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This study was conducted to update data on the force that pilots (and nonpilots) can apply to flight controls so that current performance data could be compared with values for maximum allowable control forces found in sections of the Code of Federal Regulations (14 CFR 23.143 and 25.143). We compared these tabular values with several later samples of human performance to determine what proportion of the potential and actual pilot populations might be able to exert those levels of force. We then obtained data for 12 female general aviation pilots and 12 female nonpilots as well as data for 32 male scheduled-carrier pilots for comparison with previously documented data and with the values in the CFR. 83% the female pilots were not able to exert force to the levels shown in the tables for some of the 10 primary tasks. However, only 12.5% of the male scheduled-carrier pilots did not achieve the tabled force levels for some tasks. Results were examined by task and force-application dimension.

Brief History

Parts 23.143(c) and 25.143(c) of Title 14 of the Code of Federal Regulations (CFR) prescribes maximum control force values used for the testing as required by 25.143(b) and (c). One of the first FAR control-force tables appeared in the Federal Register in 1964 (29 FR 17955, Dec. 19, 1964), coinciding with the transition from the Civil Aeronautics Authority to the Federal Aviation Agency (when the Civil Aviation Regulations were recodified into the Federal Aviation Regulations; 1961 – 1964; that table has been traced farther to CAR 3, 1946). These values were published when most aircraft control forces were a function of the mechanical linkages in the system and the aerodynamic forces working on the control surfaces.

These criteria remained largely unchanged for several decades until "harmonization" with the Joint Aviation Authorities (Europe). The final result of the process appeared in the Federal Register in August 1993 (58 FR 42136). One additional revision to the values for harmonization appears in the Federal Register in 1996 (Vol. 61, No. 28). This produced the values in use today. (See Beringer, 2006, for additional details.)

Modifications

Current values that are applied to Part 23 aircraft are shown in Table 1. This table is repeated for Part 25 airplanes in CFR 25.143(c), but without the "stick" entries. Temporary roll was decreased from 60 to 50, one-hand values were added, and short-term rudder pedal force was decreased from 180 to 150. These values are applicable under the following conditions as

Table 1. Force-exertion limits (lbs.) in 14 CFR Part 23.143(c) applied to specific controls and directions of force application. ("wheel" applies to the control yoke)

Values in pounds force applied to the relevant control	Pitch	Roll	Yaw
(a) For temporary application:			
Stick	60	30	…
Wheel (Two hands on rim)	75	50	…
Wheel (One hand on rim)	50	25	…
Rudder Pedal	…	…	150
(b) For prolonged application	10	5	20

per the rule: "(a) The airplane must be safely controllable and maneuverable during all flight phases including— (1) Takeoff; (2) Climb; (3) Level flight; (4) Descent; (5) Go-around; and (6) Landing (power on and power off) with the wing flaps extended and retracted. (b) It must be possible to make a smooth transition from one flight condition to another (including turns and slips) without danger of exceeding the limit load factor, under any probable operating condition (including, for multiengine airplanes, those conditions normally encountered in the sudden failure of any engine)." However, human-performance data are also applicable to circumstances beyond the described conditions (unanticipated or rare failures).

The question at hand is whether the current and potential pilot populations are represented by the tabular values. We now have more female and older pilots flying (see Stoll et al., 2002, for the effects of aging). Having the proper values to use as a base is critical since this type of criteria will be used to generate method of compliance limits.

Force Limitations and Abilities

Maxima

Maximum force-exertion limits for manually manipulated aircraft controls help assure that the pilot will be capable of making an effective input to the system, regardless of aircraft status. This is more of a concern with the just-mentioned changes observed in pilot demographics over the years, and with transport and other large aircraft operation open to this wider range of the population.

Effective inputs may be required during normal operations or malfunctions of aircraft systems. One example of the latter would is the UH-1 helicopter (Schopper et al., 1986, 1987; Hewson et al., 2000), having hydraulically augmented controls. Manual control operation is possible when hydraulics fail, but it is far more difficult than "normal" operation, requiring more force and skill. Examinations performed using this aircraft indicated male and female participants could meet the force requirements (except on the collective) for single-axis applications (Schopper et al., 1986), but found that 16% of males and 86% of females were unable to exert forces on multiple controls simultaneously to the levels specified in the standards of that time for helicopters (Schopper et al., 1987). This finding implies that simultaneous activation of multiple controls or control axes may be a determining factor for permissible force levels.

