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THE HUMAN FACTOR IN THE DESIGN OF STICK AND RUDDER CONTROLS FOR AIRCRAFT

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1. SUMMARY

1. This study is an attempt to determine how airplane control systems may be designed to provide the pilot with optimal sensory information by means of pressure cues obtained from operating the stick and rudder. The present approach to the problem consists of an examination and evaluation of literature pertaining to

a) the maximum forces that may be exerted by a human pilot;
b) human reaction time insofar as it may be expected to cause delays in the pilot's response;
c) the optimal design, placement, and manner of movement of controls, and
d) the optimal gradients of control forces.

2. Current specifications for stability and control characteristics of military and civil airplanes are examined. They are found to lack the precision required for insuring controlled flight at all times, for preventing the forces from exceeding the pilot's strength, or for providing for consistent responses of the plane to various motions of the controls. The control force gradients that are specified permit variations in design not always desirable.

3. The maximum force exertable by a pilot is found to depend on position of the hands and feet, type of control and the direction in which the force must be exerted. Except for certain positions close to the body, a pilot can easily exert and usually exceed the force limits set by current plane design specifications. That the pilot may sometimes be required to exceed the specified limits for a given plane is shown in certain flight test records.

4. Sensitivity to changes in pressure varies in a non-linear fashion with absolute increases in pressure. This follows a psychological relationship generally found to describe the ability to discriminate sensory effects. This means that stick forces must increase geometrically with stick displacement and with speed in order to furnish the pilot with optimal pressure cues. Pressure sensitivity of the hands is poor at pressures below 5 pounds, and control movements are fatiguing above 35 pounds. The recommended ranges of control forces, for optimal accuracy and consistency of performance, are 5-30 pounds for stick, and 15-60 pounds for wheel and rudder. Friction forces of about 2-3 pounds on hand controls, and about 7 pounds on foot controls, are not undesirable.

5. Hand controls are more precise than foot controls, but no difference is found between stick and wheel as far as efficiency of performance is concerned. Fore-and-aft hand motions are slightly more precise than right-and-left or rotary motions. Controls should be shaped for maximum convenience of grasp, and placed symmetrically with respect to the pilot, with hand controls at about elbow height. Increments of about 15% may be detected in the linear displacement of hand-operated controls, under constant load conditions.

6. Simple reaction time to sound is slightly faster than to touch or light, and approximates 0.600 seconds for a complex task. Where discrimination and judgment are involved, about 1-2 seconds is required. The rate of motion of controls depends on the load, and appears to be higher for push than for pull motions.

7. Stick force characteristics should be consistent for various types of aircraft. The responses of the plane to control stick deflection should also be standard, consistent, rapid and smooth. There is doubtful value in maneuvering characteristics which so affect the pilot that he becomes disoriented. Stick forces should change with speed, acceleration and load to provide information and warning as stress limits are approached.

8. Stick forces should increase geometrically with stick deflection. It is recommended that stick forces increase more rapidly at very slight and at very great stick deflections than equally over the extensive range between these extremes. At very slight deflections, although the absolute force is small, a rapid increase is needed to overcome the masking effect of friction; at very great deflections, it serves as a warning that the stress limit is being approached. The force vs. deflection gradient should be increased as the speed is increased. Thus, a family of curves should describe the force-deflection relationship at various speeds for a given type of plane. A quantitative description of these gradients is suggested but should be verified by flight tests.

9. Various types of booster systems are described. It is recommended that if booster systems are employed, the desired stick-feel characteristics should be provided by artificial means.

10. Experimental validation of all recommendations is urged.

2. STATEMENT OF PROBLEM

The handling of high speed aircraft requires the control of enormous forces by the application of equal counter-forces, only a part of which can supplied by the pilot. Since aerodynamic pressures increase markedly with speed while the pilot's strength is relatively fixed, some means must be ava able to assist the pilot in moving the control surfaces on the newer airpla Using conventional stick and rudder controls, the pilot may be assisted by vices which utilize mechanical as well as aerodynamic principles.

Conventional control linkages permit the pilot to perceive some of the airplane's flight characteristics through position and pressure effects on stick and rudder controls. These effects are called "stick (or rudder) fee and many pilots rely upon them in flying the airplane. "Stick feel" depend in part, on the cues arising from the feed-back of some fraction of the aero dynamic forces developed with displacement of the control surfaces. Mechanical boosters introduce special "feels" on the controls due to friction, time lag, pulsation, inertia and other attributes of the system. Thus, as the fraction of force supplied by the pilot diminishes, feel becomes more and mo dependent on the operating equipment rather than on flight conditions. Some modern planes employ mechanisms with a booster-to-pilot force ratio of 10:1, (i.e., the pilot supplies only 1/10 of the required control force) while future designs may require ratios of 33:1 and even 990:1

At the present time, pilots have come to expect certain stick-feel effe as the control stick is moved to various positions at various speeds. Boost mechanisms may so modify this relationship that stick-feel varies almost independently of control surface pressures. In one system, for example, displ ment of the control stick is related directly to displacement of the control surface, while stick pressure remains constant at a low value, thereby elim any possible differential pressure cues. Or, the stick may be used as a pointer to direct control surface motion while the degree of stick deflection monitors the rate of change. In this case, normal pressure and displacement cues are altered. "Normal" control feel may be maintained by artificial means, but to accomplish this, it would first be necessary to examine the properties of "normal" control feel. Current specifications do not rigidly determine "standard control feel" and it can be shown that current airplanes actually differ in their feel characteristics.

An airplane may be flown without "normal" control feel, as has been shown by the operation of remotely controlled aircraft. However, it has not yet been demonstrated that it is possible to maneuver a fighter aircraft in simulated combat in this manner. Jet fighter pilots, 15 of whom were interviewed in connection with this project*, indicate that there is time for only slight attention to the instruments during high speed acrobatics in planes like the P-80 Shooting Star and P-84 Thunderjet. These pilots maintain their primary orientation during maneuvers by reference to the horizon and stick-feel, with secondary regard to three of the instruments: the Mach meter, yaw indicator, and altimeter. They regard stick-feel as a particularly valuable cue because it is always available without distracting the pilot's attention from his target. A pilot upon whom is placed the tasks of navigation, communication and aerology, in addition to flight and combat, approaches the limit of his abilities. For such a man, a stick with feel is equivalent to a host of flight instruments.

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* The author of this report conducted interviews on the subject of stick-force curves with 15 test pilots and 13 aeronautical engineers at the Naval Air Test Center, Patuxent, Md.; the Flight Test Division, Air Material Command, Wright Field; and at three plants where jet fighters are built. Ten of the pilots had extensive experience in jet fighters, such as the P-80, P-84 and FJ.

Since current airplanes are not consistent in their control feel charact istics, present practice alone does not dictate a desirable standard for futu aircraft. It would appear useful to examine several questions generally applicable to all airplanes regardless of their speed:

a. What are the maximum forces that may be exerted by a human pilot

b. What delays may be expected as a consequence of the pilot's reaction time?

c. Where should the controls be placed and how should they move for most efficient manipulation by the pilot?

d. What gradient of stick forces will provide the pilot with optimum pressure cues?

In this paper, the problem is approached by an examination of published information and by extensive interviews with jet plane pilots. The study indicates a direction for the experimental work which may be desirable to verify the present conclusions. Attention in this study is directed primarily to fighter aircraft equipped with conventional stick and rudder controls.

3. CURRENT SPECIFICATIONS FOR CONTROL FORCES

The current specifications for stability and control characteristics of military airplanes were established in 1945 by agreement between the Army and Navy (73, 74).* Control forces are limited to the following maxima on stick type controls:

elevator	35 lbs.**
rudder	180 lbs.
aileron	30 lbs.

The Civil Aeronautics Board has established similar requirements for stick controls on transports except that the elevator force limit is extended to 50 lbs. in the cruising and 80 lbs. in the landing configuration (67).

Besides these specifications, there are other feel characteristics which are considered desirable (73, 74):

1. Stick movements should enable controlled flight in specified configurations, such as landing and maneuvering.
2. Control forces should increase with airplane speed, acceleration, and with stick displacement from neutral.
3. Control forces should trim to zero in cruising flight.
4. An elevator control force gradient of at least 3 pounds per "g" is specified for steady turns and quick pull-ups.
5. A smooth curve with sufficient gradient to return the control to approximate trim position is required for the ailerons.
6. Friction in the control system should be as low as possible and not exceed 3 lbs. for elevator, 7 lbs. for rudder, and 2 lbs. for the ailerons.
7. When released, the controls should return to the trim position, i.e., self-centering.

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* Numbers in parentheses refer to references listed at the end of this report.

** Extended to 150 lbs. in recovery from high speed dives.

As may be expected, these requirements attempt to insure controlled flight at all times by preventing the forces from exceeding the pilot's strength and by providing for consistent responses of the aircraft to various motions of the controls. It may be noted that a precise definition of feel characteristics, which would consist of specified relationships between stick displacement and stick force, and between speed and stick force, are not present in the military specifications. For that matter, neither is it in the Civil Aeronautics Board statement, though the latter is more explicit when it requires that there be a "stable slope of stick force curve versus speed...such that any substantial change in speed is clearly perceptible to the pilot through a resulting change in stick force". This describes a necessary condition, but provides no specifications of a quantitative nature, so that the aeronautic designer is left to his own discretion.

4. EVALUATION OF HUMAN CAPACITIES FOR AIRCRAFT CONTROL

In this section of the report, there will be summarized considerable information, which may be found in the literature, on the human abilities related to aircraft control forces. The findings fall into categories concerned with maximum forces, speed of response, location of controls, and sensitivity to pressure differences (kinesthetic sensitivity).

A. The maximum forces that may be exerted by the pilot

It is obvious that the maximum control forces required of a pilot must never exceed the limit of his strength. All present specifications for control stick forces appear to be based on a study of two pilots carried out by the National Advisory Committee for Aeronautics in 1936 (17). A comparable study for wheel-type controls was reported in 1937 (43). The forces which may be exerted by a pilot in the prone position have also been examined (52, 7), but will not be described here.

The maximum forces which may be exerted depend upon the direction of motion and the *position of the hands and feet*. These in turn are almost completely determined, in this case, by the manner in which the cockpit is usually constructed. For purposes of reference, Fig. 1 presents some dimensions which are specified for the standard cockpit, based upon extensive anthropometric data collected by the AAF (49, 50):

distance from back of seat to stick	19.00	inches
horizontal adjustment of seat	± 1.50	"
stick throw, forward	5.00	"
stick throw, aft	9.00	"
stick throw, lateral (right or left from neutral)	7.00	"
height of stick above floor	25.50	"
vertical seat adjustment	± 3.50	"
rudder pedal position (from back of seat)	34.75	"
rudder pedal adjustment	+ 2.00	"
rudder pedal travel (forward and aft)	± 3.75	"

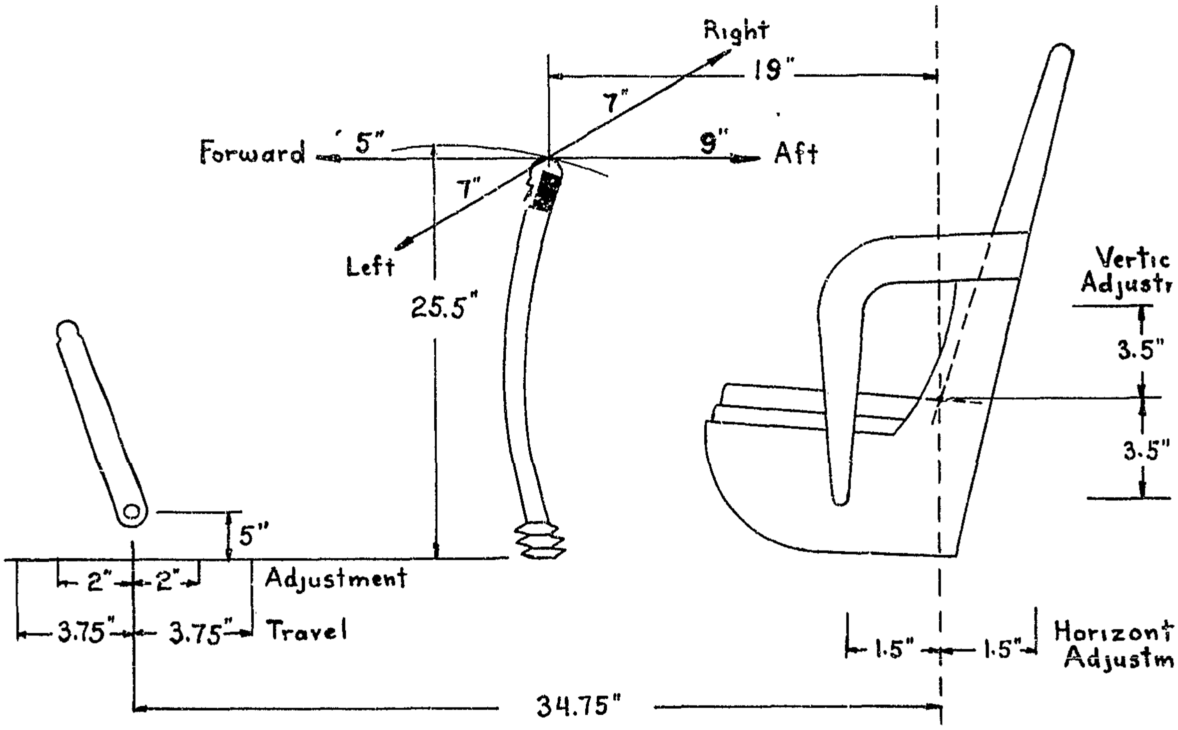

Fig. 1 Basic cockpit dimensions in the standard airplane cockpit.

Inspection of these dimensions and Fig. 1 will show that hand motion may occur within an area of 14 by 14 inches as measured at the top of the stick. Considering maximum fore-and-aft seat adjustments, the stick may be moved to within 8.5 inches from the back of the seat, or as far as 25.5 inches from that point. Similarly, by rudder motion, and rudder and seat adjustments, the rudder may be brought anywhere between 28.5 and 41 inches from the back of the seat.

The NACA study measured the forces that could be exerted by a pilot operating a stick with his right hand in many hand positions and with the cockpit tilted in several attitudes. Using as reference values the maximum forces that could be exerted by the weaker of the two pilots who served as subjects, it was found that "the average of the ...push and pull forces that could be exerted in all attitudes with the controls in the neutral positions is 35, 95 and 400 lbs. respectively...for ailerons, elevator and rudder" (17). Two comments arise with respect to the significance of these findings. First, two pilots can not be considered an adequate sample upon which to base standards for all pilots, particularly when large numbers of subjects are readily available. The factors that may produce variation in the experiment (e.g., height, weight, age, physique) are more numerous than the subjects used, and this decreases the reliability of the present data. Using the equipment described here, further information must be collected, with adequate statistical controls. Second, the figures quoted from the NACA summary above are misleading because they represent only the forces that may be exerted in the neutral control position. The fact is that in other hand and feet positions, less force can be exerted, and this will be shown below.

(1) Elevator Control Force

Figure 2 is derived from data presented in the NACA report. The two upper curves represent the maximum push and pull forces that may be exerted in the most favorable lateral position, which was right-of-neutral for these right-handed pilots; the two lower curves represent the forces in the least favorable lateral position. It is clear that greater pull forces than push forces may be exerted in all positions except when very close to the seat. The ability to exert a push or a pull force increases with distance from the seat.

This NACA data may be used to set up certain provisional specifications for maximum allowable elevator forces at the various limits of movement in the standard cockpit. However, two minor reservations may be noted: (a) estimates were made with the stick drawn aft to 12 inches from the back of the seat where as specifications permit motion to 10 inches, and (b) estimates were made at 8 inches lateral throw, whereas specifications limit such motion to 7 inches. Table 1 presents the maximum elevator forces that were exerted in the several limiting positions of elevator travel, as shown in Figure 2. Maximum push forces in the central position increase from 39 lbs. at a position close to the seat, to 76 lbs. in neutral and to 109 lbs. at a position furthest from the seat. The maximum push forces are sometimes as low as 30 or as high as 109 lbs depending upon lateral position. The pull forces are 24, 91 and 129 lbs. in the central position and range from 24 to 129 in other lateral positions. Using the lowest force that may be exerted in any combination of fore-and-aft and lateral position, maximum elevator push should not exceed 30, while maximum elevator pull should not exceed 24 pounds.

