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Foot Forces Exerted at Various Aircraft Brake-Pedal Angles

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This study reports the forces (means and standards deviations) exerted by the foot at various angles of extension about its ankle. A sample of 100 rated pilots was selected by height and weight. The forces were measured in a cockpit mock-up constructed around a specially instrumented F-80 rudder-pedal assembly. The right rudder pedal (hinged on the rudder bar) could be rigidly set to any desired angle between vertical and 75° forward of vertical. Foot forces were measured at 11 positions of the instrumented brake pedal in both neutral and extended positions of the right leg, and in three cockpit sizes (37 in., 39¼ in., and 41 in.)–66 measures on each man. In all three conditions, maximal forces were exerted within a 20° zone between 15 and 35° forward of vertical. Subjective comfort preferences, expressed by 86 pilots, closely paralleled the force findings. It is concluded that aircraft brake-pedal systems should be designed to maximize the effectiveness of the foot in that optimal zone, and that the same zone should be considered for other foot-operated controls, like automobile accelerator pedals.

INTRODUCTION

Anyone who does work with his muscles knows that effort and fatigue can be minimized by finding and using the position of optimal mechanical advantage of the limbs for any given task. A shoveler, for instance, quickly learns the best grip location to minimize the effort of continued work. But when the worker on a fixed machine must conform to the situation built in by the machine designer, he may be at a considerable muscular disadvantage and consequently suffer undue fatigue. This is the condition encountered in some airplane brake pedals, and not infrequently in other types of pedals. Although rudder-and-brake controls have to be generally similar in location and adjustability, the design variation in angle of brake-pedal face among different airplanes is often a source of complaint among pilots. This is because the specifications require only that the brake pedal shall travel 30° from full "off" to full "on".

With that situation in view, the present study was undertaken to ascertain the pedal angles in the cockpit through which the foot can exert its maximum torque about the ankle, as well as the magnitude of the forces themselves. The data were gathered during 1949-50, but could not then be written up. As no similar leg-strength study has appeared since then (but compare Hunsicker [1955] for arm strength measured according to Air Force instructions) these results seem still timely as data assisting optimal brake-pedal design.

For the purpose of this study, it was assumed that pressures could be exerted equally by either foot. While this is not strictly true, only the right-foot pressures were measured, as these are generally the subject's maximal forces, and hence those needed for non-fail structural design.

RUDDER AND BRAKE CONTROL: THE GENERAL PROBLEM

It is a cardinal principle in vehicle design, and especially in aircraft, that the control levers must move in the direction in which the operator's limbs naturally move and thereby exert force. But this by itself is not enough as a design criterion; there must be considered also a zone in the arc of travel of any limb in which the operator can exert force with the least

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effort; i.e., with the greatest efficiency. All control levers, therefore, should be designed so that they can move and transmit the operator's force through just that zone. But such zones have received relatively little attention, and that is the reason for this study of leg and foot action in the cockpit.

To an investigator seeking to improve the efficiency of foot controls for pilots, it may seem paradoxical that the greatest range of leg-and-foot positions required, and of foot forces to be exerted, is usually encountered on the ground rather than in the air. Taxiing the aircraft to and from the runway often calls for extreme displacements of the control levers because of the low efficiency of the rudder and aileron surfaces at slow air speeds. At such times, braking forces often are very important in maneuvering the aircraft. In terms of body action, the shift from control in the air to control on the ground can be rather complex, yet it is all a part of the pilot's responsibility. For the reader unfamiliar with the cockpit rudder-and-brake situation, a brief analysis may be desirable.

In any given aircraft, canopy height and overall cockpit size are fixed, but various adjustments, both vertical and horizontal, are provided. On entering the cockpit, the pilot first adjusts his seat up or down according to his sitting height, so that his eyes reach the point from which he can see out satisfactorily, and move his head freely. This eye location is an important design point, from which many cockpit dimensions start. In Air Force aircraft, the ranges of those dimensions have been anthropometrically chosen to accommodate at least the central 90% of body sizes in our pilot population. Next, the pilot adjusts the rudder-bar location horizontally forward or aft for his own leg length, so that the balls of his feet rest comfortably but positively on the bars, with his heels usually on the cockpit floor. As the rudder and its controls (the rudder bars–one for each foot) form a tight operational loop, it is obvious that when the pilot pushes the right rudder bar away from him to turn the aircraft to the right, the left rudder bar must come closer to him by the same displacement. Thus the rudder bars are equidistant from the pilot's seat when he is flying in a straight line. This is called the neutral position for both the rudder bars and the pilot's legs. His knees are comfortably bent, so that he can straighten one knee toward what is called the "extended leg" position, and bend the other knee further to retract that leg as it conforms to the aft-moving rudder bar. As takeoffs and landings demand sensitive control but no great leg displacement, it is during taxiing that the pilot may have to exert considerably higher forces with more complex limb movements. In flight, the pilot does not actuate his brakes, and seldom needs full leg extension except perhaps during violent combat maneuvers; but on the ground, turning the aircraft in a strong cross-wind, he often has to exert a maximal braking effort by one foot while that leg is fully extended. Thus the aircraft rolling at low speeds on the ground may present problems of control more critical than those in flight, when considered in terms of the muscle groups and limb positions needed to exert the controlling forces.

