.057	.065			
12/13. Vinyl	.60	.45	.59	.54	.40	.30	.70	.65	.43	.41	.71	.36	.75	.52	.47	.70	.58	.49	Any grain
asbestos tile	.025	.019	.052	.045	.054	.015	.129	.035	.059	.019	.028	.080	.094	.033	.036	.046			direction
14. Rubber	1.10*	.39	.65	.48	.95	.42	.72	.62	.80	.44	.80	.55	1.00	.45	.53	.77	.82	.52	
tile	.094	.016	.081	.042	.030	.022	.049	.042	.070	.025	.125	.050	.072	.059	.079	.044			
15. Rubber	1.05		.93		.95		1.04		1.13		.89		1.03		.92		.99		
pad	.037		.016		.010		.009		.060		.029		.084		.082				
16. Steel,	.80	.34	.72	.37	.72	.25	.50	.57	.58	.27	.51	.40	.73	.39	.33	.33	.61	.37	
sanded	.020	.009	.029	.026	.025	.005	.031	.012	.035	.012	.025	.025	.060	.017	.034	.023			
17. Steel grid,	.44	.31	.47	.44	.41	.19	.69	.55	.28	.26	.49	.27	.62	.43	.27	.38	.46	.35	
polished	.014	.015	.042	.030	.024	.008	.021	.017	.017	.019	.021	.056	.033	.044	.030	.063			
18. Steel,	.38	.28	.59	.28	.27	.30	.29	.52	.24	.34	.54	.34	.78	.30	.24	.28	.42	.33	
polished	.031	.006	.036	.023	.054	.018	.018	.079	.014	.017	.052	.020	.031	.050	.027	.050			
Average	.72	.45	.71	.55	.65	.41	.76	.65	.61	.46	.72	.48	.83	.52	.51	.63	.69	.52	

*Values exceeding unity indicate mechanical interlocking between the shoe and floor.

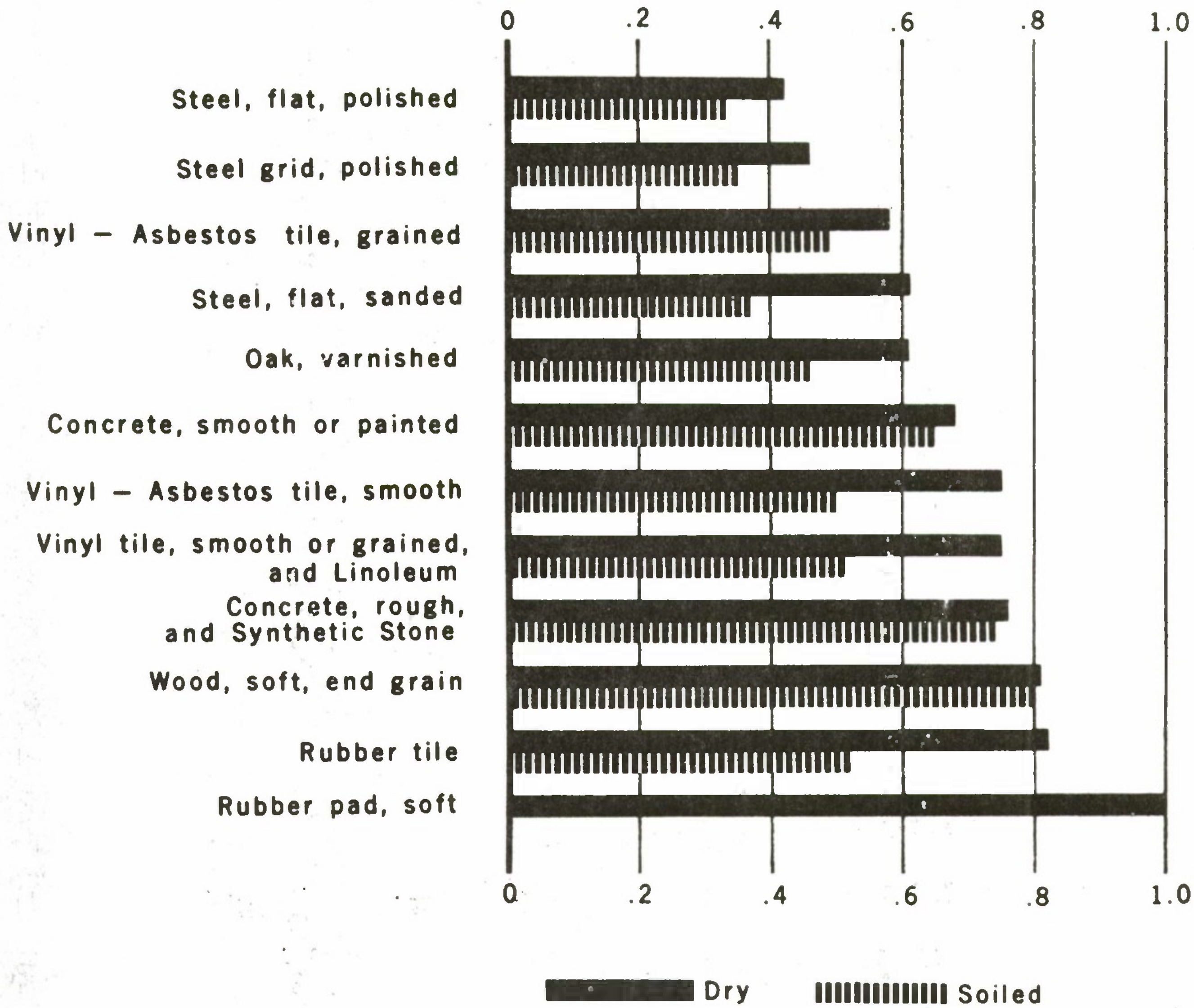


Figure 13. Mean coefficients of static friction of floor materials under eight shoe materials