The NTSB accident-report database indicated that problems with aircraft controls are frequently cited as primary or contributing causes to aircraft accidents. A large number of these cases involved mechanical failures. Sometimes, however, the initial failure is not of the control system itself but of another system that increases the force felt on the controls. This is exemplified by loss of one engine and the resulting presence of asymmetrical thrust in twin-engine aircraft. Some of these situations require considerable initial force application to the rudder to compensate for asymmetric thrust until rudder trim is applied. Accidents also occur when other factors limit the application of full control authority during a maneuver, such as individuals who are short in stature operating an aircraft where insufficient control or seating adjustment is present. These factors, however, involve limits to range of motion and not control forces per se.

Minima

Conversely, it is important to provide a minimum force resistance to the movement of the control, particularly in fly-by-wire aircraft. In such aircraft (post Airbus 320 and starting with Boeing 777), the force feedback experienced by the pilot is not a direct function of mechanical linkages and aerodynamic forces acting on the control surfaces. It may be possible in these systems to tailor the experienced forces to (1) never exceed pilot-performance limitations, which would obviate most present concerns and to (2) use force profiles such that augmented feedback is provided to the pilot regarding aircraft functioning. The latter would be important to help the pilot avoid causing extreme excursions of the controls and placing undue stress on the aircraft. One accident believed partly attributable to low resistance in the controls was the Belle Harbor, New York, loss of an Airbus A300 (NTSB record DCA02MA001), where "excessive rudder pedal inputs" were identified as a factor.

Archival Data Post-14 CFR Part 23.143/25.143

Given the modifications that have been made to the table since its first appearance in the FAR, it is worthwhile to compare the values with data from later surveys with a more diverse population sample. One such survey was captured in the tool Humanscale 4 (Diffrient et al., 1981). Tables 2 and 3 are comparisons of the values in the current CFR and the values for different segments of the population presented in the 1981 survey.

Table 2. Percentile population data from Diffrient et al. (1981) and 14 CFR 23.143 values for stick roll-axis temporary inputs (lbs.).

	Roll (stick force, lbs.)				
	CFR	**Diffrient**			
		Men		**Women**	
Force application (temporary)		Strong 97.5th	Weak 2.5th	Strong 97.5th	Weak 2.5th
Stick, preferred hand, adduction (in)	**30**	111	***12***	72	***8.1***
Stick, preferred hand, abduction (out)	**30**	66	***9.7***	43	***6.3***

We can see that the stronger-population-category capabilities for both women and men exceed the stick-force limit, but those for weaker ones (underlined) do not (Table 2). For the rudder-force limits (Table 3), each of the four groups appears to be capable of exerting the required forces except the "women, weak" category. There were no direct comparisons available for yoke inputs. One must keep in mind that these are the extreme percentiles (97.5 and 2.5), and do not tell us what proportion of the population we might actually include or exclude at the present tabled values.

Table 3. Percentile population data from Diffrient et al. (1981) and from 14 CFR 23.143 for yaw-axis inputs (lbs).

	Yaw (rudder-pedal force in lbs.)				
	CFR	**Diffrient***			
		Men		**Women**	
Force duration		Strong 97.5^{th}	Weak 2.5^{th}	Strong 97.5^{th}	Weak 2.5^{th}
Temporary	**150**	449	180	292	<u>*117*</u>
Prolonged+	**20**	112.2	45	73	29.25

**Note: knee angle 135 to 155 degrees.*
+ For 4 minutes or more

More recent assessments of female muscle strength (e.g., Meyer et al. 1996) have generally not matched the dimensions of interest for the flight deck. However, Karim et al. (1972), in a joint study by the Civil Aeromedical Institute and the University of Oklahoma, compared the forces applicable to flight controls by a sample of female pilots with those specified by the CFR. Review of the maximal forces permitted for each control indicated allowable elevator and aileron levels were attainable by 50% of the sample, and allowable rudder force by 76%. However, reexamination of Karim's raw data indicates that the success rate at 160 lb. rudder force for the sample was really only 56% if both feet were considered independently (not averaged). Comparing Bonne's data with *current* CFR values, 68% could have met the 150 lb. rudder-force criterion (up 12%). Inasmuch as Karim's data were collected using the left hand on the yoke, we can compare those data with the present "one-hand-on-rim" value. In doing so, we found that 84% would have been able to attain the present criterion (25 lb.) input force. Ages in the sample ranged from 18 to 58 years. The sample used was, as represented by age, sex, height, and body type, approximately representative of those female pilots registered at the time.