It is, of course, clear that the two adjustments noted above–seat height and rudder-bar distance–affect the angle of the pilot's knees, and thus also the forces he can exert. To obtain some estimates of the magnitude of knee angle at both neutral and extended positions, and for both small and large men, a layout drawing was prepared showing the configuration of the standard USAF fighter seat (seat pan, 6.5°, seat back, 103° from horizontal), with a horizontal vision line 39¼ in. above the floor (heel-rest) level. Two plastic manikins, one dimensioned according to the 5th percentile of USAF body sizes and the other to the 95th percentile (Hertzberg, Daniels, and Churchill, 1954) were fitted to the eye line, seat angles, and heel positions. For the neutral leg position (thighs on the seat-pan line, heels on the floor, balls of feet as if on the rudder bars) the angular range was $135° \pm 10°$. The angles were taken between the centerlines running through the segment hinges, not on the upper knee surfaces. For the extended leg position, the range was $160° \pm 10°$. In both cases, the smaller manikin had the smaller angle. These figures, of course, are not experimental results; they are only approximations measured from plastic manikins; nevertheless they do give some notion of the ranges of angular magnitude. In living persons, the angles would probably be measured from the femoral trochanter to the midpoint of the knee to the ankle protuberance.

Two other factors affect the magnitude of the forces the pilot can exert on the brake pedal: one is the size (primarily the length) of his foot; and the other is the position of the foot on the rudder bar. The foot position used in this research (heel on the rudder bar) was chosen because the greater natural leverage yields the greater forces, as compared to putting the instep of the foot onto the rudder bar. The latter position would definitely reduce the force capability of a pilot with a small foot because of his reduced lever arm.

APPARATUS

Mechanical Equipment

The heart of the force-indicating equipment used in this study is sketched in Figure 1. This equipment consists essentially of the right-hand brake pedal of a standard rudder-and-brake-pedal assembly, modified so that the pedal could be rigidly set to any desired angle of foot rotation, and instrumented with a calibrated stress-ring to indicate the foot forces exerted upon it. In the sketch the pedal is shown in the vertical position, herein designated as 0°, and the utmost position of flexion of the pilot's foot about his ankle. The pedal could rotate through the arc of foot extension to an angle of 70° past vertical (forward of the seated pilot), a range greater than that shown by any of our subjects. Thus the forces measured in this study were exerted at successive fixed angles of the pilot's foot. The operation of the various parts of the apparatus is discussed in greater detail below.

The rest of the equipment used (see Figures 2 and 3) was a modification of the so-called Universal Test Seat described elsewhere (Lay and Fisher, 1940; Randall, Damon, Benton, and Patt, 1946). This was basically a cockpit mock-up which permitted the subject's seat pan and seat back to be varied in angle with respect to both the horizontal and each other, and the seat assembly to be raised or lowered and moved backward or forward, with respect to the rudder bars. The apparatus could thus be made to simulate the dimensional conditions of any conventional airplane cockpit. In these

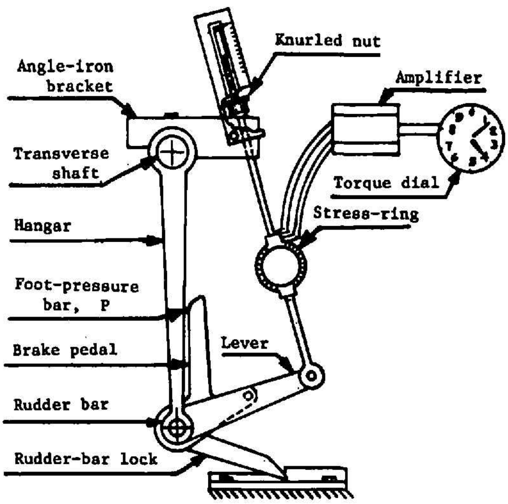

Figure 1. Schematic sketch of brake-pedal instrumentation.

Figure 2. General view of equipment: (a) sound-proof box for inverter; (b) rudder-bar adjustment rod; (c) torque-indicator dial; (d) eye-level indicator; (e) heel-marking tape; (f) screw-jacks.