1. The rubber pad, concrete, and soft wood have the highest coefficients of friction. These floors were not substantially affected by soiling. Rough concrete, even smooth concrete, is only slightly inferior to end-grained soft wood and merits consideration due to the low cost.

2. Among the working—decorative floors, the coefficient of friction varied considerably while clean. Under soiled conditions, the coefficients of friction lay within a very narrow range.

3. On soiled steel floors, the friction was very low, i.e., under 0.4.

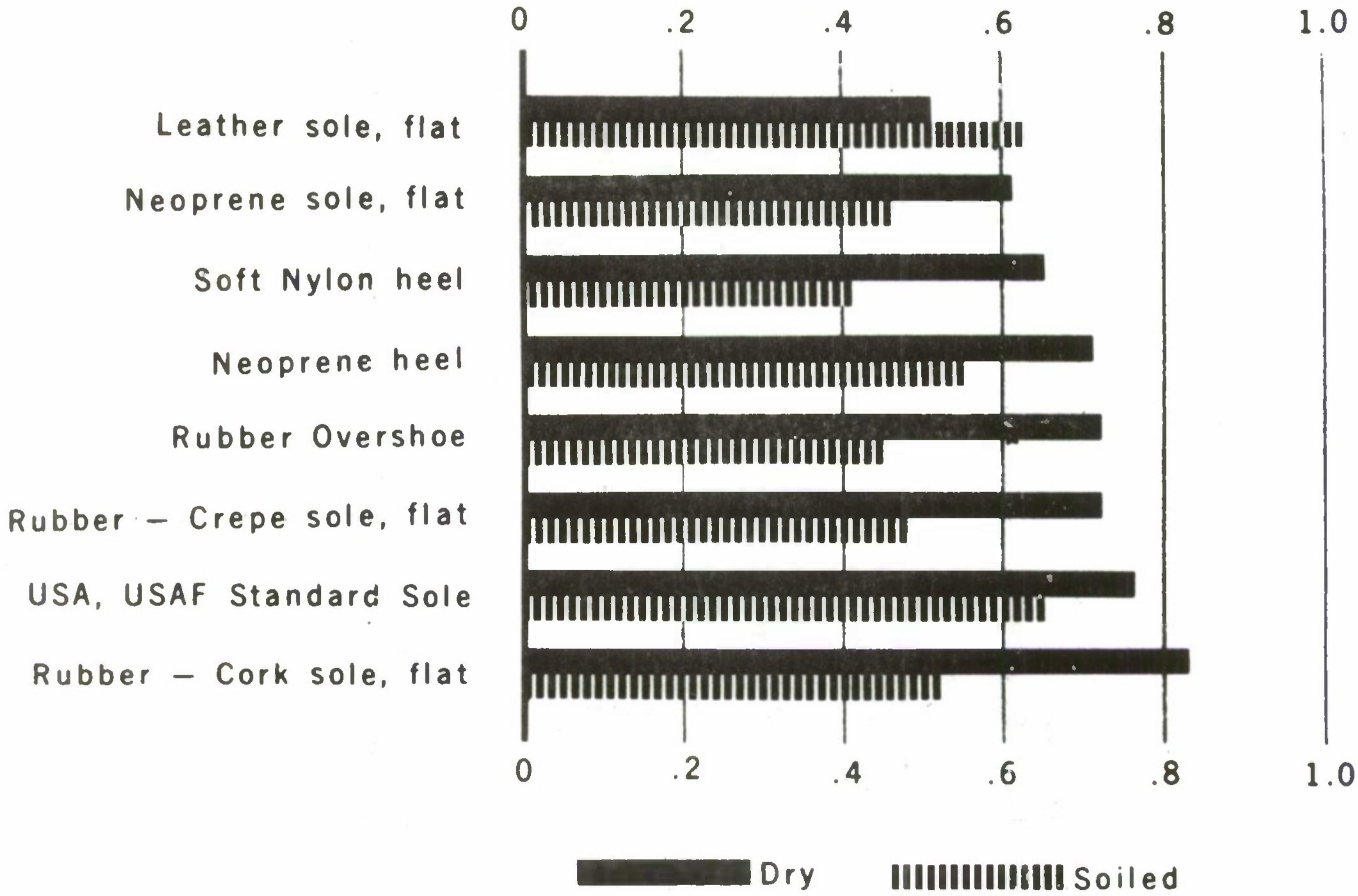


Figure 14. Mean coefficients of static friction of shoe materials on sixteen floor materials

Performance of the eight sole materials may be evaluated similarly. The average coefficients of friction on the twelve floors at 5000 g load in dry and soiled conditions (11 in soiled conditions) are shown in figure 14. Obviously, the standard rubber shoe sole for USAF and US Army is superior, showing consistently high friction. Leather was observed to absorb oil and swell up. This seemed to cause unusually high friction in the soiled condition. The high friction was probably a function of the particular oil used and should not be regarded as the general behavior. It was also observed that leather ran on clean or soiled steel floors without much change in friction.