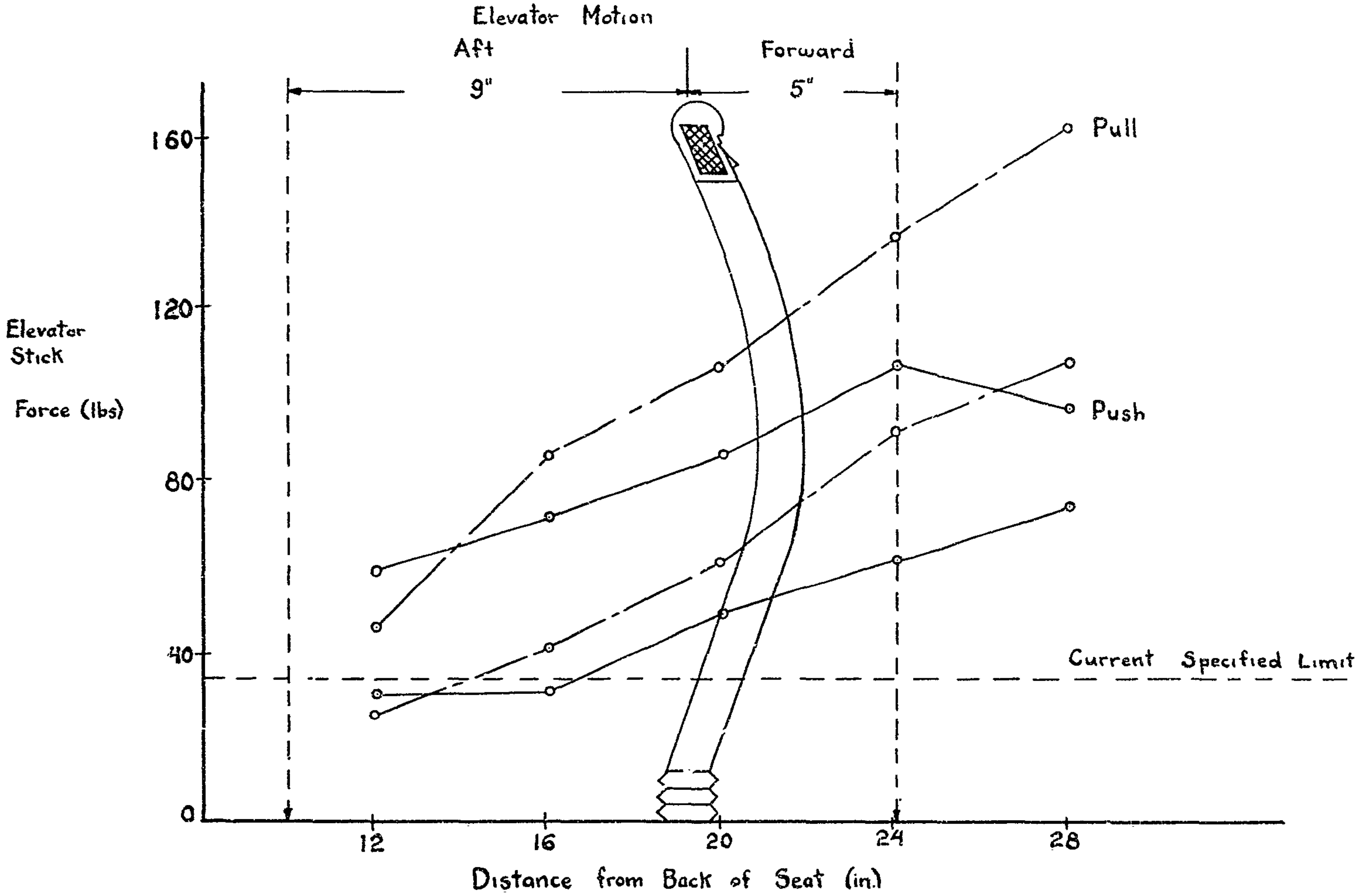

Fig. 2 Maximum push and pull forces exerted on elevator at various hand positions (lesser force of two pilots). The two upper curves represent performance in the most favorable while the two lower curves represent the least favorable lateral position (range ± 8 in. from center). The limits of elevator motion in a standard cockpit and the maximum permissible elevator force fixed by specification (35 lbs.) are indicated.

TABLE 1

ESTIMATES OF THE MAXIMUM ELEVATOR FORCE (LESSER FORCE OF TWO PILOTS) THAT MA

BE EXERTED AT THE LIMITING POSITIONS PERMITTED IN THE STANDARD COCKPIT

Stick Position	Distance from back of seat (in.)	push force (lbs.)			push force (lbs		
		lateral position			lateral positio		
		most unfavorable	central	most favorable	most unfavorable	central	mo favor
Back	12*	30	39	59	24	24	4
Neutral	19	45	76	76	51	91	10
Forward	24	64	109	109	90	129	12

* The specifications allow the stick to be drawn aft within 10 inches from the back of the seat. NACA data permit estimates to be made only up to a point within 12 inches of the back of the seat.

In order to show the importance of lateral displacement on maximum exertable elevator force, push-and-pull forces were averaged for Fig. 3. This shows, again, that more force may be exerted at longer reaches. It also shows that for most fore-and-aft positions, right-handed pilots can exert their maximum force on the right, less in the laterally central position, and least on the left.

If the designers of aircraft were to respect the effect of stick position, they would make sure that the greater forces occurred at the furthest forward position. This may not be a reasonable engineering requirement, but then neither is it reasonable that the present force required to stall a plane upon landing should approach the maximum force that may be exerted in that position. There may be some merit in permitting control forces to approach within a fixed ratio of the maximum that may be exerted in various positions.

(2) Aileron Control Force

Turning now to aileron forces, a similar analysis can be made, and attention may be directed to Fig. 4. The right-handed pilot can exert greater aileron force to the left (i.e. push) than to the right (pull) of neutral, the ability decreasing with lateral and forward displacement. From the neutral aileron positions, one may pull (to the right) 30 lbs. closest to the seat, 35 in elevator neutral, and 37 lbs. far from the seat. At all extreme right aileron positions, pull forces are 26-28 lbs. Push (left aileron) forces are greater, being 32, 44 and 60 lbs. respectively. Maximum aileron forces are less than maximum elevator forces and do not vary as much with changes in hand position (see Table 2). The curves of Fig. 4 indicate the influence of position on the ability to exert aileron forces and show that performance decreases at extreme positions. They also suggest that right-handed pilots might find it easier to perform counter-clockwise rolls and turns to the left than clockwise rolls or right turns.

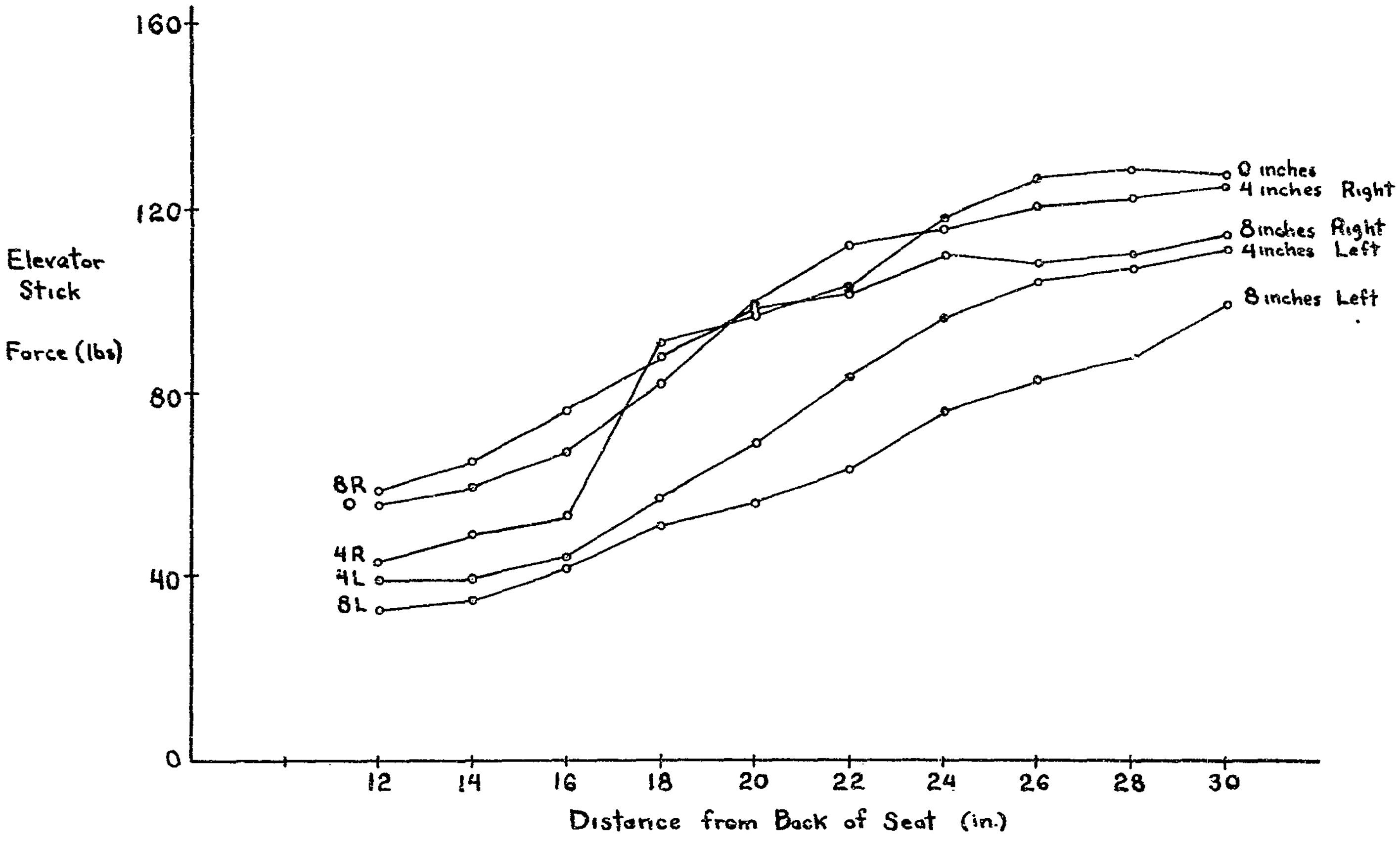

Fig. 3 Average of push and pull elevator forces exerted by a single pilot at various lateral positions.

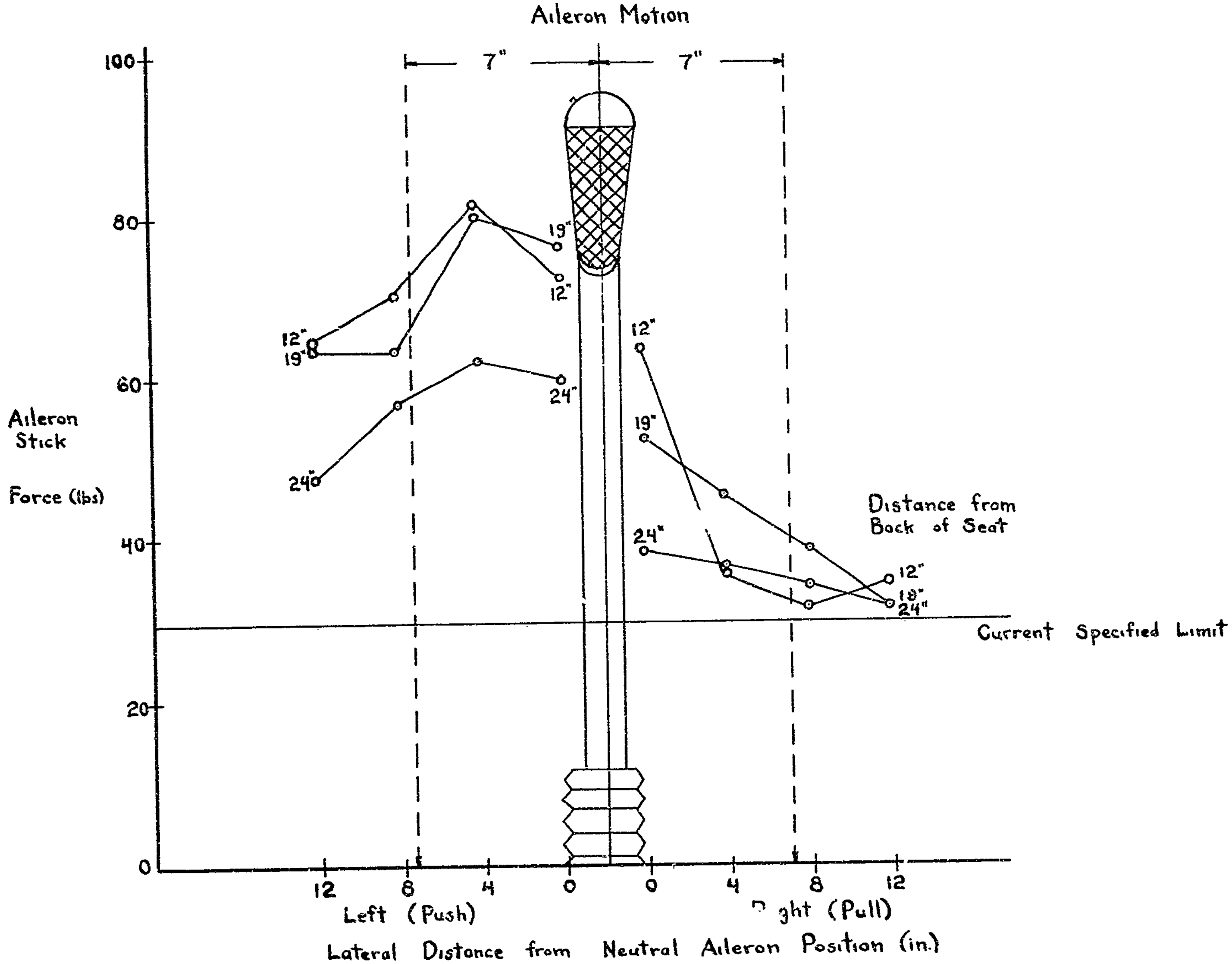

Fig. 4 Maximum aileron forces exerted at various hand positions by one pilot. The limits of aileron motion in a standard cockpit and the maximum permissible aileron force fixed by specification (30 lbs.) are indicated.

TABLE 2

ESTIMATES OF THE MAXIMUM AILERON FORCE (LESSER FORCE OF TWO PILOTS) THAT MAY BE EXERTED AT THE LIMITING POSITIONS PERMITTED IN THE STANDARD COCKPIT

Stick position	Distance from back of seat (in.)	Force (lbs.)			
		To Left (Push)		To Right (Pull)	
		extreme left	neutral	neutral	extreme right
Back	12	46	32	30	26
Neutral	19	47	44	35	26
Forward	24	40	60	39	28

(3) Rudder Control Forces

The NACA data on rudder forces indicate that the design limit of 180 lbs. can generally be exceeded. In Fig. 5 the curves represent the maximum rudder forces exerted by the weaker of the two pilots. It shows that forces as high as 430 lbs. may be exerted in neutral rudder, 246 when the right rudder bar is aft, and 315 when it is most forward, at points determined by the standard cockpit dimensions. Rudder forces fall off sharply as the seat height increases above the rudder. The present specification requires the seat to be 5 inches above the rudder. Table 3 presents the maximum rudder push force that could be exerted by the weaker pilot at three reference points in the standard cockpit.

Gilruth (14) states that the 35 lb. elevator force limit specification was selected as 80% of the maximum that could be applied with one hand and that the 180 lb. rudder force limit was 90% of the maximum for the foot. Similar reasoning must have determined the 30 lb. maximum on aileron, though he does not discuss this point. The important considerations for ailerons appear to be that control forces (a) should be as light as possible; (b) should have a lower limit of about 2 lbs. at full deflection to overcome masking by friction; (c) should not normally exceed 8 lbs., and (d) should not exceed 15 lbs. under any conditions (64).

(4) Supplementary Data

Certain additional data, from airplane flight tests, armoured tank driving tests, and motion and time studies may be used to supplement the NACA findings. Sixteen sources have been examined and are reported in Figures 6, 7, and 8 for elevator, aileron, and rudder operations, respectively. Appendix A indentifies the information shown in these graphs.

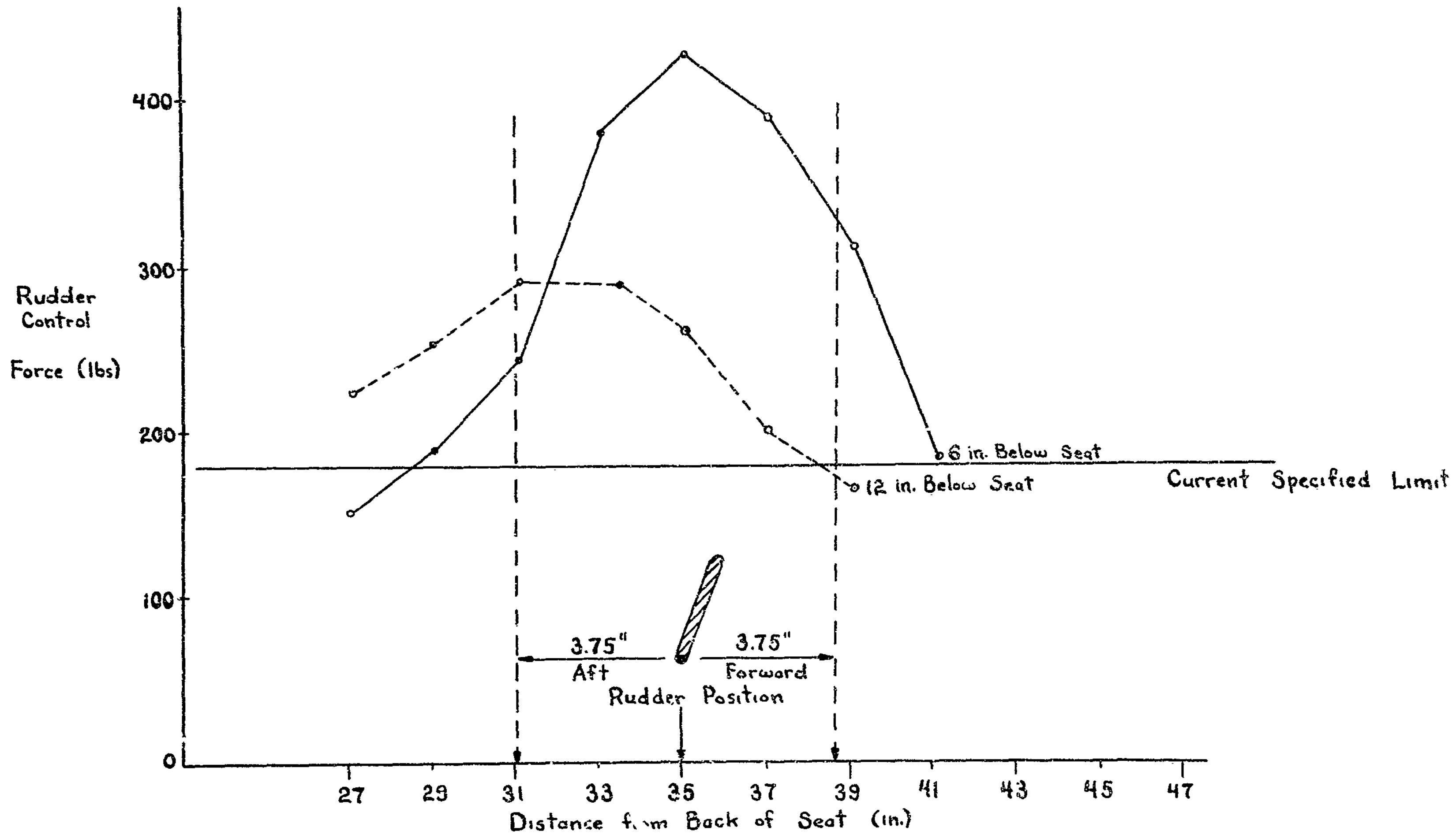

Fig. 5 Maximum rudder force (lesser force of two pilots) exerted at various foot positions with the rudder bar at two levels below the seat. The limits of rudder motion in a standard cockpit and the maximum permissible rudder force fixed by specification (180 lbs.) are indicated.