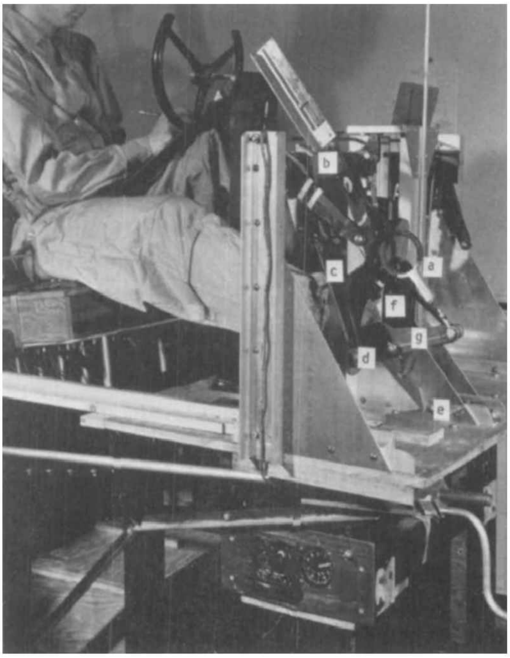

Figure 3. View of pedal and strain-gauge equipment: (a) stress-ring; (b) angle-iron bracket; (c) hangar; (d) rudder bar; (e) rudder-bar lock; (f) brake pedal; (g) lever.

tests the seat-pan angle was 6.5° above horizontal, and the seat-back angle was 103° from horizontal. These angles, standard in USAF cockpits, were kept constant.

This model of the Universal Test Seat (constructed from the original plans, and used by anthropologists at Wright Field during World War II) had spring cushions on both the seat pan and seat back. For these tests, however, each cushion was covered with a rigid plywood box. The reason for this was to avoid allowing the subject's body to be forced into the cushions during his pedal thrust, and thereby changing his distance from the pedal. The subjects were thus supported directly by virtually inflexible surfaces simulating a standard aircraft seat, as can be seen in Figures 2 and 3.

The rudder pedal used was of a standard type, salvaged from a disabled F-80 fighter aircraft. On a separate table in front of the seat, the assembly was mounted intact except for the modification described below, which did not alter the cockpit conditions confronting the pilot. The assembly consisted (see Figures 2 and 3) of two rudder bars which could swing oppositely fore-and-aft on hangers supported on a horizontal transverse shaft. The rudder bars–the pilot's rudder controls–were arranged (according to standard practice) so that their axes were 5 in. above the cockpit floor when in neutral position. Rotating about each rudder bar was the brake pedal which could be actuated independently of the position of the rudder bar or of the other pedal (see Figures 1, 2, and 3).

From previous work (Randall, 1944) it was known that most feet can rotate about 55° about the ankle. The right brake pedal was therefore modified so that it could swing about its rudder-bar axis through an arc from vertical, or 0°, to 70° past vertical (i.e., forward from the pilot's seat) in such a way that it could be stopped at any angle within that arc (Figure 1). This was accomplished by means of a stress-ring whose lower end was hinged to a lever arm firmly attached to the underside of the pedal, and whose upper end was a threaded, ¼-in. shaft running through a hole in an angle-iron bracket solidly anchored to the transverse shaft supporting the rudder-pedal hangar (Figures 1, 2, and 3). A knurled cylindrical nut on the threaded shaft above the bracket permitted rapid and precise angular adjustment of the pedal. Figures 2 and 3 show the structural bracing and general "beefing-up" needed to make the equipment immovable under the heavy forces imposed by the subjects.

In an actual cockpit, the rudder-bar assembly contains an adjustment mechanism whereby pilots can move the rudder-bar neutral position forward or rearward, and then lock it in place, to suit their own leg lengths. In the experimental mock-up, however, this mechanism was removed, and the adjustability was provided by moving the seat fore or aft with respect to the neutral rudder bars. As the seat was supported on one structure and the rudder-pedals on another, and the forces exerted would tend to force them apart, the two structures were firmly tied together by means of a threaded pipe (Figure 2). Running horizontally through the support structure of the pedal assembly, this pipe was fixed to one column of the seat-support structure. A large nut (with crank attached) at the forward end of the pipe enabled the experimenter to adjust the distance between seat reference point (SRP) and the rudder-bar satisfactorily and solidly for each pilot's leg length.

Because the pilot's eyes, regardless of his body size, must be positioned at a certain level in the cockpit for him to see out, the vertical dimension, floor-to-eye height (usually called "cockpit size"), is one of the most important dimensions of a cockpit. Once this distance has been decided upon, other cockpit dimensions flow from it (*AFSC Design Handbook,* 1970 revision, subnotes 1[1], 1[4]). In the present study, three cockpit sizes were chosen, 37, 39¼ (AF standard for fighter aircraft), and 41 in., to learn whether the pilot's ability to apply foot torque might vary with the height of his seat reference point above the cockpit floor. To determine cockpit size, a simple eye-level indicator was mounted on the rudder assembly in front of the subject. This indicator consisted of several pairs of threads fixed on a vertical rod, so that each pair generated a horizontal plane at one of the specified heights above the mock-up floor (Figure 2). The seat was adjusted vertically (by built-in screw-jacks) so that when the subject, seated in his normal flying position, could see only the near thread of the pair at a chosen level, his eyes were in the desired plane. This device allowed the operator to re-position the subject's eye rapidly and accurately from one plane to another.