A series of runs was carried out to compare a new leather sole (with smooth surface) against a used one. The results showed an approximate 10% reduction in friction at 5000 g load and about 20% reduction at 500 g load.

Only Fox's study (1967) was found to contain comparable data. Fox tested, among other combinations, the friction between concrete and such shoe materials as leather, rubber, neoprene, and crepe. The coefficients of friction obtained in his and this study are rather similar. Sigler, Geib and Boone (1948) described a pendulum device to measure "slipperiness of walkway surface" when using rubber and leather heel materials. Due to their different testing method, their results cannot be compared quantitatively with those obtained here. However, they also found concrete to be of rather high traction dry and soiled, and the rubber heel generally less slippery than the leather specimen.

SUMMARY

Static friction between eight shoe sole specimens and nineteen floor materials was measured. The results may be summarized as follow:

1. There were some wide variations in friction between individual combinations of floor materials and sole materials.

2. A soft rubber pad had the highest coefficient of friction ($\backsim$ 1.0) among all flooring materials tested.

3. End-grained soft wood provided good friction ($\backsim$ 0.8) as a working floor and did not tend to become slippery when soiled.

4. Rough-finished concrete had fairly high friction ($\backsim$ 0.7) whether clean or soiled and provided an excellent low cost floor for working areas.

5. All the working-decorative floor coverings tested had similar coefficients of friction (about 0.5) when soiled. Selection among them should be based on considerations such as durability, appearance, and cost.

6. Steel floors were generally slippery, especially when soiled, with nearly all shoe materials.

7. The standard shoe sole of USAF and US Army provided more traction on dry and soiled floors than soles of other design. The flat rubber-cork and rubber-crepe soles and the contoured neoprene heel were the next best specimens.

REFERENCES

Caldwell, L. S., The Load-Endurance Relationship for a Static Manual Response, *Human Factors, 6*:1, 71-79, 1964.

Deming, W. E., *Statistical Adjustment of Data.* Third printing, New York: Wiley & Sons, 1946.

Fox, W. F., *Body Weight and Coefficient of Friction as Determiners of Pushing Capability,* Human Engineering Special Studies Memorandum No. 17, Marietta, Georgia: Personnel Subsystems, Lockheed-Georgia Company, and Personal Communication, 1967.

International Study Committee for Wear Tests of Flooring Materials, Performance of Abrasion Machines for Flooring Materials, *Wear, 4*, 479-498, 1961.

Kroemer, K. H. E., *Push Forces Exerted in Sixty-Five Common Working Positions,* AMRL-TR-68-143, Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1969.

Kroemer, K. H. E., *Human Strength: Terminology, Measurement and Interpretation of Data,* AMRL-TR-69-9, Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1970. Also published in *Human Factors, 12*:3, 297-313, 1970.

Kroemer, K. H. E., and J M. Howard. *Problems in Assessing Muscle Strength,* AMRL-TR-68-144, Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1970.

Laubach, L. L., Body Composition in Relation to Muscle Strength and Range of Joint Motion, *J. Sports Medicine and Physical Fitness, 9*:2, 89-97, 1969.

Laubach, L. L., and J. T. McConville, The Relationship of Strength to Body Size and Typology, *Medicine and Science in Sports, 1*:4, 189-194, 1969.

Rohmert, W., Ermittlung von Erholungspausen fuer statische Arbeit des Menschen, *Int. Z. angew. Physiol. einschl. Arbeitsphysiol., 18*, 123-164, 1960.

Rohmert, W., Untersuchung statischer Haltearbeiten in achtstuendigen Arbeitsversuchen, *Int. Z. angew. Physiol. einschl. Arbeitsphysiol., 19*, 35-55, 1961.

Santschi, W. R., J. DuBois, and C. Omoto, *Moments of Inertia and Centers of Gravity of the Living Human Body,* AMRL-TDR-63-36, Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratories, 1963.

Sigler, P. A., M. N. Geib, and T. H. Boone, Measurement of the Slipperiness of Walkway Surfaces, Research Paper RP 1879, *J. of Research of the National Bureau of Standards, 40*, 339-346, 1948.

Snook, S. H., C. H. Irvine, and S. F. Bass, Maximum Weights and Work Loads Acceptable to Male Industrial Workers While Performing Lifting, Lowering, Pushing, Pulling, Carrying, and Walking Tasks, Manuscript of a paper presented at the American Industrial Hygiene Conference, Denver, Colorado, May 1969.

Soles and Heels, Rubber, Traction Tread, Shoe, Military Specification MIL-S-22777B, June 1967.