TABLE 3

ESTIMATES OF THE MAXIMUM RUDDER FORCE (LESSER FORCE OF TWO PILOTS) THAT MAY BE EXERTED AT THE LIMITING POSITIONS PERMITTED IN THE STANDARD COCKPIT (RUDDER BAR 6" BELOW SEAT REFERENCE POINT).

RUDDER POSITION	DISTANCE FROM BACK OF SEAT (in.)	FORCE (lbs.)
Back	31	246
Neutral	34.75	424
Forward	38.5	334

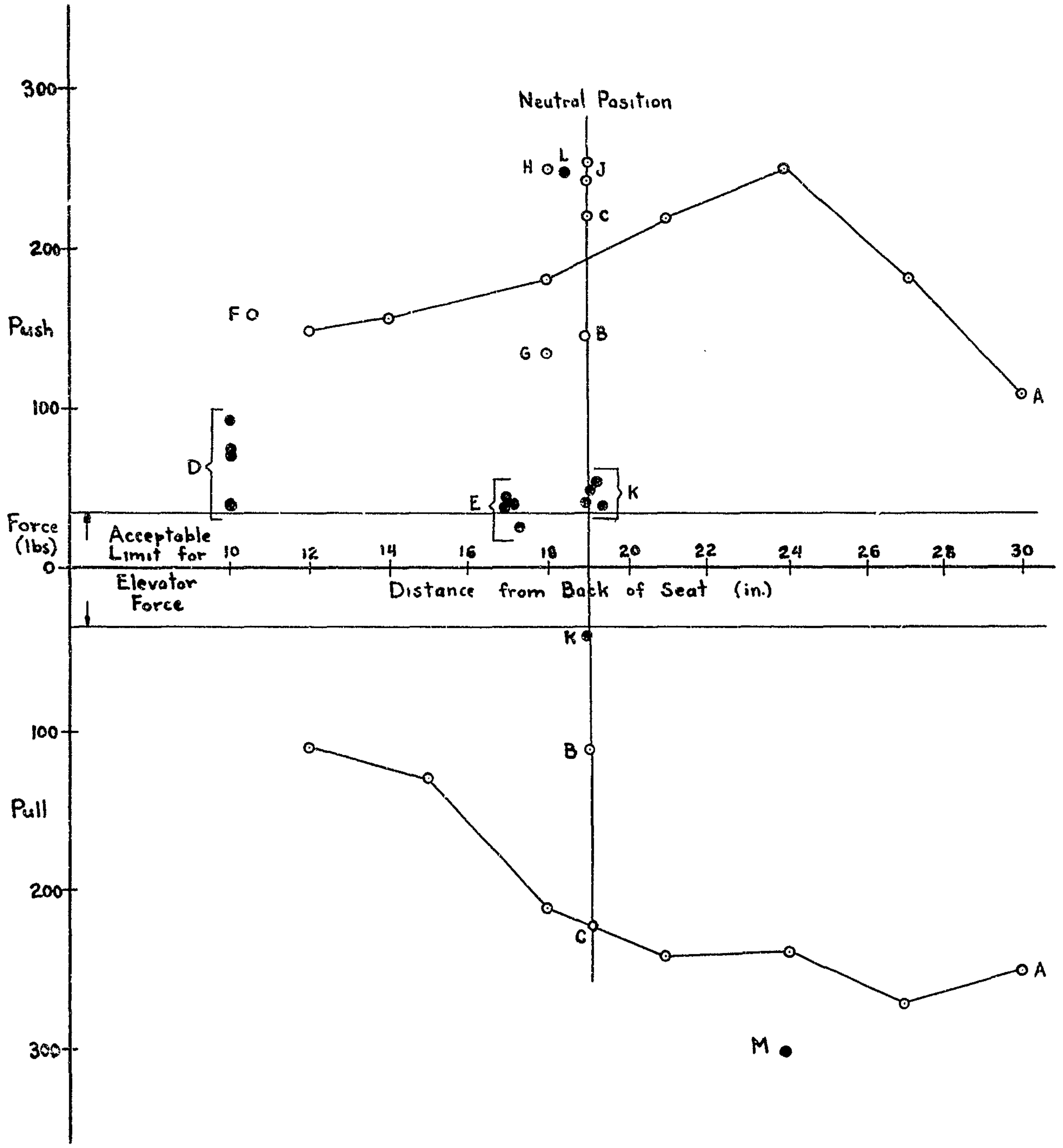

Fig. 6 Maximum push and pull forces (elevator type motion) that may be exerted, as estimated from various studies. The solid circles represent measurements made during flight tests and are not necessarily maximum effort. The letters identify the sources of this information as listed in Appendix A.

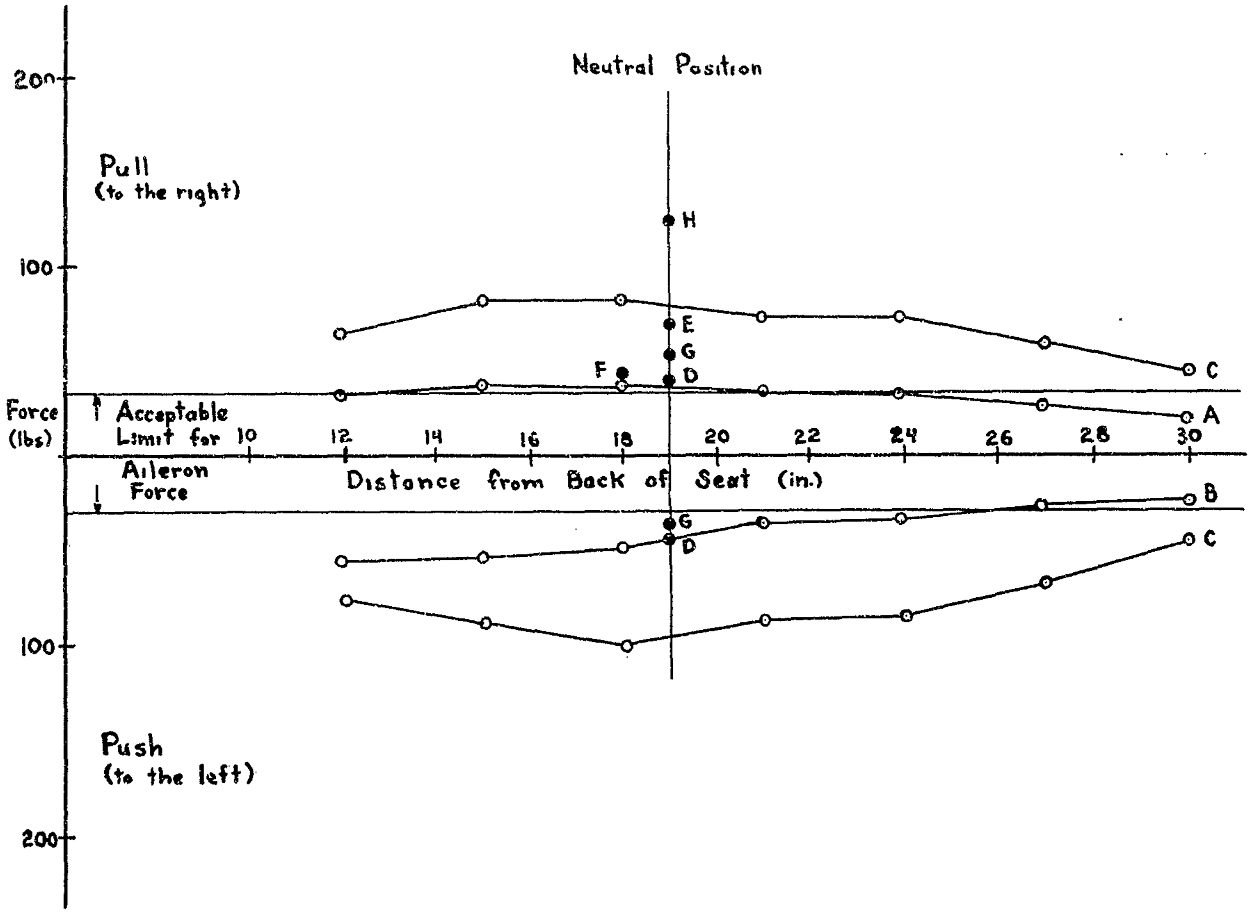

Fig. 7 Maximum lateral forces (aileron type motion) that may be exerted, as estimated from various studies. The solid circles represent measurements made during flight tests and are not necessarily maximum effort. The studies are identified in Appendix A.

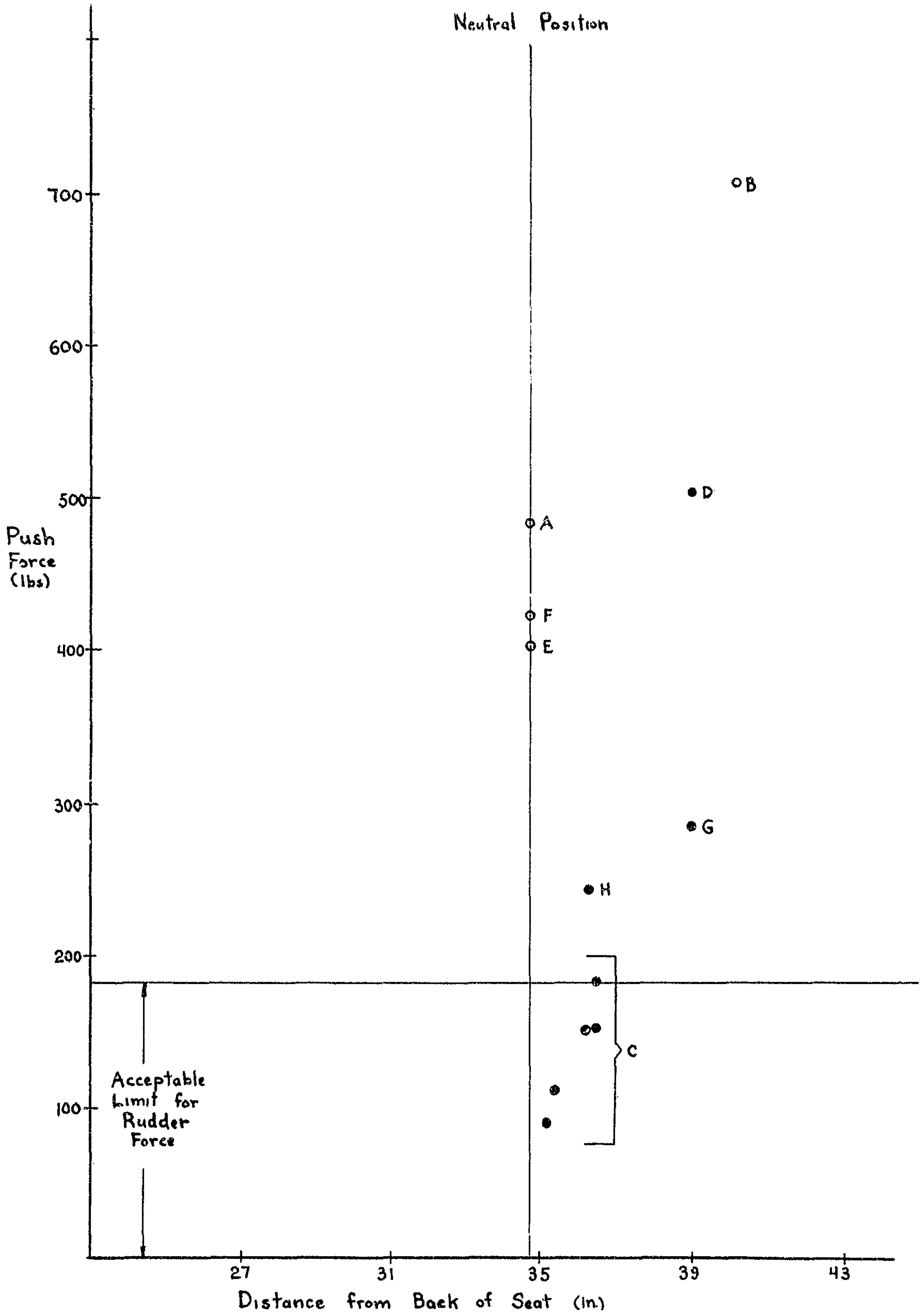

Fig. 8 Maximum pedal forces (rudder type motion) that may be exerted as estimated from various studies. The solid circles represent measurements made during flight tests, and are not necessarily maximum effort. The studies are identified in Appendix A.

An inspection of these graphs suggests the following conclusions:

(a) the force limits imposed by current design specifications are generally lower than the maximum forces which humans can exert.

(b) the forces required of pilots in some instances as recorded on flight tests exceed the limits imposed by present specifications.

(c) the permissible aileron forces approach human limits for this type of motion.

(d) there appears to be a reasonable margin between elevator and rudder forces and the human limits for these types of motion.

An evaluation of the forces which can be exerted in various hand grip and leg strength tests shows that 99% of the population can usually perform within a range of ± 50% of the mean (44). This suggests that a standard, based on some rational amount less than the average, can be applied in specifying limit forces; the averages may be determined by tests, as attempted by NACA, though on an adequate population.

Pilot acceptance of present control force standards might be interpreted as a demonstration of their validity; however, pilots often have endured undesirable practices without objection. Furthermore, another requirement in addition to specifying forces which are within human capacities, is that the actual force expenditure be optimum to minimize fatigue and to facilitate delicate control adjustments. The next section is devoted to the latter consideration.

B. <u>Sensory discrimination of control pressures</u>

Various control motions are required for take-off, maneuvering, and landing and according to design requirements, the forces involved should not be excessive. An important psychological question is whether these forces increase by magnitudes which permit the pilot to make his most sensitive adjustments. A pilot cannot detect changes of a few ounces in the pressure, i.e., "feel" of the controls; nor, while exerting a force of 100 lbs., could he detetect an increase of 1 lb. There is probably an optimum pattern of pressure increases which would furnish the pilot with a maximum number of discriminable cues.

This consideration relates to the Weber-Fechner law, a famous psychological generalization, first stated in 1834, on the perception of differences, i.e., human sensitivity. As Woodworth paraphrases it, "in comparing magnitudes, it is not the arithmetical difference but the ratio of the magnitudes, which we perceive" (66). The significance of this generalization, insofar as it applies here, is that one should not expect a pilot to detect the same differences in pressure at all points in the pressure continuum. He might, for example, discern a difference between 5 and 6 lbs. (ΔI* equals 1 lb.), but require an increase from 15 to 18 lbs. (ΔI equals 3 lbs.) before he could again note a difference. That is

$$\frac{\Delta I}{I} = k^{**},$$

where ΔI is the just discernible increase in intensity ^{I}, and k is a constant. Intensity perception is relative and not absolute.

An investigation of pressure discrimination has been carried out by Jenkins (32, 33, 34) at the Aero Medical Laboratory, Wright Field. A cockpit mock-up was prepared so that the accuracy of reproducing the various types of control pressures on stick, wheel and rudder could be determined. The subjects were blindfolded and, after practice, were required to apply designated pressures on the controls. By this technique data were gathered on the accuracy and consistency of performance of 20 AAF pilots and 13 non-pilots. No information was collected on discrimination of angular displacement or on a flight-simulating task requiring continuous adjustment.

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* ΔI represents the discernible increment in intensity, or the just noticeable difference.

** Alternative expressions of this relationship are:

$\Delta I/_{I} = k$, $\Delta I/_{I} = k$, and $\Delta I = k \log I$ (21).

The accuracy of performance in reproducing various stick pressures is given by Jenkins in tabular form (32). Figure 9 plots this data to show the constant errors of judgment (difference between standard and mean attained pressure) in the several directions of control stick motion.* This shows that pilots tend to overexert (overestimate) when trying to push (or pull) small pressures while they underexert for the larger pressures. As we already know (Fig. 2), pulling tends to be easier than pushing, while leftward motions are easier than rightward ones for the right-handed subject. This is confirmed in Fig. 9 where the greater strength that may be exerted in these directions facilitates accuracy (slight overestimation) as contrasted with considerable underestimation for the opposed motions. Since none of the differences due to direction of motion are statistically reliable, Jenkins combines the data on various directions of motion for his comparison of stick, wheel and rudder control accuracy.

One may observe, in Fig. 10 (based on data in Jenkins' study) that more sensitive control is possible by means of the stick than by either wheel or rudder. At all pressures up to 30 lbs., the constant errors are least for the stick control, with wheel and rudder following in that order. This is more sharply indicated in Fig. 11, which shows relative accuracy as determined by the ratio of constant errors to the standard pressures. The lower the ratio, the more accurate the performance. The stick is, of course, the most accurate control agent among the three types considered, and its relative accuracy is fairly constant from 5-40 lbs.; the relative accuracies of the wheel and rudder are constant from about 15 lbs. to 60 lbs., the largest value tested.

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* Errors may be of two types: Overestimation (positive constant error) and underestimation (negative constant error). The closer a value is to zero constant error, the more accurate is the performance.