In the airplane the rudder-bar travel (after adjustment for leg length) is limited by built-in stops. These also had been removed from the mock-up, so a metal tongue was hinged under the right rudder-bar to act as a rudder stop. The tongue, when swung down, could fit into a groove on the cockpit floor to form an effective lock at either the neutral or the extended rudder position. Stopping the travel of the rudder bar, of course, had no effect whatever on rotation of the brake pedal, whose bottom portion is a tube fitting over the rudder-bar axis (Figure 3). Thus the pedal could rotate independently about that axis. The aft surface of the pedal tube was in fact the rudder-bar surface on which the pilot's heels were placed.

Since the point of thrust on the pedal could vary widely with different foot lengths and foot positions on the pedal, a low, narrow pressure bar was affixed to the brake pedal near its upper tip, parallel to the axis of rotation and having its centerline just 6.15 in. from the axis. The bar was about .2-in. square in cross-section, extending the width of the pedal except for a small gap at its midpoint (needed for calibration; see below). This pressure bar established a constant lever arm at a distance convenient for the ball of every foot.

It should be noted here that there is a small difference of definition between the pedal angles as used in this study and as called out in Figure 2 of Specification MIL-B-8584B (*Military Specifications,* 1963). Figure 4 shows the difference. In the specifications, the pedal face is considered vertical when the line from the pedal axis to the pedal tip (line AT) is 9°. In this study the practical foot angle was determined by the line tangent to the rudder bar and the pressure bar near the pedal tip. The actual difference between the two is 6°, and it means that 6° must be subtracted from the data presented herein to convert them to the engineering terms used in the specification. From the experimental point of view the angle used in this report was easier to measure, and is therefore retained throughout.

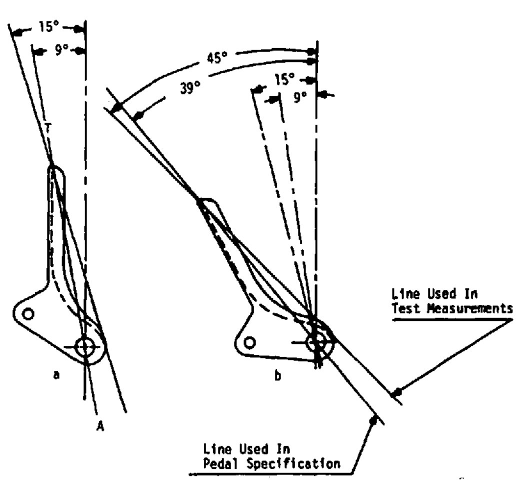

Figure 4. Pedal angle defined: these tests versus pedal specification.

Electronic Equipment

The stress-ring (see Figure 3) was instrumented with strain gauges to measure forces up to 300 lb. applied to the pedal. These strain gauges were energized with 400-cycle alternating current generated by an aircraft inverter operating on 24-v. direct current. The indicator dial did not read directly in pounds of force; it was marked off in units from 0 to 100, each unit being large enough to permit readings to 0.5. The overall error of the system was found to be well under 1%.

Although there had to be some tensional elongation of the stress-ring during foot pressure, this was minimal. The unaided eye could detect virtually no change in the ring, and the position of the rudder pedal under maximum thrust did not alter more than about .02 in. Biomechanically, therefore, the pedal could be considered isometric at any angle.

The essential parts of the pedal arrangement are schematically shown in Figure 1, where the instrumented pedal is shown at 0° and its rudder bar is locked in the neutral leg position. As thrust is applied on the pressure bar P, the pedal is held immovable by the structure of the lever and the stress-ring shaft. The shaft length can be altered by means of the knurled nut, thereby changing the pedal angle as shown on the linear scale. The reading on the indicator dial shows the torques applied by the foot.

The simple and rapid method used to calibrate the system is shown in Figure 5. One end of a 300-lb. Chatillon spring scale, previously calibrated (having no more than 0.5% of error), was bolted through the pedal and the gap in the pressure bar, when the pedal was set at vertical. The other end of the scale was attached to a long handle anchored on the mock-up floor as shown. Pulls on the handle by an assistant permitted full calibration of the torque dial. After initial calibration, the system was checked frequently, often daily, to assure correct response. This calibration system, which could be installed and removed in seconds, showed the pressure-indicating equipment to be stable and reliable.