Present Data Collection

Two of three phases of an ongoing data collection by CAMI have been completed. Preliminary data have been collected for current populations of pilots and nonpilots (Phase 1), the female pilots being the primary concern regarding potential force limitations..While the sample for the male Part 121 pilots (Phase 2) is large enough for consideration, the samples from the other populations should be considered as only preliminary indicators, requiring completion of larger samples (Phase 3) before any firm inferences can be drawn.

Method

Participants and Dependent Variables

Two preliminary samples were obtained in Oklahoma City, one of female General Aviation (GA, Part 91) pilots and one of female nonpilots (12 each). The pilots ranged in age from 21 to 64 (mean = 45.75, s.d. = 13.7, median = 49.5), while the nonpilots ranged in age from 17 to 71 (mean = 48.1, s.d. = 14.9, median = 50.5). A subsequent larger (n = 32) sample of male scheduled-carrier pilots (Part 121 operations) was obtained at American Airlines' Flight Academy. These pilots ranged in age from 38 to 58 (mean = 49.7, s.d. = 5.8, median = 49.5). Although the data collection targeted female pilots as well, only two Part 121 female pilots participated in this phase. Their data are only briefly mentioned here and a fuller accounting is deferred until a larger sample is obtained. Ten measures of force application were taken that were common to all of the samples, and those are reported here: yoke rotation force (roll); each hand, clockwise and counterclockwise (4); yoke pitch force, push and pull, each hand (4); and rudder force application, left and right foot (2).

Apparatus

A cockpit mockup was constructed similar to that used by Karim et al. (1972). An adjustable Cessna seat was mounted on rails on a platform and positioned such that its adjustable range, relative to the yoke and rudder pedals plane, was the same as that found in a Cessna 172 (Skyhawk). A Skyhawk yoke was mounted on a shaft in the same position as that found in the aircraft, and precision mechanical force meters (0-100 lb) were used to measure force in pitch and roll input. A precision digital medical scale (0-400 lb) was mounted between two dead pedals, such that application of foot force could be measured at the plane of the rudder pedals for either foot (see Figure 1).

Figure 1. Experimental apparatus.

Procedure

Two roughly balanced orders of the ten tasks were used to distribute any potential serial effects across the tasks. The orders were also designed to keep any repetitions of muscle-group exertions separated by as much time as possible, usually at least 2.5 - 3 minutes. Two rest periods were specifically inserted in each order to ensure adequate spacing between trials (trial spacing and rest periods per Stoll et al., 2002). Participants were instructed to exert as much force as they could on the designated control and in the direction specified, and to apply smoothly increasing force to the control rather than sudden force. Performance was recorded after approximately 3 sec (stabilized reading). A small group of the second-phase female Part 91 pilots and of all the male Part 121 pilots sampled applied force for a longer time and stepped down to forces that they could maintain for a longer time period. The primary focus herein will be on the initial force inputs.

Preliminary Results

The primary concern in this preliminary sampling was to determine the distribution of force-application capabilities in the populations of interest. Specifically, the issue was one of a pass/fail for applying force up to the criteria allowed in control systems. The best way to illustrate these outcomes is to present distributions of the raw data, and several of these will be presented.

Pass/fail comparison

We assigned a percentage score representing the proportion of the ten trials on which criterion was met or exceeded to each participant (50 lb. in pitch, 25 in roll, and 150 in yaw/rudder). Figure 2 presents the distribution of female pilots and nonpilots and scheduled-carrier pilots by their percent-passed score. From this figure one can see that only 17% of either female GA pilots or female nonpilots (two each) successfully met or surpassed the criterion levels on all of the trials. The female pilots were more likely to pass more of the trials than the female nonpilots, and all but one operated at the 50% level or above. The male scheduled-carrier pilots had 88% at or above the tabled values on all tasks, with no *individual* at less than a 70% pass rate. The female 121 sample was too small to discuss as a population approximation.