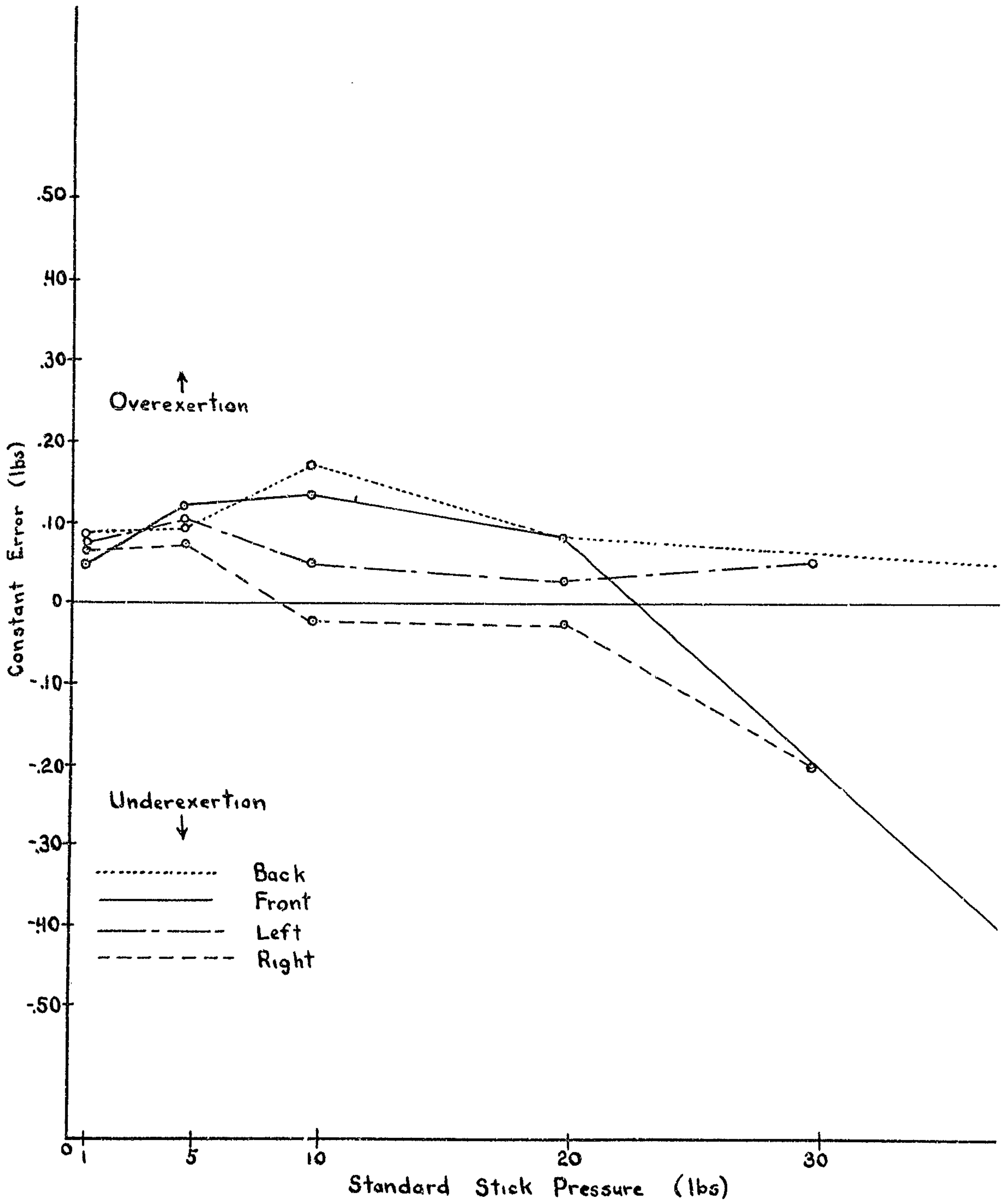

Fig. 9 Accuracy of performance (constant errors) while exerting certain specified stick forces in different directions of motion.

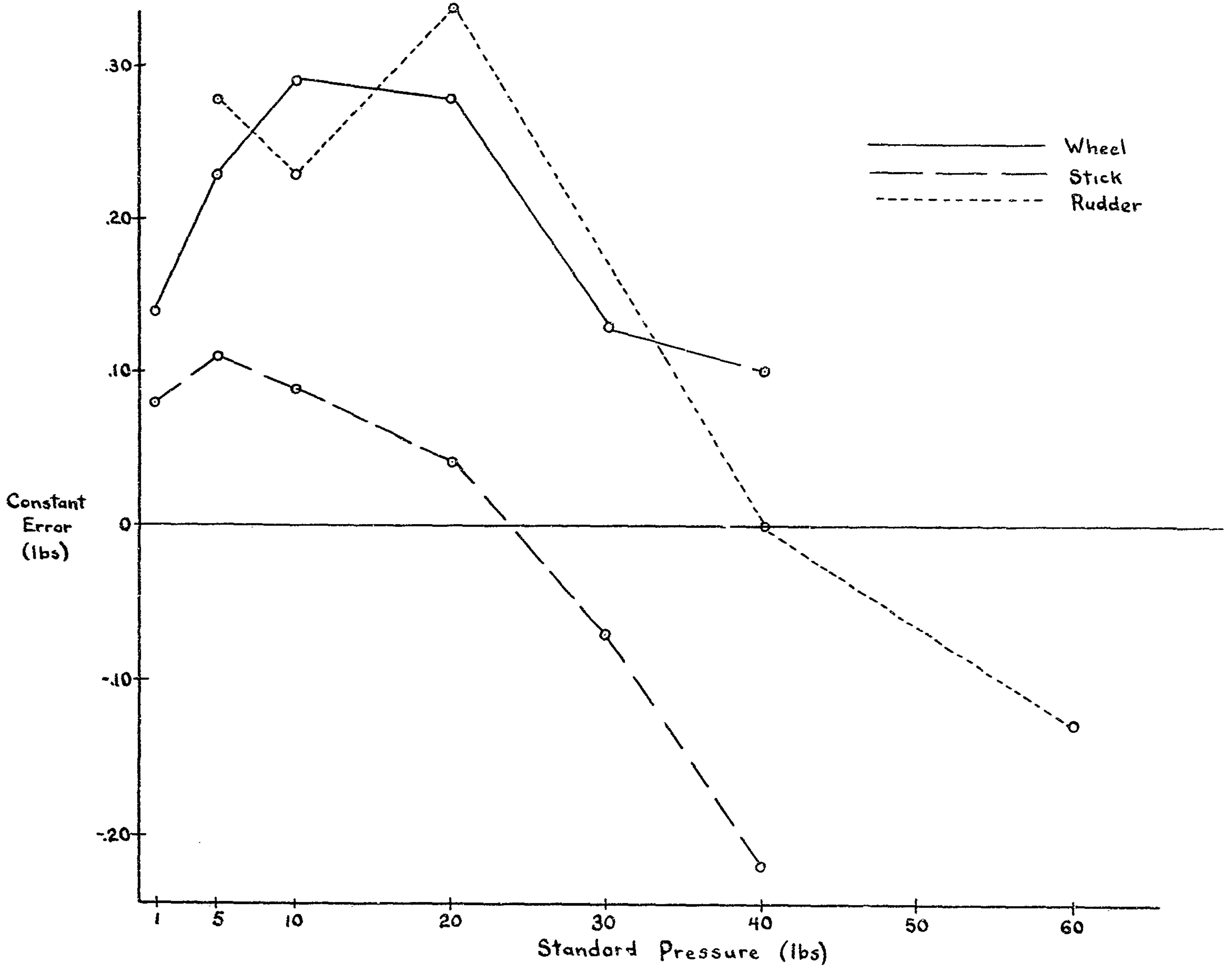

Fig. 10 Accuracy of performance in applying certain specified pressures to stick, wheel, and rudder controls.

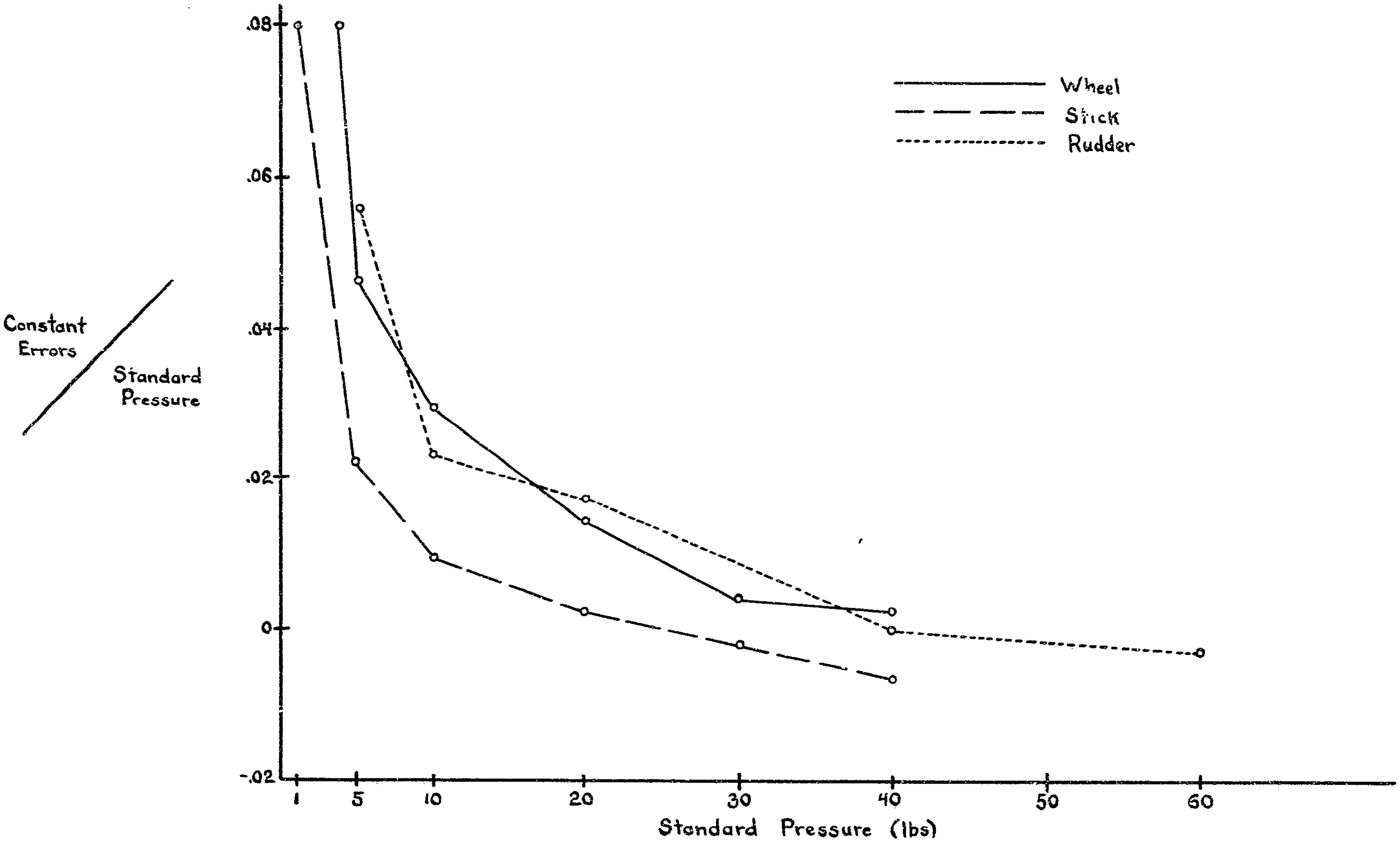

Fig. 11 Relative accuracy of performance in applying pressures to stick, wheel, and rudder controls.

The consistency of exerting the various pressures was estimated by computing the variability (standard deviation) of each individual's performance from his average. The lower the standard deviation, the greater the consistency. Twenty pilots served as subjects for these performances and, in addition, there were 13 non-pilots for the stick tests. The latter subjects exhibited less consistency of performance as judged by the criterion of variability adopted here. As shown in Fig. 12, variability increases (i.e., consistency decreases) directly with the magnitude of applied pressure with stick performances exhibiting less consistency than either wheel or rudder. Finally, the relative consistency (standard deviation/standard pressure) is shown in Fig. 13. It is clear that all control performances become quite consistent at values beyond 10 pounds, and Jenkins points out that the over-all differences in Fig. 13 are not statistically reliable.

The Weber-Fechner "law" often breaks down at extreme limits of the stimulus range and it has, therefore, been questioned as a complete generalization. This criticism of the law is irrelevant here because Figures 11 and 13, drawn from actual data, contain a simple fact concerning control stick pressures. A pilot will be able to discriminate more pressure cues if stick pressure increases in a non-linear (rather than linear) manner with respect to its independent variable, such as stick displacement or airplane speed.

Other conclusions to be drawn from Jenkins' studies are that:

(a) Control pressures should occur over a wide range in order to provide the pilot with as many perceptible pressure differences as possible. Specifications should require that force limits reach approximately 30 lbs. for stick and 40 lbs. for wheel; 60 lbs was the maximum tested for rudder.

(b) When control pressures are very low, they provide poor cues. They should rarely be less than 5 lbs. This requirement would also appear to be necessary to overcome the masking effect due to friction. Merely resting the hand on the stick results in some pressure due to the weight of the arm; the same is true for the rudder pedals where the average pressure due to the weight of the feet was found to be 7 lbs.

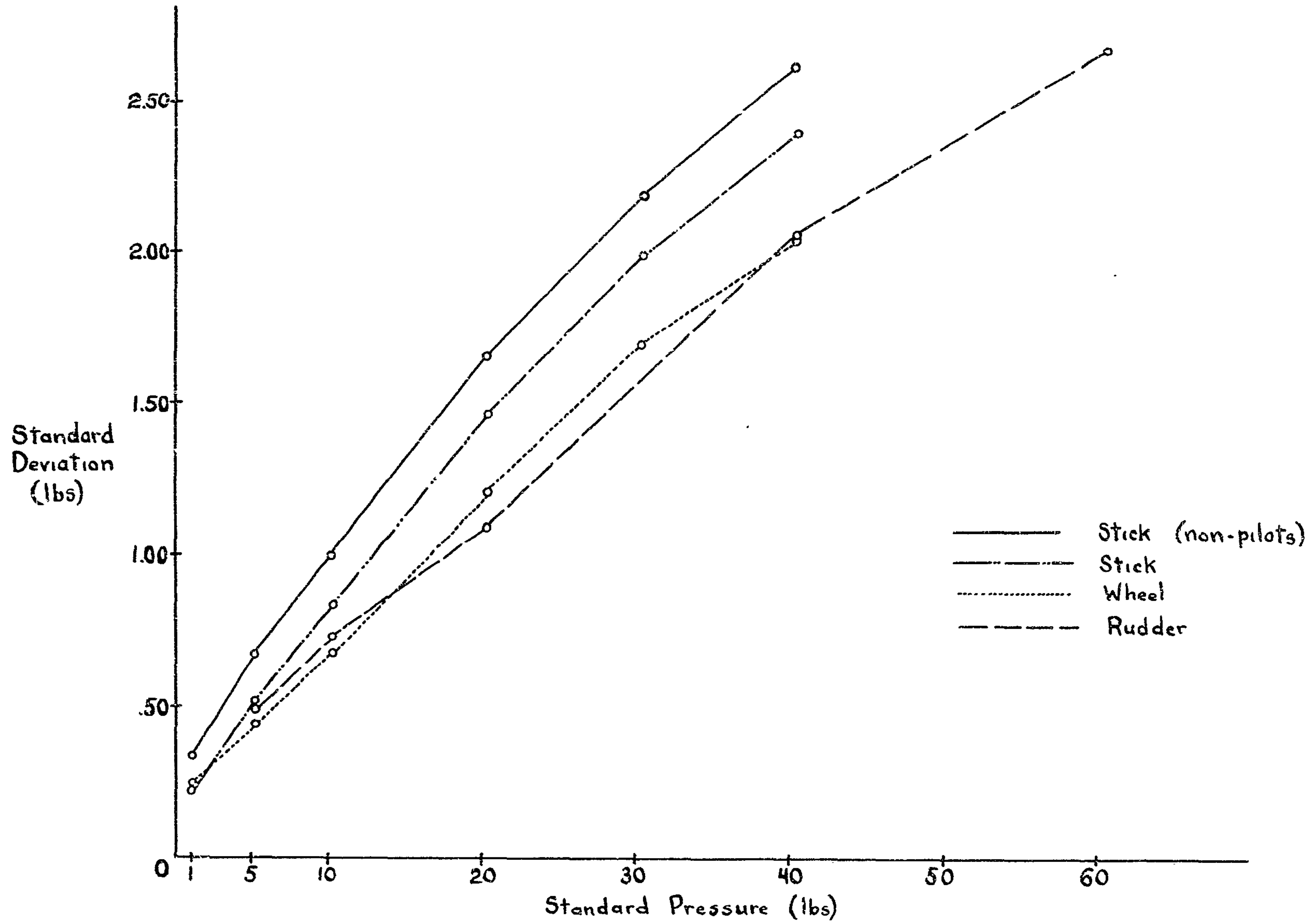

Fig. 12 Consistency of performance in applying pressures on stick, wheel, and rudder controls. Twenty pilots served as subjects for all curves except the top curve, which represents

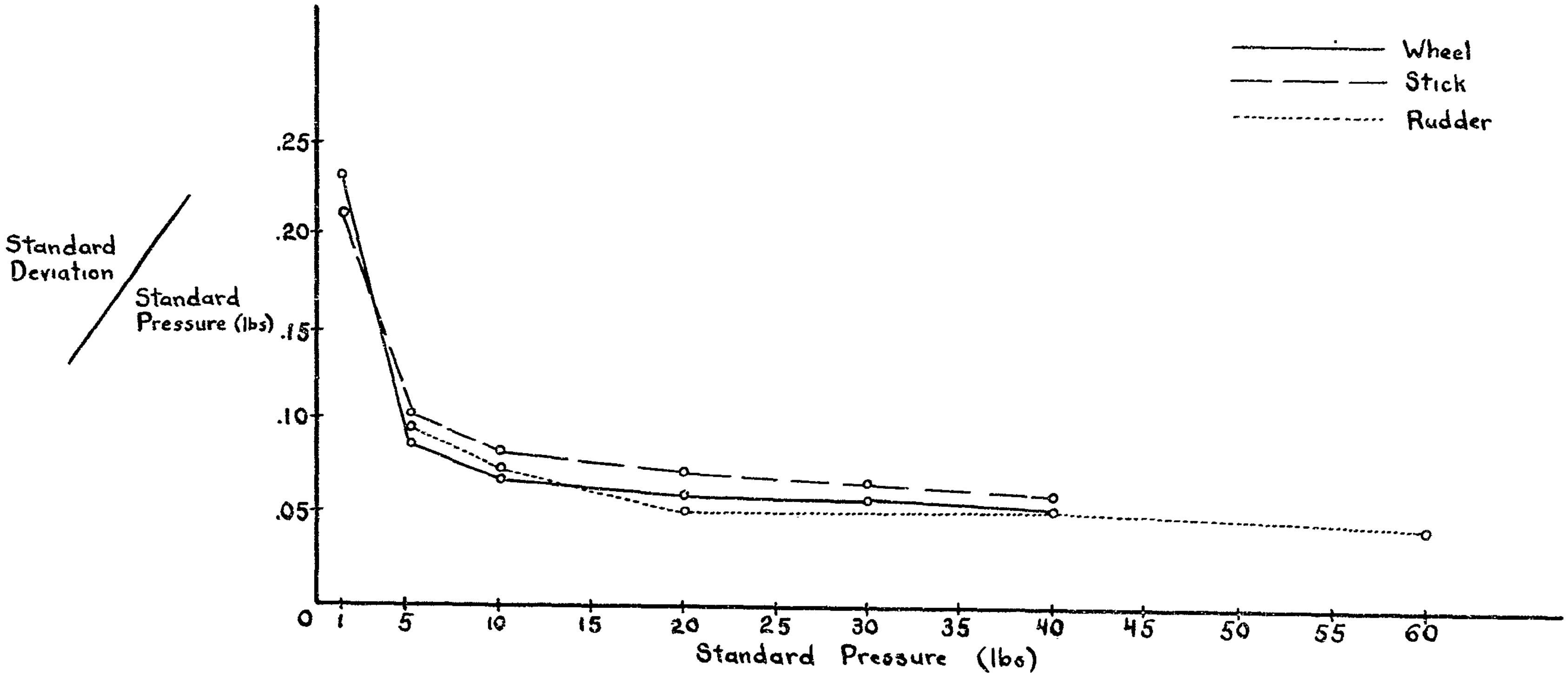

Fig. 13 Relative consistency of performance in applying pressures to stick, wheel, and rudder controls as a function of a number of standard pressures (Ref. 34, Fig. 1).