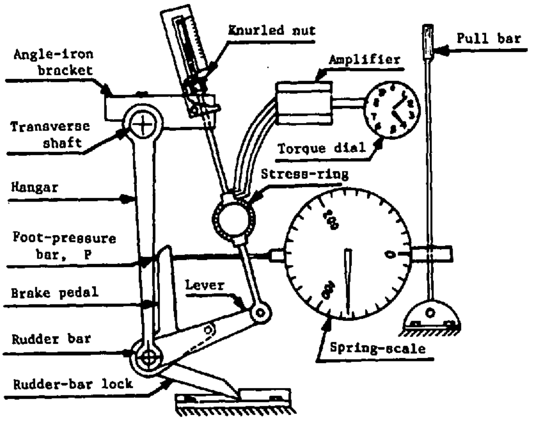

Figure 5. Method of calibrating brake-pedal instrumentation.

METHOD

The Sample

One hundred rated Air Force pilots were selected by height and weight as subjects. When weighed and measured, they wore light summer clothing, which added about 4 lb. to body weight without appreciably affecting sitting height. Shoes raised the stature about 1.1 in. (Both clothing weight and shoe height were measured on a small, selected subsample of subjects.) In these circumstances the subjects varied in stature from 64.7 to 76.5 in., averaging 70.7 in.; in weight from 132 to 226 lb., averaging 172.8 lb.; and in sitting height from 34.2 to 40 in., averaging 36.6 in. Allowing for clothing effects, the sample represented in stature about 99% of the Air Force flying personnel, in weight about 95% and in sitting height about 99%, according to Air Force anthropometric data taken in 1950 (Hertzberg, et al., 1954).

The subjects in their flying duties had experience in nearly all aircraft current at that time. Light, medium, and heavy bombardment airplanes were represented by pilots of B-17's, B-26's, B-29's, and B-36's. Pilots of F-86, F-84, F-80, F-51, and F-47 fighter aircraft were also tested. Pilots of cargo and transport planes (C-47, KC-54, YC-74, C-82, C-119) and of utility and trainer airplanes (B-25, C-45, T-6) were included, and there was even one helicopter pilot.

Number of Trials

The basic experimental sequence consisted of a torque trial at every 5° increment within the 5–55° range, or 11 trials. As this sequence was performed for three cockpit sizes and two leg positions, neutral and extended (to insure that all muscle combinations of braking during landing roll, ordinary taxiing and turning the aircraft on the ground in a wind were represented), the total number of trials per man was 66.

Test Procedures

The procedures began with the determination and recording of weight, stature, and sitting height (the distance from seating surface to top of head when sitting erect) in light clothing.

Cockpit and seat adjustment. The subject settled himself comfortably in the Universal Test Seat mock-up and was brought by the operator to the selected eye level (37, 39¼, or 41 in.) for the first tests. He was then adjusted forward or backward in relation to the rudder pedals according to his body size, within the limits prescribed in what were then drawings AD-1 and AD-3 of the *Handbook of Instructions to Aircraft Designers* (now the *AFSC Design Handbook,* revised 1970). Plenty of time was allowed for this so that the pilot's usual or preferred body position for operating the brakes could be reproduced. During initial adjustment, rudder bars were placed at neutral, and brake pedals were arbitrarily set at 25° forward of vertical to ensure consistency of cockpit adjustment from subject to subject. That angle was chosen because the foot was approximately at the midpoint of its angular travel between the extremes of flexion and extension.

Two possibilities exist for foot placement in the actuation of brake pedals. The long-footed pilot often presses his instep against the rudder bar, having sufficient leverage on the pedal with the ball of his foot. Conversely, the short-footed pilot generally sets his heels on the rudder bar to obtain adequate leverage (see Figure 3). An informal preliminary poll indicated that more than half the pilots adopted the latter practice to be sure of an adequate reserve of braking force.

During the planning of procedures for this study, it was realized that the measurement of both conditions would double the number of trials and thus unduly prolong the study. The condition of greatest leverage was therefore chosen (heel on rudder bar), regardless of foot size, because it produces maximum torques.

Because pilots are seriously concerned with secure and comfortable foot placement on rudder bars and brake pedals, the subject and operator gave full, careful consideration to these matters. No tests were conducted until the subject had been satisfactorily adjusted in the mock-up and he had indicated his approval. The operator then placed the midpoint of the ball of the subject's foot squarely over the pressure bar (P), marking its location under the foot by a piece of tape on the edge of the subject's shoe sole. He also placed another strip of tape on the shoe heel over an axial line scribed on the rudder bar. That position was retained for all tests, so the foot could easily be repositioned after a rest.

Instructions. At this point the operator explained the purpose of procedures used in this test. Regarding the force to be exerted, he said,

> You have been told that there are 66 separate trials in which you must exert muscle force. In each trial you are to exert your greatest level of effort, but only through the ball of your foot with the muscles of your foot and calf. During the exertion, *you are not to raise your heel from the rudder bar, nor your buttock from the seat.* You should exert as much pressure as you can while still retaining strength and control for other movements that might become necessary in an emergency during flight simulated by these tests. Sudden lunges are not allowed, and you must especially guard against "locking" your foot in some position and then pressing against the seat back with your shoulders while you straighten your leg and hold your body rigid.

Because the object here was cooperative performance rather than a test of comprehension and memory, the instructions were repeated or rephrased as necessary for those who asked questions about them. The subject was given six carefully supervised practice runs, after which he rested about five minutes.

Torque tests. When sufficiently rested, the subject applied pressure with the right foot to the brake pedal. On reaching maximum pressure he held it momentarily so the operator could note and record the reading. The subject then relaxed while the operator reset the apparatus. The indicator dial could not be seen by the subject undergoing tests.

The order of tests was varied to avoid sequence effects. All three types of variable–pedal angle, leg extension, and cockpit size–were changed in a random fashion to minimize fatigue errors and others that might result from too-vigorous initial efforts.

Comfort poll. Experience soon showed that subjects strongly disliked the tests at extremes of pedal angle, so the last 86 men were polled for subjective attitudes toward the comfort of each pedal angle. Of this group, 83 men gave data for each pedal angle at each cockpit size; the remaining three covered only the 37- and 39¼-in. cockpits. The opinions were expressed on a six-point verbal scale from "very poor" to "excellent" for each pedal angle. Altogether, the subjects expressed 256 sets of opinions.

RESULTS AND DISCUSSION

The data presented numerically in Tables 1 and 2, and graphically in Figure 6, give realistic and remarkably consistent values of the forces that USAF pilots can exert on their brake pedals in the several test conditions. When used with their respective standard deviations, the data permit calculations of the least weight of material required in the pedal subassembly to withstand those forces safely.

As expected, actual pedal forces varied widely according to such factors as body size, body condition, and motivation, but also biomechanically according to the angle of the foot in its arc of travel. Like the adjustabilities of the seat and the rudder bars, body joints also have their built-in stops, and the associated muscles are limited in the amount of their stretch and contraction. For both the flexed (5°) and extended (55°) foot positions, these pilots as a sample had clearly reached their limits. At either extreme, the values for both leg positions are far below their peaks, and are dropping very rapidly. When the flexor or extensor muscles can no longer contract, the foot can move no further, and hence cannot increase its force output.

More important than the numerical values, however, is the determination of the pedal angles that provide each man his greatest mechanical advantage, whatever his individual strength or size may be. The pattern of these angles is shown in the polar graph (Figure 6). In this graph, the forces in pounds exerted by the ball of the foot (with a constant lever arm of 6.15 in.) are plotted against the pedal angles. For all three cockpit sizes and for both leg

TABLE 1

Means of Pedal Forces (lb.)[1] Exerted in the Neutral Pedal Position

	Cockpit Size (in.)								
	37			*39¼*			*41*		
Foot-Pedal Angle	*N*	*Mean*	*S.D.*	*N*	*Mean*	*S.D.*	*N*	*Mean*	*S.D.*
5	55	109.7	54.60	34	98.7	41.74	39	102.3	46.54
10	97	120.6	64.70	95	111.7	57.68	94	118.5	60.62
15	99	131.8	67.63	100	124.3	61.13	98	129.7	65.86
20	99	138.5	69.90	100	131.9	65.23	98	136.9	71.12
25	99	140.5	69.45	100	137.4	68.47	98	141.0	69.58
30	99	136.7	68.43	100	136.9	67.08	98	142.0	67.37
35	99	128.7	60.78	100	127.3	59.74	98	132.0	58.12
40	99	116.4	53.68	100	115.1	53.67	98	119.7	51.94
45	99	104.3	43.13	100	106.7	49.75	98	110.2	48.92
50	99	87.4	39.04	100	91.4	41.81	98	98.5	45.96
55	99	74.2	34.18	100	77.9	37.18	98	83.9	40.16

[1] To obtain torques in inch-pounds, multiply these values by 6.15.

TABLE 2

Means of Pedal Forces (lb.)[1] Exerted in the Extended Leg Position

Foot-Pedal Angle	Cockpit Size (in.) 37			39¼			41		
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.
5	47	123.9	48.34	29	109.1	44.94	29	100.2	45.67
10	96	148.0	57.94	92	135.3	58.76	86	122.3	52.71
15	96	169.3	66.05	99	156.5	68.17	93	144.6	61.43
20	98	177.1	70.18	99	166.8	72.38	95	157.1	70.97
25	98	184.5	75.33	99	171.2	71.39	96	173.8	77.59
30	98	183.6	71.59	98	177.0	71.67	96	174.2	76.01
35	98	179.6	70.36	98	173.4	67.36	96	166.5	69.53
40	98	163.4	62.74	98	158.1	64.02	96	156.8	64.71
45	98	150.7	58.48	98	149.3	54.04	96	146.0	60.54
50	98	133.7	51.29	98	132.6	49.16	93	136.3	52.72
55	96	112.6	50.13	98	113.0	45.60	91	118.8	50.05

[1] To obtain torques in inch-pounds, multiply these values by 6.15.

positions, the peak forces were exerted between 20 and 30° past vertical, with the "shoulders" of the curves occurring roughly between 15 and 35°. This 20° segment, obviously the zone of maximal mechanical advantage in this type of torque exertion, should be utilized in the design of aircraft rudder pedals. This means that the entire braking system should be designed to optimize the use of those 20°. The same is true for other foot controls using the same foot action.