(c) When attempting to exert a small force, the individual tends to apply a greater force than is required. Conversely, he underexerts when a large force is required. There is, therefore, an optimum range for control forces which may be estimated as 5-30 lbs. for elevator and aileron and 7-60 lbs. for rudder.

(d) Pilots appear to be more accurate than non-pilots in these tests. The number of flying hours and body weight were not related to accuracy. Performances improved with practice, and with knowledge of results. When a light force immediately follows a heavy one (or vice versa), there is some evidence that the accuracy of a performance is adversely affected.

Pilots' opinions concerning the stick forces they have exerted in flight show that they are apt to be inaccurate judges. Thus, Gough and Beard (17) report that two very experienced test pilots made estimates which were found to be in error by as much as 50% when checked against instrument records. They were most accurate in reporting pressures of about 10 lbs.; they exerted more force than they thought they did in the case of small values, and less in the case of large values. De Beeler (4) showed that pilots vary considerably in reproducing in a mock-up the rate of motion they would use to pull out of a dive. The present author has examined records which show that pilots actually exerted only 40-50 lbs. during flights when they reported they had exerted 100 lbs.

A number of English investigators have examined the factors which influence accuracy in the operation of hand controls. Their interest has generally been directed at manual controls for tanks and guns, but some of the findings may be applicable to the present topic. Craik and Vince (9, 10, 11) report that friction of approximately 2 lbs. in a hand control is desirable to eliminate the effects of body sway, hand tremor, jolting and vibration to protect the operator against involuntary sagging of the arm, as well as to smooth out control movements. On the average, mean errors on their apparatus decreased with increased friction up to 1 lb., becoming constant from 1-5 lbs., although fatigue developed with friction above 3 lbs. Performance is more accurate when visual observation of the controls is permitted in addition to detection of pressure cues. They also studied the accuracy of hand winding a gun control mechanism at various rates of speed. An analysis showed that errors in tracking a target fell in a pattern which is a reasonable motor analogy to that implied in the Weber-Fechner law of intensity discrimination. The magnitude of control motion error was of the order of 5-15 percent (10). It is apparent from these studies that a pressure-gradient must be relatively steep ($\Delta I/I$ equal to approximately 10%) in order for changes in pressure to be detected by the subject (11).

For precision of adjustment, Hick (24) advises no control motion below the limits of 2 lbs. pressure and 2 in. movement, which is confirmatory of work already discussed. His experiments, as do those of Craik and Vince, show that small forces and distances are overestimated, while large forces and distances are underestimated. Errors of 5-15% are found in manual exertion of force (26). A pressure-gradient with velocity led to an improvement in handle-winding performance. According to Hick, friction (up to 4 lbs.) at the handle reduces average error by about 15% under conditions of jolting but is unfavorable when no jolting is present (25).

One may conclude on the basis of these studies that:

(a) The perception of changes in pressure, such as observed in airplane control systems, is not an absolute ability, but is relative to the level of pressure at which the change occurs. The increments of stick pressure in response to changes in stick displacement, or speed, should be geometric rather than arithmetic in order to furnish the pilot with the maximum number of discriminable pressure cues.

(b) The pilot is most sensitive to pressure differences when controls are operated against a moderate work load. The optimum range of this load for accuracy and consistency of performance is of the order of 5-30 lbs. for stick and 15-60 lbs. for wheel and rudder controls (higher values were not tested for the two latter controls). Higher loads would probably increase fatigue to an undesirable degree.

(c) Some friction on the controls is advantageous in eliminating the effects of hand tremors, jolting and vibration because it tends to smooth out motion. The level of desirable friction on hand control is reported variously as 2-5 lbs. While there are no data on desirable rudder pedal friction, there is a hint that it should be of the order of 7 lbs., as judged by the average pressure exerted by the resting weight of the foot.

C. The position of controls and the direction of motion

This investigation is limited to consideration of the form and placement of airplane controls in the conventional stick and rudder aircraft. The advent of power operated controls permits the design of controls in any size, shape and position deemed desirable for ease of performance. An evaluation of novel type controls may be recommended, but it is beyond the scope of this paper. However, attention should be directed to the effect upon performance of such factors as direction of movement, size, shape and position of the controls.

Considerable anthropometric data are now available on the population likely to operate airplanes (12, 49, 50), tanks (2) and similar military equipment. The dimensions of the standard cockpit are based on such information. Recently, King (39) measured the functional reach of 139 young males of whom 79 were Navy pilots, and his findings should be used for distributing airplane controls where they may be operated most conveniently. The limits of motion of the stick and rudder in the standard cockpit place these controls where they could be manipulated by 97% of that population, but 3% would have difficulty.

It may be expected that the precision of linear adjustment, such as required on stick and rudder controls, varies somewhat with the position of the hand and foot. King remarks that "the precision of movement of the hand and fingers decreases as an unsupported arm is extended". None of the available investigations, however, give quantitative measures of the accuracy of manual (or pedal) control motion for various positions and distances, similar to what Jenkins has done for control pressures. Ideally, such investigation would reveal the distance through which the hand (or foot) must move, at various extensions and under various loads, before a just noticeable increment occurs.

Vince (60) shows that the direction of control motion should be similar to the expected direction of its effect, especially for performances requiring rapid adjustments. This finding, which is confirmed by Warrick (62), is of special applicability in airplanes, where rapid adjustments of controls are so frequent; with further development of high-speed aircraft, the importance of relating direction of control motions to direction of effects will increase tremendously. In another paper Vince reports that a non-linear relation between a control and its display is undesirable (61). Grether (20) summarizes the work of a group of German workers led by Henschke (22) and concludes:

> "(1) Control is less efficient with the feet and legs than with the arms and hands;
> (2) Control with the entire arm and shoulder including the wrist and hands is more efficient than with the fingers only;
> (3) Control is best when the joints are at a moderate degree of flexion;
> (4) Friction, mass, and backlash are all undesirable in controls; and
> (5) A single control grasped by both hands and moved in two or three dimensions can be controlled with greater precision than can the necessary number of separate controls having unidirectional movement. These German studies were, however, carried out with small numbers of subjects and apparently were not given adequate statistical treatment to establish significance of the differences. For this reason the German conclusions cannot be accepted as final."

Grether then proceeded to test the relative efficiency of several types of aircraft control motion in a simple pursuit task. The subjects (24 non-pilots in one experiment, 36 rated pilots in three other experiments) were required to move each control so that a pointer, randomly activated, returned to its reference mark. The efficiency of performance was measured by a clock which cumulated the time intervals during which the pointer was kept within the reference mark. Five control motions, i.e., rudder, stick aileron, wheel aileron, stick elevator and wheel elevator, were studied. The four experiments were concerned with such conditions as equal or unequal extent of control motion, and angle of knee or arm flexion on the controls. Grether concludes that:

(a) Hand controls (stick or wheel) are better than foot controls (rudder), for equal and unequal extents of movement.
(b) Elevator movements (fore and aft) are slightly better than aileron movements (lateral or rotary) on stick and wheel controls.
(c) The wheel and stick controls yield approximately equal efficiency for aileron and elevator type motion.
(d) There are differences in comfort but not in efficiency on tests performed under average leg and arm angles of 105, 120, and 135 degrees.

Further investigation should be undertaken to locate the areas in which occur the largest proportion of errors of motion. Then, control movements could be allocated to areas with known degrees of performance efficiency. Another problem for investigation is to ascertain how much hand (or foot) motion develops before the pilot perceives a difference in position. This information could be used to specify the amount of control motion that must occur before it becomes useful as a cue to the pilot. Similarly, it would also indicate the precision to be expected from the pilot in attempting a particular maneuver, i.e., moving the controls to certain specified positions under given loads. In this study, Grether examined the effectiveness of various control motions in a task which affected the return of an instrument pointer to its reference mark. One instrument, similar to the rate-of-turn indicator, was used for the rudder and aileron motion experiments while another, similar to the rate-of-climb indicator was used for the elevator motion experiments. Since there probably is some relation between a control movement and its display, it would appear desirable to establish the effect of varying the instruments upon the relative efficiency of the several control movements.

One study (27) investigated the effect on 18 pilots of offsetting the stick and rudder controls from their normal central positions. There is a strong tendency to pull the controls back to a laterally symmetrical position, while fore-and-aft motion does not appear to be affected. Control motion is most accurate when the position of the hand is at normal elbow height, while hand tremor increases appreciably when the hand is more than 8 inches above or below the level of the heart (9). When the operator can observe visually the effect of his manipulations, his accuracy of control is greater than when he is dependent on kinesthetic cues alone (5).

It was demonstrated by Brown (5) that positioning movements away from the body exhibit smaller errors than movements toward the body. The variability of movements increases with the distance moved, and movements away from the body show more variability than movements toward the body at distances of 10 and 40 cm, but the relationship is reversed at distances of .6 and 2.5 cm.

Pauling (51) showed that touch estimates of linear distance increase in error with increasing distance of the arm from the body. Gräf (18) required his subjects to reproduce linear distances perceived originally by touching with the two forefingers. Short distances were overestimated and long ones were underestimated. This was also true while judging distance from the body, and it would appear that there is a point in space of maximum convenience to the subject, so that accordingly he over or underestimates his judgments. Few subjects were used in these studies. Klingelhage (41) instructed his subjects to relocate a point in space after first touching it with the fingers. Computations using his data indicate an average error of displacement of about 15%, which decreases slightly at extreme hand positions. The right hand was superior to the left; points below the shoulder were relocated too high while those above were relocated too low. Errors were greatest in the vertical plane, at least in the right-and-left and fore-and-aft planes, accuracy being slightly superior in the latter. While these last three studies are based on few subjects and on procedures which are unnecessarily complex for our purpose, they indicate definitely that the accuracy of kinesthetic judgment varies with distance. In addition, it would appear that due to the structure of the human body, there is an area in which the limbs may be moved with maximum convenience and accuracy. These facts should not be disregarded in designing instrument panels and control layouts.

The shape of a handle affects the ease of control of machines and tools, but mention will be made here only of studies of interest to aircraft design. A shift from a round knob to a pistol-grip control improved by about 8 percent the tracking, ranging and triggering performance on the B-29 pedestal gun-sight (45). The diameter of a hand grip should be approximately 1.5 inch and provide friction (e.g., be rubber covered) to facilitate the maximum exertion of force (46).

To summarize the studies reported in this section, the following facts appear to be known with reasonable certainty:

(a) Hand controls are superior to foot controls. There seems to be no reason to prefer wheel over stick control, as judged by efficiency of performance in simple tasks. Fore-and-aft hand motions can be made with slightly greater precision than right-and-left or rotary hand motions.

(b) Conventional controls should be placed symmetrically with respect to the pilot, and the hands should be at elbow height. No penalty seems to be involved if the pilot adjusts his controls for personal comfort. The shape of controls affect efficiency of performance, and the guiding principle seems to be to shape the control for maximum convenience of grasp.

(c) Full information is not yet available on the accuracy of hand and foot motions of the type used in airplane control. Data are required particularly for various conditions of pressure load. The best present estimate is that increments of about 15% may be detected in the linear displacement of hand-operated controls, under constant load conditions.

D. Reaction time and rate of motion of controls

(1) Reaction time

There are many studies which describe the conditions which affect the time required to perceive and respond to a stimulus (37,66). Reaction time is often measured in laboratory situations which require a minimum of movement, such as may be entailed in pressing or releasing a telegraph key with one finger. The basic finding in such studies is that the reaction time is influenced by many variables among which may be included the sense organ stimulated, the intensity and duration of the stimulus, the motor response involved, the subject's readiness to respond, the complexity of the task and the subject's age. The aircraft designer should know that the shortest reaction time generally reported is of the order of 0.120 sec. to sound, 0.140 sec. to touch and 0.165 to light. These times increase with the complexity of a task, and 0.600 sec. is a fair estimate of the time required for such a response as applying brakes to a car after perceiving the cue. An early experiment in a cockpit mock-up showed that reaction time on a control stick averaged 0.200 sec. with a freely moving stick, and increased to 0.600 sec. with a loaded stick (69). While a simple reaction will usually require about 0.200 second, a reaction involving discrimination and judgment necessarily will take more time, and in such instances 1 or 2 seconds may be considered a rapid response. The consequences of such delay may be clear upon reflection that within 0.600 sec. an airplane may travel 88 ft. while landing at 100 mph., or 733 ft. at 500 mph. in the air and that these speeds are often surpassed at present. The effects of such influences as anoxia, fatigue, and drugs which prolong reaction time may be examined in McFarland's book (44).

(2) Rate of motion of controls

Once the response is initiated, the speed of hand motion is a function of the work load and the direction of effort, as well as such factors as fatigue, anoxia, and temperature. As the stick force per unit displacement increases from 0 to 33 lbs./in., there is a decrease in the rate of stick motion from 75 to 23 in/sec. when pulled and 105 to 33 in/sec. when pushed (minimum rates of 9 pilots) (4). The rate of push motion exceeds the rate of pull motion, while the maximum rate increases with stick displacement. This contradicts an earlier finding in which Hertel (23) reported that elevator and aileron controls could be moved at a maximum speed of about 78 in/sec. regardless of load. However, Hertel had reported a decrease in speed from 24 in/sec. to 8 in/sec. for foot motion on the rudder as the load increased up to 330 lbs. A British study (69) finds a maximum elevator pull at the rate of 63 in/sec., when all conditions of load from 10-190 lbs. are averaged. These data show the rate to have varied from 26 to 80 in/sec., the slowest rate occurring for two subjects at the maximum load.

Airplanes which are flight tested by modern methods are instrumented heavily so that, among other items, data on the force, speed of motion and position of the controls are recorded automatically during maneuvers. Table 4 reports the data of four accelerated stalls in a F8F-1 airplane where the pilot exerted maximum effort in endeavoring to obtain full up elevator displacement (23°) in 0.200 seconds (70). It shows that for approximately equal distances of stick travel (6 - 8 inches) the rate of motion dropped markedly from 52 to 10 in/sec. as the maximum load increased from 35 to 97 lbs. Even though the pilot tried to achieve this motion within 0.200 seconds, the actual time for the response increased from 0.160 to 0.750 seconds as the maximum load increased from 35 to 97 lbs. The speed of control motion can be deduced from a NACA study (63) where the maneuvering effect of "instantaneous" full deflection of the ailerons was computed from wind tunnel data. This agreed

[redacted]

TABLE 4

RATES OF ELEVATOR STICK MOTION UNDER VARIOUS LOADS (DUE TO AIRSPEED) ON ACCELERATED STALLS IN A F8F-1

Pull-up no.	Distance stick moved (in.)	Maximum force exerted (lbs.)	Response time (sec.)	Rate of motion (in/sec.)
1	8.4	35	.162	51.85
2	7.4	74	.475	15.58
3	6.6	77	.600	11.00
4	7.7	97	.750	10.27

with flight test information, except for a constant error of 0.150 sec. Taking this as the time to account for full aileron deflection, which is 7 inches in the standard cockpit, one may estimate 46.9 in/sec. as the average rate of aileron motion in those tests.

The data from these studies have been plotted in Fig. 14 and inspection of the curves reveals clearly the general agreement that the rate of control stick motion decreases as the load increases. Pull rates of the order of 50 in/sec. appear reasonable at a load of 35 lbs. (maximum elevator limit according to specification). Rates as high as 75 in/sec. under lesser loads, and as low as 10 in/sec. under 100 lb. loads may be expected. Such evidence as exists suggests that the rate of push motion exceeds the rate of pull motion by about 25%. The data on rate of rudder motion are scanty.

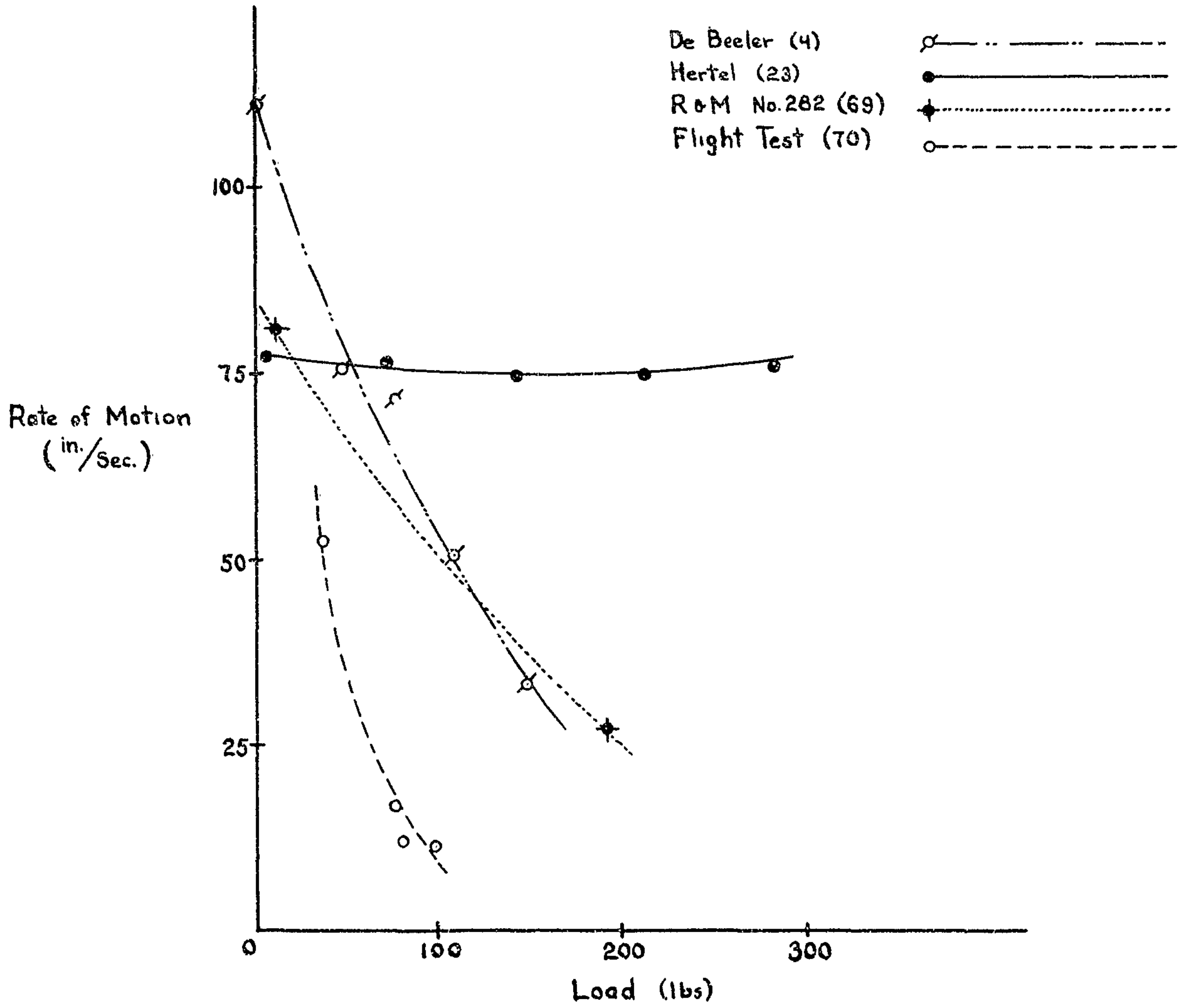

Fig. 14 Relation between rate of control stick pull motion and maximum load, as shown in four studies.

5. THE RELATION BETWEEN FLYING QUALITIES AND HUMAN CONTROL

The precision of control during flight is limited by psychological as well as engineering considerations. Human control over an airplane is achieved by motions which change the power settings and control surface positions, but engineers tend to consider handling characteristics as a function of aeronautical factors alone. Obviously, good control requires a stable airplane that may be maneuvered easily, but military duties still require the presence of a pilot. In this section there will be a discussion of the flying qualities which are generally proposed as desirable and the effect they may have on pilot capacity, booster design, and stick force requirements. To reduce the possibility of confusion, the terms "flying quality" and "stability and control characteristics" will refer to properties of the airplane, while "pilot control" or "control stick motion" will refer to pilot performance.

A. Satisfactory flying qualities for military aircraft

The NACA has issued a variety of reports on its project for the investigation of satisfactory handling and control characteristics. One may overlook the many contributions leading to more efficient aircraft structures in order to stress the human factors which will be considered in this research. For example, it has been necessary to rely upon pilots' opinions in order to develop parameters which measure and predict flying qualities. Yet, the report of the tests does not disclose the number of pilots who participated or to what extent they were in agreement (56). In another report (15), an index* was developed to express the rate of roll in response to abruptly applied aileron deflection, and a total of 28 airplanes were flight tested. A table shows the index value for each airplane and the response ("Yes" or "No") to the question, "Satisfactory in pilot's

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* This is the non-dimensional expression "pb/2V", where p = rolling velocity in radians per second, b = wing span in feet, V = air speed in feet per second. The measure represents the lateral displacement of the wing tip in a given forward travel of the airplane, i.e., the helix angle generated by the wing tip.

opinion. What the table does not show is how many pilots were polled to indicate whether the opinions were truly representative.* Nor does it appear likely that a report on satisfactory handling qualities may be encompassed by the single-worded reply of "Yes" or "No".

Gilruth (14) describes the handling characteristics currently desired by NACA and analyzes the reasons for these requirements. The psychological content of these requirements is that they attempt to set up consistent and rational control characteristics, such as some positive stall warning, an invariable elevator push force always required to increase speed from trim position, no overbalancing on the controls, maximum control forces within human limits, and an increase of control force with speed, acceleration and load factor. There is a two-fold significance in such studies. On the one hand, they provide an impetus to describe and, if possible, to quantify design characteristics and flying qualities. On the other hand, they represent an interim proposal for the flying qualities of new airplanes until newer developments suggest the nature of further modification.

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* This study appears to commit another error in claiming "that regardless of size or category of the airplanes tested, which included pursuit, transport, training and bomber types, a value of pb/2V of 0.07 represented a criterion of minimum satisfactory aileron effectiveness" (p. 1). The logic of this finding may be true for <u>all the planes as a group</u> because 5 airplanes with a pb/2V less than 0.07 are judged unsatisfactory while 23 airplanes with a pb/2V greater than 0.07 are judged satisfactory. There are 6 pursuit planes, all judged satisfactory, and all with pb/2V over 0.07, and none either unsatisfactory or with an index below 0.07. Therefore, no conclusion can be drawn on how a pursuit plane with an index of less than 0.07 might be judged. The same is true for the classes of trainer, scout bomber, transport, and commercial airplanes. The bomber class, with a total of 4 airplanes, is the only one for which some conclusion appears to follow. Here, 2 airplanes with pb/2V greater than 0.07 are judged satisfactory while 2 with pb/2V less than 0.07 are judged unsatisfactory. Thus, if one does not raise questions concerning the statistical significance of this difference and the reliability of the judgments, one may say that rate of roll is a critical parameter for bombers. The same is also true for the 8 airplanes in the experimental class where 3 with a low pb/2V are judged unsatisfactory, except for the rather obvious fact that this is not a homogeneous class of airplanes. It may also be pointed out that if the concept of a quantitative index expresses satisfactory rate of roll, that this control characteristic should continue to get better as the index increased. No attempt was made to verify this aspect of the concept by getting quantitative estimates of just <u>how</u> satisfactory were the handling qualities.

A recent paper shows that military flying qualities may be based on rather scanty experimental tests. Abzug (1) reports that the specifications shown in Table 5 were set at the upper limit of judgments for "acceptable control friction" made by an unstated number of Navy test pilots. These pilots accepted higher friction limits for wheel rather than stick type controls. The pilots desired higher rates of roll, up to 270° per sec., as a tactical requirement for new aircraft, but this opinion was not based upon any test. Such specifications must be examined with due consideration for the physical demands which they put upon the pilot. In addition, it is important to know whether the pilot can control effectively such radical flight procedures since his ability to detect shifts in orientation in a fast roll, his reaction time and his physical stamina may be inferior to the demands imposed by the maneuver. Abzug suggests a requirement of steadiness in flight, necessary for gunnery and bombing and desirable for takeoff and landing, as defined by a particular period and natural damping of the lateral oscillation. The psychological aspect of this requirement is that the period of natural oscillation should be of sufficient duration so that the normal lag in the pilot's reaction will not cause him to reinforce the oscillations while attempting to damp them. In general, any corrective movement, to be effective, must respect the pilot's ability to sense the need for corrective adjustment, the time required to organize a response, and the magnitude of movement and work load required. Gray (19), an airline pilot, has offered some suggestions along these lines for transport aircraft.

One desirable handling quality is that the force necessary to deflect the control stick (or rudder) should increase with speed so that maximum energy must be exerted when maximum permissible load factors are operating. As a warning device, this protects the pilot and airplane from the danger of extreme stress. In practice, this may be accomplished only with difficulty

TABLE 5

CURRENT SPECIFICATIONS ON THE LIMIT OF CONTROL FRICTION (IN POUNDS)

Control	Airplanes with Stick-Type Controls	Airplanes with Wheel-Type Controls
Elevator	3	8
Rudder	7	15
Aileron	2	6

because distortions in the shape of control surfaces alter their properties as high speeds are approached. Sometimes there may even be a reversal of control effectiveness at high speed. It is clearly desirable that aircraft be designed so that the aerodynamic forces furnish intrinsic, functional data to indicate stall and other critical conditions to the pilot.

For psychological purposes, it is desirable that control surfaces continue to be effective at all speeds. This characteristic is not always achieved, as shown, for example, in the P-80 and B-29 in which maximum rudder deflection at low airspeeds does not produce an appreciable change in heading. Consistent effectiveness is essential for "control coordination", by which pilots mean the dynamic relation of the controls during maneuvers. The response of the airplane should be proportional to control stick deflection, and changes in heading should develop smoothly and without any appreciable time lag. As far as possible, such effects should be standard and consistent for all airplanes within the same category. An extended discussion of these factors may be found in McFarland (44), Abzug (1), Gilruth (14), and Soule (56).

Because of military requirements, airplane performance tends to be limited by engineering feasibility rather than by human factors. Combat pilots appear willing to pay the price of exposure to "g", to low air pressure and to various temperature effects in order to gain greater maneuverability and speed. While this is understandable, there is a tendency to disregard the question of whether the pilot can withstand high rates of rotation and whether he can make the discriminations required for accurate control at high speed. Since it is abundantly clear that human tolerances are being approached, if not exceeded, it is urgent that in specifying future performance standards, full advantage be taken of the considerable body of psychological and physiological facts which already exist and that any gaps in our knowledge be filled in by carefully controlled experimentation. Such an approach may permit the attainment of better performance by men as well as aircraft.

B. Psychological aspects of handling qualities

Stick feel may be measured in terms of the relationship between control stick deflection and control stick force under various conditions, such as speed and center-of-gravity position. Current specifications on control stick feel are expressed in general terms which permit considerable latitude in design. Thus, it is required that control stick pressure increase with stick deflection from neutral, but the magnitude and regularity of the increase are not specified. Similarly, control force must increase with acceleration at a rate of at least 3 lbs. per "g" and not more than 8 lbs. per "g". It should be clear, however, that 3 lb. increments cannot warn the pilot as effectively as 8 lb. increments. As a matter of fact, the specifications allow such leeway that the relationship between stick force and stick displacement may be linear or curvilinear. The results of the interviews with jet plane pilots and aeronautical engineers show that they believe a linear relationship to be most desirable. However, they were generally receptive to the suggested advantages of a curvilinear relationship when the Weber-Fechner law was described to them.

Figure 15 shows the relationship between aileron deflection and control force at several airspeeds in the XP-51 (65) and Fig. 16 for the rudder in the F4U-4 (53). Such curves, which are based on flight test data, show that there are families of curves in which control forces increase in a non-linear fashion with deflection of the control surfaces. It may be observed that the curves in the two figures differ from each other in their shape. The following discussion is concerned primarily with two aspects of these curves: (1) control displacement versus control force at any airspeed and (2) the variation of control forces for any displacement at several airspeeds. Other gradients, such as between force and "g", and between force/"g" and center-of-gravity position, also influence the character of the control feel.

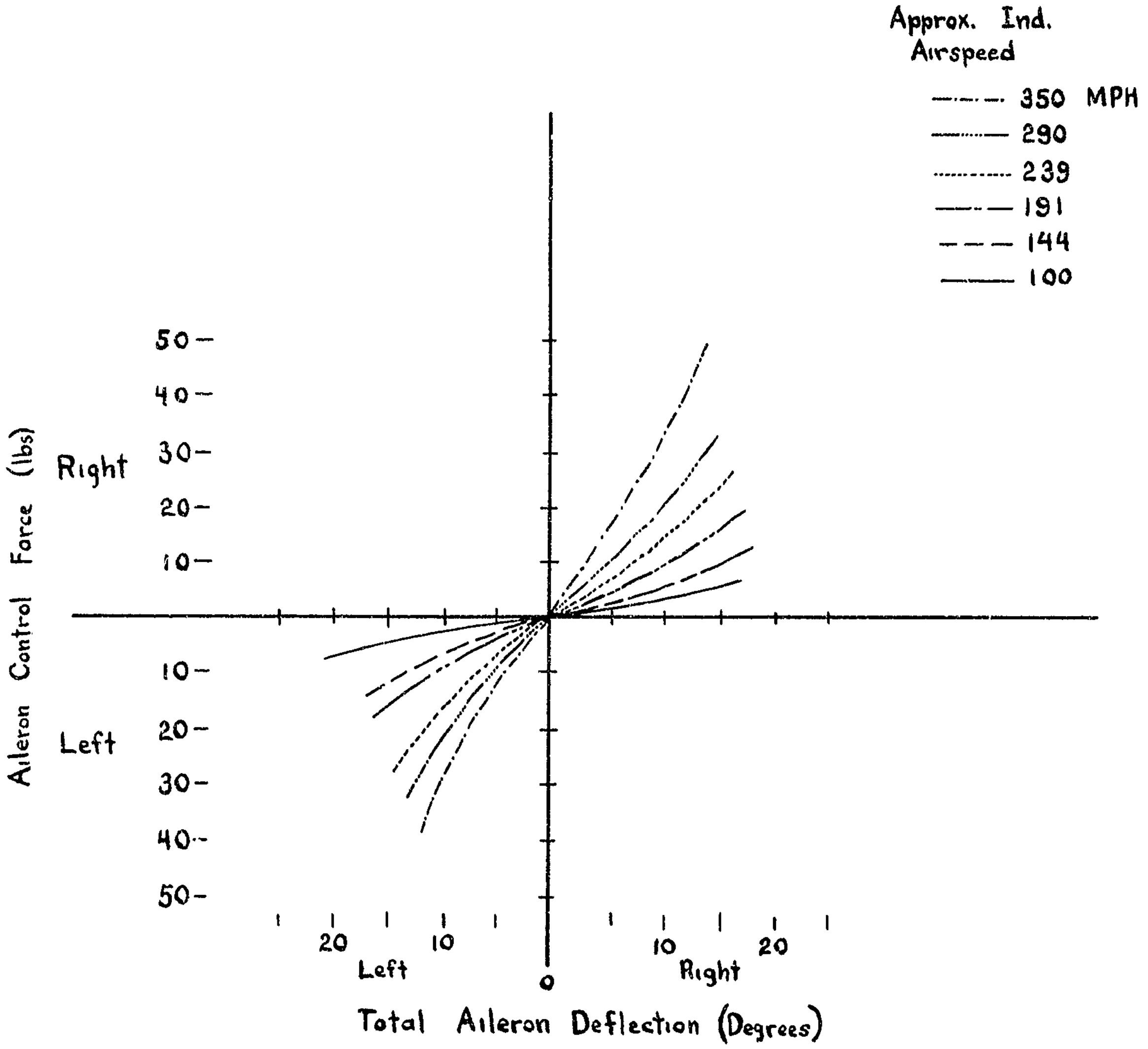

Fig. 15 Variation of aileron force with total aileron deflection in the cruising condition on the XP-51 airplane (Ref. 65, Fig. 28).

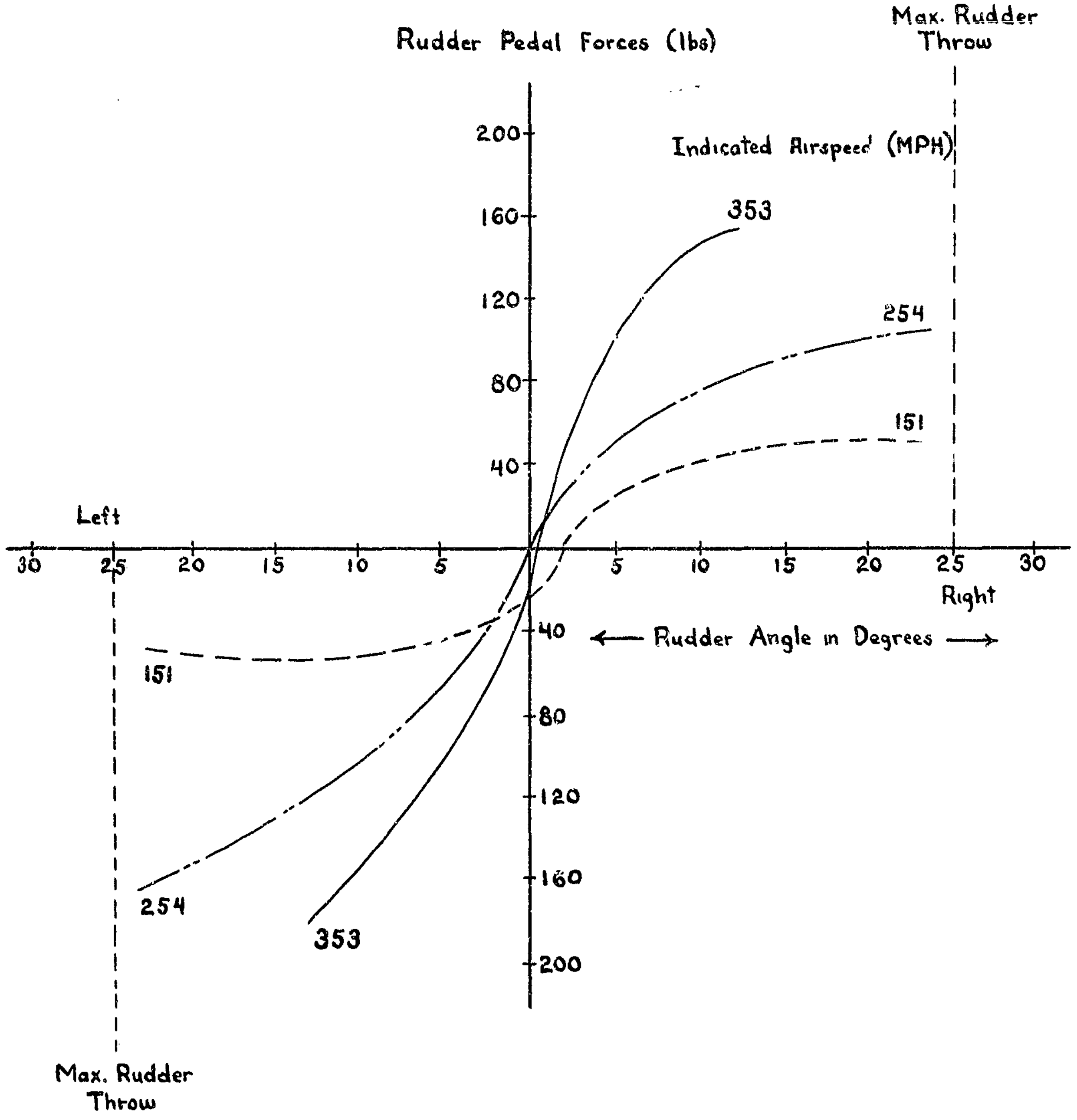

Fig. 16 Variation of rudder pedal force with total rudder angle in the F4U-4 airplane (Ref. 53).