The foot torques exerted about the ankle of the extended leg are almost everywhere greater than those of the leg at neutral, excepting only a few in the 41-in. cockpit. In both leg positions, the forces at angles up to about 25° were greatest in the 37-in. cockpit, as might have been expected because the buttocks were lower, i.e., more nearly in a horizontal line with the pressure bar of the pedal. In the extended leg position, at least in the two smaller cockpits, it apparently becomes easier for a subject to hold the body rigid, like a strung bow, and then to exert thrust at the foot and the shoulders, using the large torso muscles. Thus the smallest cockpit size appears to provide a mechanically more advantageous situation for maximal thrust, at least at the 5 and 10° pedal angles. The seat back and the pedal are more nearly parallel, and the leg can be made more nearly straight and horizontal between them, permitting the knee toggle action that produces the greatest leg forces. In this study, the subjects were warned against this action, but it is a tendency difficult for a subject to avoid when exerting maximum force, and difficult for the operator to detect in a subject wearing loose clothing. So some of this effect is undoubtedly reflected in these results.

Beyond those observations, no dominant relationship emerged in this study between torque applicability and cockpit size. It may be generally concluded that cockpit size per se is not an overriding factor, if pedal adjustability is great enough to compensate for the changes in seat height with respect to pedal height above the floor. This is fortunate, because it permits the use of a standard cockpit as well as of rudder assemblies having standard characteristics of motion and adjustability.

Not more than half of these pilots were able to move their feet through the pedal test range of 5 to 55°, so it is of interest to note the percentages of those who could not, and at what angles they fell short (see Table 3).

In the 37-in. cockpit, about half of the subjects could not flex their feet sufficiently to maintain the 5° angle at either leg position; 2–5% could not at 10°, and 6% could not extend their feet to 55° in the extended leg position. In the other two cockpit sizes, the situation was worse: about two-thirds of the