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Consider, first, the relationship between control force and position at some particular airspeed which, since we are concerned with fighter airplanes, may be the normal maneuvering speed. Fig. 17 is a conventionalized drawing to demonstrate three possible relationships between displacement and force at one airspeed. Curve A represents a relationship of the type existing for rudder on the F4U-4 at 353 mph. (53); B, the type for aileron on the XP-51 at 290 mph. (65 and C, the type for aileron on the P-47N-1 at 250 mph. (6).

The significance of curve A in Fig. 17 is that initial stick deflections develop large increases in stick force, while the magnitude of the increments decreases with further stick deflection. This is conducive to strong self-centering characteristics upon even slight deflection. However, the normal work load would be relatively high and this might lead to unnecessary fatigue. Furthermore, since there is no rapid peaking of forces at extreme deflections, there is no warning to the pilot that he may overstress the airplane. The shape of this curve is contrary to the nature of human sensitivity.

Curve B represents a linear relationship in which stick force is directly proportional to stick deflection over the entire range. This is the form often thought to be most desirable and, indeed, there should be no a priori objection to it. The deviation from a linear relationship, unavoidable on some airplanes, is often a consequence of the variation of hinge-movement characteristics with angle of attack of the control surface (54). In a strictly linear relationship, self-centering characteristics may not be strong near neutral and there may not be a marked warning of an approach to critical conditions.

Curve C bears a strong resemblance to the relationship which, as has been shown in this paper, describes the human ability to make discriminations of intensity. Since intensity discrimination is a relative and not an absolute ability, the increasing changes in pressure occurring with variations in stick displacement would be experienced as equally apparent steps. Thus, one might

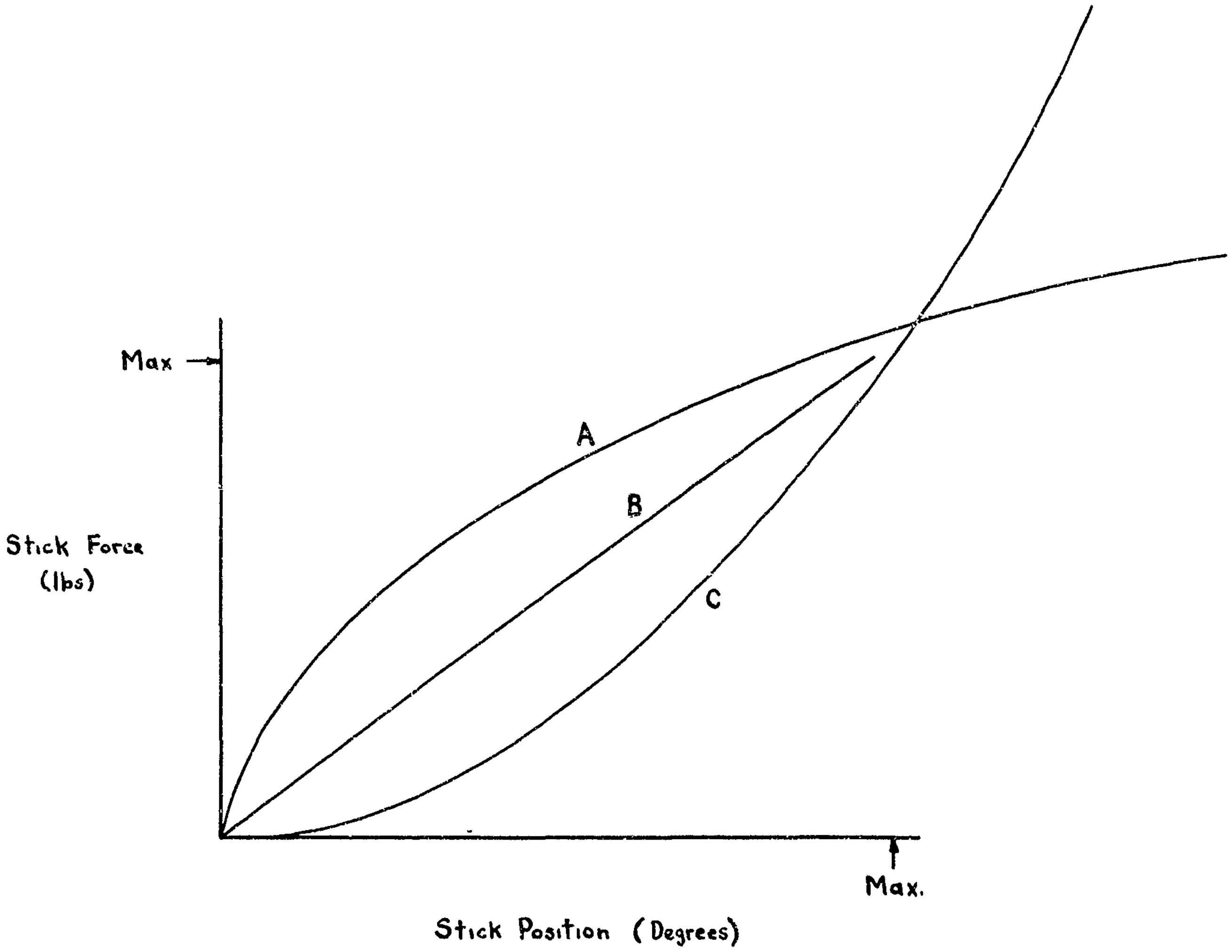

Fig. 17 Conventionalized rendition to demonstrate 3 possible relationships between stick force and displacement at one selected airspeed.

expect curve C to provide maximum sensitivity to differences of pressure. T curve might prove deficient at positions near neutral where self-centering characteristics would be weak. However, control forces would be light over most of the stick deflection range.

An ideal force curve should satisfy problems which arise in three areas identified in Fig. 18. This is a conventionalized curve and the straight li their lengths, and the points of inflection are intended only for purposes o discussion. The A band represents the area of initial stick deflection. Go stick feel requires that there be strong self-centering characteristics even with slight stick displacement from neutral. In practice, (as revealed in interviews with pilots) the friction generally inherent in control systems masks self-centering and diminishes the feeling of confidence which the pilo gets when the stick is "in the groove". It is clear, then, that slight stic deflection should produce forces which will exceed the control friction limi permitted by present specifications. The amount by which stick force exceed control friction should be a discriminable magnitude. Jenkins (32) has reported that accuracy of performance is poor for stick pressures under 5 lbs. (15 lbs. for rudder), and this would be a fair approximation to an upper lim for the A segment of the curve.

The B band represents the area within which most maneuvering occurs. I this area there are two major requirements: (a) stick forces should be as l as possible to reduce pilot fatigue; and (b) maximum sensitivity of control should be achieved, i.e., when constant stick deflection increments produce constant pressure feel steps, or just noticeable pressure differences. This has already been discussed, and the curve should be similar to C in Fig. 17. Pressure increments which produce equally noticeable steps ($\Delta I/I$) are of th order of 10%.

Area C in Fig. 18 represents the area of extreme stick deflection. In this area stick forces should peak rapidly as a warning to the pilot that he is in danger of exceeding the structural limitations of the airplane. This information is transmitted only when the force increments at limiting stick deflections are great enough to be detectable. The limit currently imposed by requiring that forces in this area approach the maximum which can be exerted by a pilot is not sufficiently reliable because maximum strength varies among pilots. Secondly, present limits may occasionally be exceeded, with unfortunate results, during the emotional stress of combat. The general requirements of area C are satisfied by continuing the curve already considered desirable for area B, but increasing somewhat the increment ratio, $\Delta I/I$, in the C area. A demonstration of a smoothed curve which conforms to the criteria discussed here is shown as Fig. 19. While the opinions of the pilots and engineers who were interviewed cannot be substituted for experimental data, one must report that they all agreed, without any reservations, that the stick force curve, as described in Fig. 19, may prove effective.

Since control forces are related to and increase with speed, the single curve of Fig. 19 must be surrounded by a family of curves representing various speeds. If control stick feel must yield information on speed (and approach to a stall), these curves should be distinguishable from each other. These curves cannot all be psychologically equal. The best curve, i.e., the one providing the largest number of discriminable pressure steps, should primarily be detailed to the most important tactical requirement. In a fighter, this might well be the maneuvering speed, while in a transport it would probably be the cruising speed.

The problem may be illustrated by reference to Fig. 20, which is a demonstrative plot of the control force at full stick deflection versus airspeed. The ordinate represents control force (at full stick deflection) with a maximum set

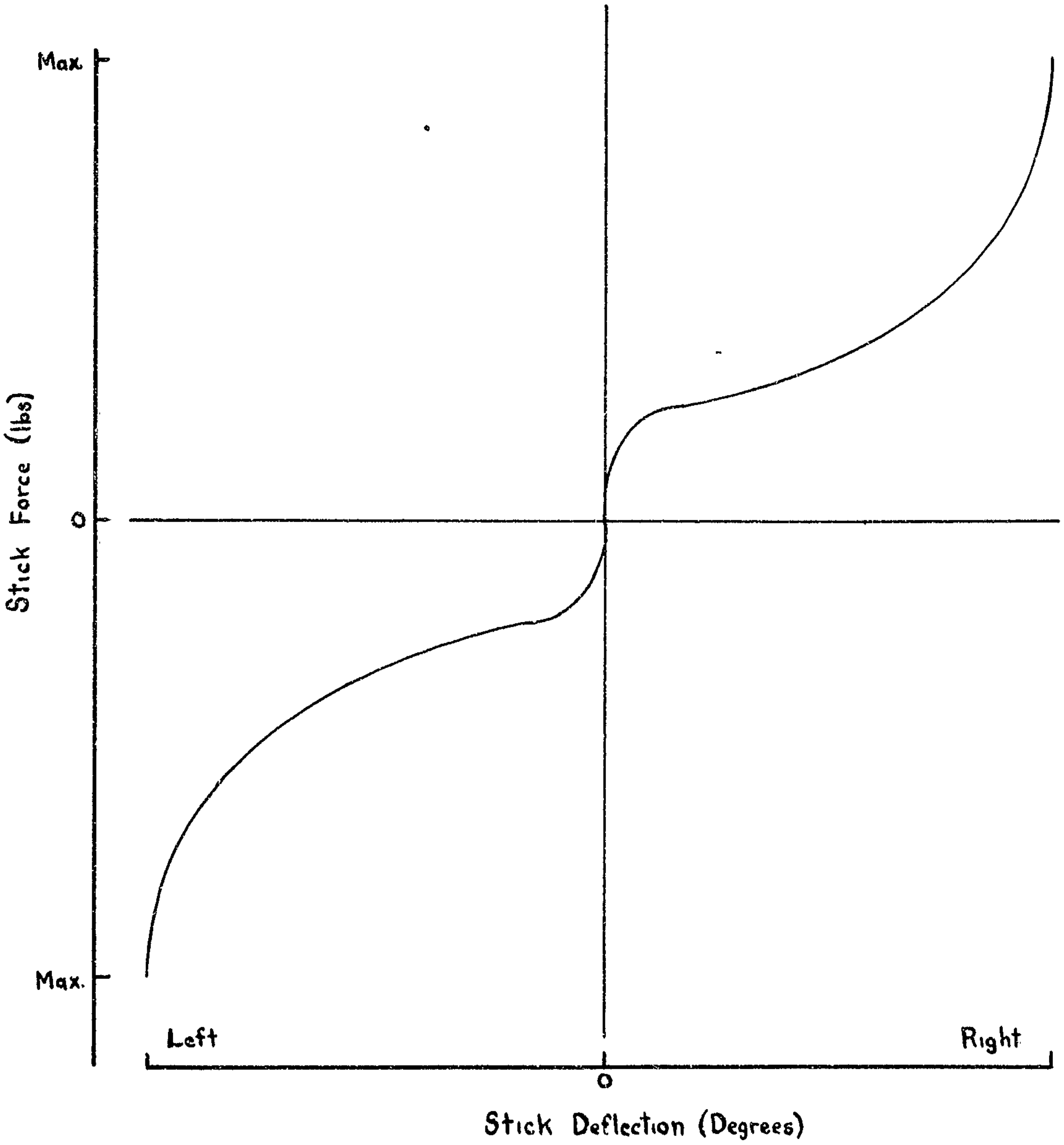

Fig. 19 Demonstration of a stick force versus stick displacement curve which would satisfy certain conditions proposed in the text. This curve would be true for one selected airspeed.

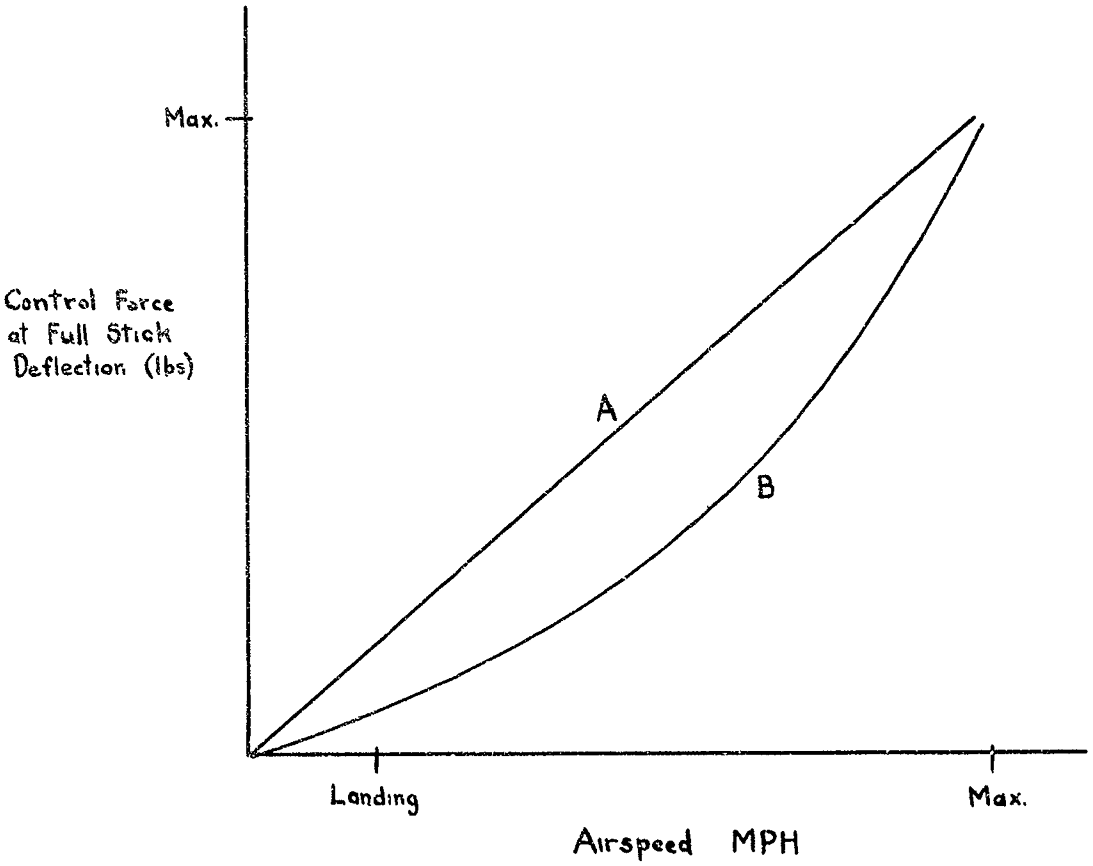

Fig. 20 Two possible relationships that may exist between control force at full stick deflection versus airspeed.

by the specifications for stick and rudder. The abscissa is related to the flight characteristics of the airplane under consideration. One airplane may land at 60 mph. and have a top speed of approximately 180 mph; thus a factor of 3 (180/60) expresses the range between its lowest and highest speed. New airplanes may have a range of 100-600 mph., or a speed range factor of 6. Since control forces are limited by an acceptable maximum, as for example 35 lbs. in the case of elevator motion, the range between minimum and maximum force must serve various speed ranges. In other words, the control force gradient in lbs./mph. (i.e., the change in force per unit speed) becomes smaller as the speed range increases. This gradient, which is of the order of .175 lbs./mph. for training airplanes, drops to 0.05 for some planes and has been calculated at 0.03 lbs./mph. for some new types. The problem confronting the designer is whether this gradient, such as 0.03 lbs./mph., shoul be spread equally over the speed range as in Curve A of Fig. 20, or otherwise as in Curve B. The reasoning which has already appeared in this paper would indicate a preference for Curve B, the shape of which is dictated by the natu of the human ability to discriminate pressure differences. Figure 21 demonstrates a possible family of curves for a given airplane showing the relation between stick displacement, force applied, and speed. The curves are in simplified form because no adjustment is made to allow for the overcoming of initial friction. Curves for other speed ranges may be computed from the fol ing formula* which was used:

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* This formula was suggested by Dr. John D. Coakley of The Psychological Corporation.