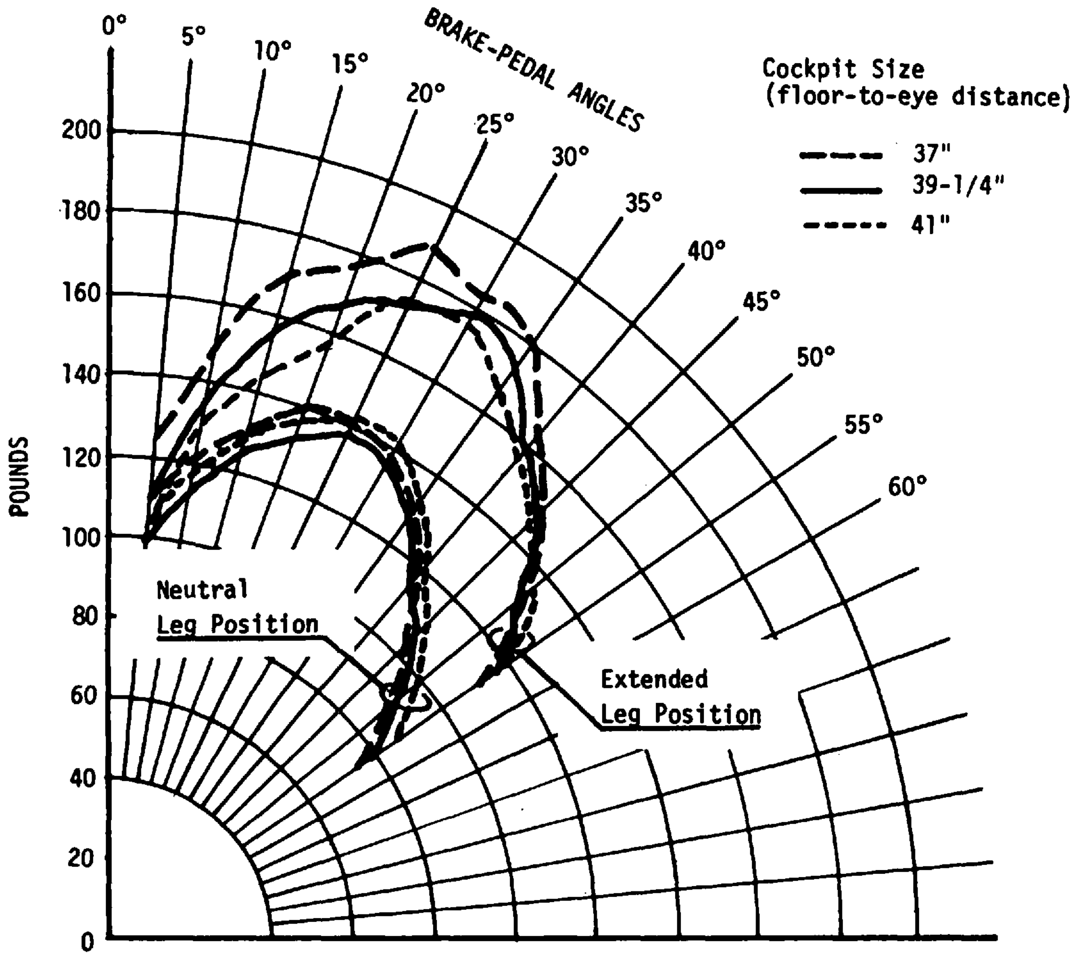

Figure 6. Maximum brake-pedal forces in various leg and foot positions (means of 100 subjects).

An early version of this graph previously published in this journal (Hertzberg, 1960) contained some errors which have been rectified as follows: (a) The words "buttock-to-eye distance" should have read "floor-to-eye distance," as shown in this graph. (b) Correction of some small arithmetical errors in the first data reduction has slightly changed a few peak heights. The present curves supersede the previous ones. The first author assumes full responsibility for both errors.

subjects could not maintain the 5° angle; 3–10% could not extend the foot to 55° when the leg was extended. The torque results and the mobility results are, of course, directly related: if the foot cannot move farther, it cannot exert yet more force.

The above angular values, of course, do not apply to all mankind. They appear valid only for our population whose cultural patterns of posture do not include the so-called "squatting position" (feet flat on the ground and the body folded up so that the knees are just under the chin and the hands are usable close to the ground). Persons born into a Western culture tend to restrict their body positions to standing, sitting on chairs, or lying, and so do not flex their ankles much. People born into Oriental cultures, however, especially in Southeast Asia, begin to squat at an early age and continue it through life. Such persons

TABLE 3

Percentages of Subjects Able To Keep Feet on Pedals Through The Total Angular Range

	Cockpit Size (in.)											
	37				*39¼*				*41*			
	Foot-Pedal Angle (deg.)											
Leg Position	*5*	*10*	*15*	*55*	*5*	*10*	*15*	*55*	*5*	*10*	*15*	*55*
Neutral	55.5	98	100	100	34	95	100	100	41	97	100	100
Extended	48	95	99	94	31	94	100	99	30	90	98	97

could be expected to have distinctly larger angles of foot flexion and extension than were found in this study.

As might be expected, the comments of the subjects regarding ankle comfort also parallel the torque findings. Table 4 shows that 80% of the 86 men polled preferred angles between 25 and 35°, and 98.7% preferred angles between 15 and 45°. Not a single pilot stated that his foot felt comfortable at 55° or even 50°, and almost none at 45°. At the opposite extreme, not one pilot said that 5 or 10° was a comfortable angle.

If we accept this selected, 100-man sample as representative of the capabilities of the Air Force population, the results suggest the parameters of a brake-pedal design that should maximally utilize the mechanical advantage of the Air Force pilot's foot. At the brake-off position (0% of brake application), such a pedal would begin its travel at not less than 15° past vertical, terminating its arc at 35° with 100% of brake application. This is the optimal range. But if a greater angle of pedal travel were required for valid design reasons, the rapid decay of the pilot's ability to exert pedal force would have to be considered.

These findings appear to have relevance for the design of automotive accelerator-pedal travel, even though the position of the foot in this study is not precisely the same as on an accelerator in an automotive vehicle. The position of greatest mechanical advantage, however, probably is the position of least fatigue, and therefore it seems reasonable that these findings may be useful in setting the limits of accelerator pedal travel in automotive vehicles, especially long-distance trucks.

CONCLUSIONS

Torque tests of 100 pilots' feet on an instrumented rudder pedal showed that at various angles between 5° past vertical and 55° past vertical, the highest mean forces were

TABLE 4

Percentages of Preference for Different Ranges of Foot-Pedal Angles[1]

Foot-Pedal Angle (deg.)										
5	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*
0	0	3.5	9.0	25.0	32.0	23.0	6.2	1.2	0	0
					80%					
					95.2%					
					98.7%					

[1] Opinions: $N = 256$. No opinion; 1.3%.

exerted between 15 and 35° past vertical, for all three cockpit sizes and for both leg positions, neutral and extended. Comments on foot and ankle comfort at each angle, solicited from 86 of the men, showed a strong preference for the same arc as a zone for comfortable brake-pedal actuation. As the region of high torque output indicates the arc of maximal mechanical advantage of the foot, and thus probably the zone of least fatigue, these findings should be considered in the design of any pedal in which maximal integration of pedal action with foot motion is sought, whether it be an aircraft brake pedal, automotive accelerator, or other similar lever.

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