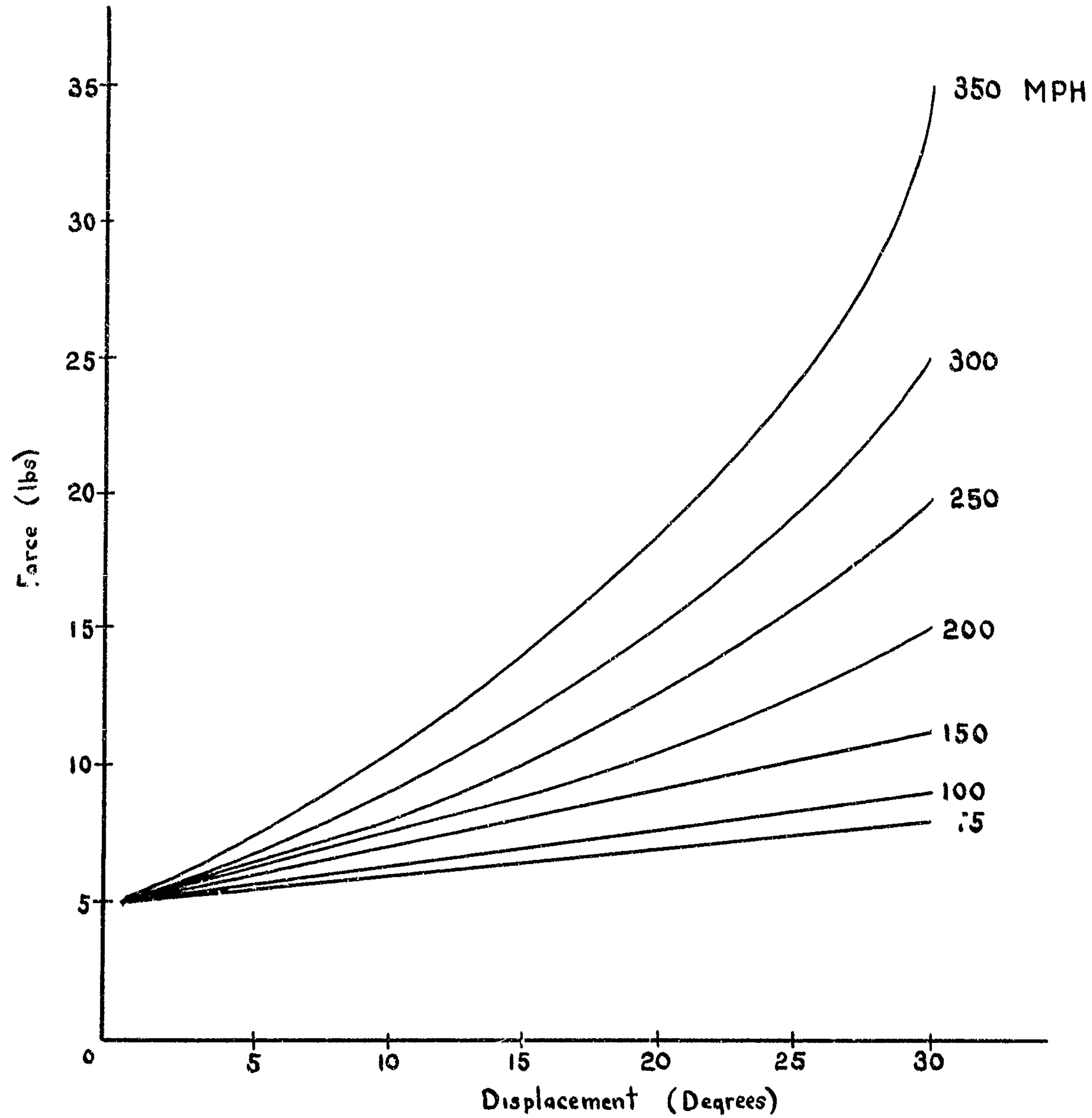

Fig. 21 Simplified family of curves relating stick displacement, stick force, and airspeed in accordance with the formula:

$$d = \frac{k\,(\log f - \log f_1)\,V_1}{V}$$

d = displacement in degrees
k = constant for range and units
f = force applied (lb)
f_1 = minimal force, e.g., 5 lbs.
V = airspeed in mph
V_1 = stalling speed, e.g., 75 mph

d is defined by setting f, d, and V to maximum values, e.g., f = 35 lb., d = 30°, and V = 350 mph.

$$d = k\,(\log f - \log f_1)^{V_1/V}$$

where d = displacement in degrees

f = control force applied in lbs.

f_1 = minimum force

V = speed of plane in mph.

V_1 = stall speed

k = a constant defined by setting f, d, and V to permissible maximum

These curves are one of several which may be suggested; but before any fina curves are adopted, they would have to be validated by flight tests.

One important problem is the relation between elevator control force a the weight-and-balance of the airplane. The usual situation is one in whic stick force/"g" decreases as the center-of-gravity position shifts rearward Another problem is how to insure the continued effectiveness of the control surface in producing such desired responses as a specified rate of roll, ma: mum lift coefficient, and directional stability over the entire speed range At present, these are primarily aerodynamic problems, but their solution an standardization would go a long way to simplify such psychological problems coordination of the controls for smooth flight and consistent flight charac istics for all planes of the same type.

C. <u>Problems with booster-operated controls</u>

On the basis of wind tunnel data, it is possible to calculate the forc to be expected on the control surfaces of an airplane. With this informati one may compute the magnitude of force multiplication required between the pilot's hand and the control surface, and thus determine whether the contro can be operated by direct linkage, or whether a booster system, either aero dynamic or mechanic, is required (58).

It seems unlikely that the pilot's force applied through conventional linkages will be capable of supplying the energy required to control high speed aircraft. This is already true for some transport aircraft, and it has now become evident for fighter types. The history of their development shows that control systems exploited various aerodynamic balancing arrangements until problems encountered at high speeds made such constructions an extremely difficult matter. Distortion in surface-coverings, control cable stretch, and actual deformation of the entire airplane contribute to this difficulty at high speeds.

Various means have been devised to supplement the pilot's force by using power drawn from the air stream. These devices may use tabs (spring, fixed, booster, geared, etc.), dynamic pressure pistons, or variable pitch windmills called whirlerons. In mechanical boosters, the force is derived from a power supply which may be electrical or hydraulic. A very high multiplication of pilot-supplied force is thereby possible. However, the gain in force is accompanied by some liabilities which affect the precision of control and control feel. The response of the booster must be instantaneous, since any time lag at onset and completion represents a loss of maneuverability. The necessity of adequate power for peak rate of maneuvering requires a very large power supply or an energy accumulator (36).

Control stick feel, in the normal sense, may be absent with irreversible power controls where there is no feed-back of force to the pilot's hand. Aerodynamic balance, which could be used to operate controls at high speeds and to supply the desired feel characteristics, is thought to be unsatisfactory for several reasons: 1) The balance is so critical that variations in manufacturing tolerances can produce unexpected effects; 2) the speed range is now so great that it may not be possible to obtain, by aerodynamic balance alone, the control forces required at both ends of the speed range; and 3) aerodynamic balance is inferior to booster systems in that the latter may prov means to control surface flutter or "buzz" and also to limit control defle in order to avoid excessive loads on the control surfaces. However, it do become essential to consider some type of artificial feel when boosters ar used.

Devices to produce artificial feel can be made with provision for any of stick force-deflection relationship with effects for speed, acceleratio load factors, and stall warning included as desired. Some of these may be described to indicate the nature of the engineering problems.

A set of springs may be attached to the control stick in a manner tha give displacement feel and self-centering characteristics. By increasing number of springs in operation as the deflection of the stick is increased specified force-displacement relationship can be achieved. An automatic a justment of the end-point of the centering springs can provide the changes accompanying use of the trim tabs, and a similar effect, depending upon dy air pressure, may be used to indicate the changes due to airspeed. Bob we may be attached to the control stick to give a stick force/"g" gradient.

The requirements of "artificial feel" may be accomplished functionall detecting the variation in aerodynamic pressures without recourse to the c surfaces themselves. Thus, an air ram bellows is utilized on the Northrup flying wing to provide synthetic feel proportional to speed. A pneumatic, hydraulic, system can be devised with inputs which furnish the pressure differences required to yield "g", acceleration, and other cues while reli valves in the system limit the application of excessive loads. Special "feeler" surfaces and spoilers have been used experimentally to accomplish purpose. While devices are available which could yield "g" information fo artificial feel systems, no device is yet available for angular accelerati (42).

Current practices regarding control feel characteristics are largely compromises. Though boosters are coming into use, the pilot still supplies an appreciable fraction of the motive power, and there is some residual aerodynamic feed-back. The problem of adapting boosters to the considerable gap between landing and top speeds is often satisfied by some expedient. Thus, the P-80 has a Funk spring which lowers the booster ratio at low stick loads, while a 10:1 hydraulic boost operates at high stick loads. The XF-12, a large transport type airplane, uses a combination of spring tabs and aerodynamic, but not hydraulic, boost. The F7F employes a boost for the rudder control only. There has been objection to the P-84 boost which operates so abruptly above a given force that the pilot tends to overcontrol. Some airplanes are designed with variable boost ratios, which may vary automatically with speed or be set by the pilot for his comfort. A system employing servo-mechanisms for partial boost has also been developed (71).

It should be pointed out that aircraft control is possible, though not necessarily desirable, without any control stick feel at all. An extreme instance is the awkward means by which radio-controlled airplanes are flown. The "pilot" operates one or more toggle switches in a "bang-bang" system, so-called because one flick on a switch may cause the airplane to climb while two flicks may cause it to descend. Similarly, the manual adjustments by which maneuvering flight may be accomplished with a gyroscopic auto-pilot do not furnish feed-back forces, and are different from those required on a control stick. While flight may be controlled without feel, and contemplated push-button schemes promise just this for the future, the real question is whether such methods are adequate for all purposes.

The issue may be a minor one for transport type aircraft, where the maneuvering requirement is negligible and where feel may be desirable only for purposes of landing. In jet fighters, however, the pilots report an almost complete reliance upon stick feel and the position of the horizon during combat maneuvers, with an occasional reference to the Mach meter and yaw strain gauge. Their experience leads one to the conclusion that some stick feel is highly desirable. It would follow, similarly, that radio-controlled aircraft may be maneuvered more readily by a control system with a stick-and-rudder configuration to which pressure and displacement cues were supplied. Such synthetic cues may be based on two types of information: 1) on the power settings and control impulses which the pilot transmits to the aircraft, or 2) on the forces which are relayed back from the control surfaces of the aircraft itself. The latter type are more basic in that the pilot is given a more complete picture of the plane's flight, which may not correspond exactly with the control-setting impulses that have been relayed to it. It may not be too far-fetched to consider the merit of this proposal for the operation of guided missiles as well.

6. SUGGESTIONS FOR FURTHER INVESTIGATION

This report is based primarily on an evaluation of the available literature and on discussions with pilots and engineers able to offer informed guesses. It has not involved any direct experimentation. The first suggestion for future investigation is that standardized flight tests be undertaken with complete instrumentation to examine the effectiveness of various control stick-force gradients in several critical maneuvers. It would appear reasonable to test on such flights the stick force curves which this report indicates as rational with respect to the human ability to discriminate pressure cues. Such a proposal was made to the Bureau of Aeronautics of the Navy Department by Chance Vought Aircraft in February 1947 (72) and it should be quickly put into effect. This was endorsed in August 1946 by NACA (75) which supported the recommendation. Specifically, Chance Vought proposes to flight test an irreversible power boost control system on a F4U-4, equipped so that the pilot may choose between manual and power operation for each control system independently. It will be possible to furnish artificial stick feel characteristics, which vary linearly or otherwise with displacement, and which incorporate variation with speed and acceleration. Provision is also made for flight with a no-feel system. The flights should be made with complete instrumentation. In endorsing such a project, one may express a desire that some attention will be directed towards obtaining data <u>in a standard series of maneuvers by a sufficient sample of pilots</u>. This aircraft company has already made a beginning by an excellent study of control system characteristics for high speed fighters.

Flight safety may not be promoted by relating control force requirements to the maximum which may be exerted by the pilot because current standards are based on insufficient data. The normal variability of human strength, as well as its still unmeasured increase with emotional stress, suggests that there be only partial reliance on a human limit for avoiding excessive loads. A careful examination should be made, therefore, of load-limiting devices as an essential attribute of mechanical control boosters. It is essential that any study of maximum forces, rates of motion, etc., include tests during actual flight.

There is need for an adequate study of human sensitivity to linear displacement of the hands and feet in the directions of stick, wheel and rudder motion. It is important to know the human discrimination function for various displacements just as it is approximately known for pressure. Further, it is advisable to study the relation between linear motion sensitivity and various pressure loads. Since control motions are used to develop and arrest changes in attitude, acceleration, rolling, yawing and pitching velocity, it is important to understand the pilot's ability to discriminate such changes. The meaning of this approach is that it should become possible eventually to assig just-detectable-pressure (and/or displacement) steps to corresponding just-detectable-shifts in the flight configuration. This would appear to be the logical basis for the optimum relationship between human sensitivity, control feel, and flying qualities.

A further study of control feel characteristics should be based on information which already exists, but has not been sufficiently utilized. "Flying Qualities Reports" contain the data from which various stick-force versus stick-displacement relationships, including the effects of speed, acceleration, center-of-gravity position, etc., may be evaluated. It should be rewarding to obtain pilots' opinions of the airplane handling qualities implied by these relationships. Some opinions are available in the reports from "fighter pilot clinics" conducted during the war, and it may be useful to gather further comments.

Since stability and controllability specifications have existed for some time, a tabulation should be made to judge the extent to which various operational aircraft conform to these specifications. An analysis should then be made of the reasons why aircraft differ from the specifications. By soliciting pilot opinion of handling characteristics and relating these to particular aircraft, it should be possible to judge the significance of the various engineering characteristics in determining handling qualities.

In lieu of actual flight tests with various experimental stick-feel characteristics, a preliminary study towards the same end may be accomplished by using the latest model Link Trainer. After ascertaining actual sensitivity to pressure and displacement studied simultaneously, proper rigging of the servo-mechanisms should make it possible to study Link flight under various control-feel arrangements. In a simple form of this experiment, one may study a pursuit-task operated by several types of controls. Perhaps a closer approximation to reality involves the use of the Landing and Take-off Trainer (Special Device 12-BK-1). The subject may be expected to maneuver the model airplane in a standard procedure through controls set up to yield several types of feel. It must be pointed out, however, that present instrumentation does not permit an accurate score for performance on these devices.

The study of control systems should not be limited to conventional forms such as the stick, wheel, and rudder. The innovation of booster systems implies strongly that future controls may be of any size or shape and that they may be placed in any location. Preliminary investigation should collect data on the various principles of control motion which have been proposed and flight tested, not neglecting those for the prone position. One should be careful to guard against the well-known tendency to favor those techniques to which one has become accustomed. In the event that new control systems may be proposed, the important matters for psychological evaluation are: Which type (a) permits the most precise flight control, (b) best promotes learning, and (c) may be operated with the least fatigue. Questions concerning unconventional appearance, cost, engineering feasibility, and procurement are important, but fall in another field of discourse. The psychologist's duty is to make the human factor paramount in designing equipment for human operation and to promote wide experimentation on their feasibility.

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Appendix A

SOURCE MATERIAL FOR FIGURES 6, 7, 8.

Maximum elevator-type force, Figure 6

letter	type of motion	how studied	no. of subjects	reference
A	wheel-type control	cockpit mock-up	2	McAvoy (43) Fig. 5
B	stick, right handed	cockpit mock-up	11	Hertel (23) Table IV
C	stick, two handed	cockpit mock-up	11	Hertel (23) Table IV
D	control stick	4 flight tests on accelerated stalls	1	F-8F-1 (70) report
E	control stick	3 flight tests on dive recovery F7F-1	1	original record inspected
F	control wheel	flight tests	?	Johnson (35)
G	tank driving, one hand	tank mock-up	6	Hugh-Jones (31)
H	tank driving, two hands	tank mock-up	6	Hugh-Jones (31)
J	lever pull (two hands)	dynamometer	?	Vernon (59)
K	control stick	4 flight tests on c.g.	1	Christophersen (6) Fig. 11, 12
L	control stick (two hands)	1 flight test P-47	1	original record inspected
M	control wheel	1 flight test XF-12	1	original record inspected

letter	type of motion	how studied	no. of subjects	reference
A	one hand on side of wheel	cockpit mock-up	2	McAvoy, (43) Fig. 19
B	one hand on top of wheel	cockpit mock-up	2	McAvoy, (43) Fig. 19
C	two hands on control wheel	cockpit mock-up	2	McAvoy, (43) Fig. 19
D	control stick, right handed	cockpit mock-up	11	Hertel, (23) Table V
E	two hands on control stick	cockpit mock-up	11	Hertel, (23) Table V
F	control wheel	flight tests	?	Johnson (35)
G	control stick	one flight test XP-51	1	White (65) Figs. 28, 30
H	control stick two handed operation	one flight test XP-84	1	original record inspected

<u>Maximum rudder-type force, Figure 8.</u>

letter	type of motion	how studied	no. of subjects	reference
A	rudder pedal	cockpit mock-up	11	Hertel (23) Table V
B	tank pedal	tank mock-up	38	Hugh-Jones (28)
C	rudder pedal	13 flight tests F4U-4	1	original record inspected
D	rudder pedal	flight tests	?	Johnson (35) 4 eng. transport
E	tank clutch pedal	tank mock-up	32	Hugh-Jones (30)
F	foot lever	experiment	3	Müller (47)
G	rudder pedal	two flight tests	1	original record inspected.
H	rudder pedal	flight test, P-47	1	Christophersen (6)