This pass/fail comparison is a coarse measure, at best, because any effort short of the criterion was categorized as "fail" and, thus, being *close* was not taken into account. Examination of the relationships between input force and other covariates for the samples (age, stature, weight) did not reveal any of the expected correlations often seen in broader samples with greater ranges of these variables. Range restriction was especially present for the male 121 pilots as seen in their age distribution. The two female scheduled-carrier pilots exceeded tabled values for all tasks, and their data will not be discussed further due to the small sample size.

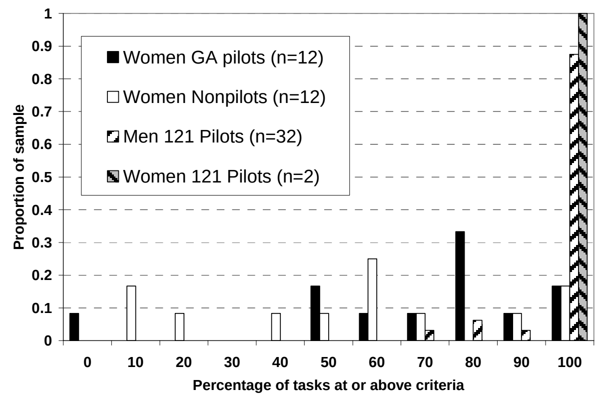

Figure 2. Distribution of pilots and nonpilots by percentage of tasks performed at or above force criteria.

Figures 3, 4, and 5 depict the task outcomes for the female GA pilots and nonpilots in more detail, showing for each specific input task the percentage of the two populations that met the present criteria (right-hand category on each graph), and how the percentage of the populations meeting or exceeding the criterion would increase for lower criterion force levels.

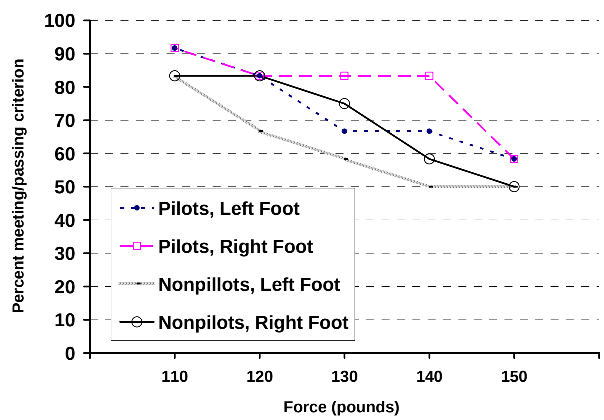

Figure 3. Percentage of "meet-or-exceed" outcomes by female population, task, and force level for rudder input.

It is apparent in Figure 3 that the pilots performed better for the input of leg force (rudder) in general, and that a 10 lb. decrease in the criterion would increase their success, with the right foot, from about 58% to about 83%. However, the increase for left-foot usage is not as pronounced (58% to only 67%), the two not coming together, at 83%, until we drop to 120 lb. of force.

Figure 4 presents similar data for the application of rotational force, categorized simply as "up" or "down," in the roll axis of the yoke control. One can see that, in general, more force can be applied in the downward direction by either hand than in the upward direction, as expected. It is interesting to note that the left-hand down and right-hand down meet-or-exceed rates for pilots, given the present criterion are both above 90%; dropping the value to 20 lb. would produce 100% compliance with the criterion for those two tasks, as well as right- and left-hand up (all aileron-related inputs would meet criteria for the female pilots at that level). The nonpilots would reach three-of-four success at 100% at 15 lb of force.

Similarly, Figure 5 shows the data for forces exerted in the pitch (push/pull) axis. Right-hand push and left-hand push for the pilots is at 75% success at the present criterion level (50 lb.). Right-hand pull, however, does not reach a 75% rate until reduction to 45 lb., and left-hand pull starts at 50% and does not meet or exceed 75% until a reduction to 35 lb. One can see that the pilots had higher success rates than the nonpilots, in general, from the present criterion down through 40 lb.

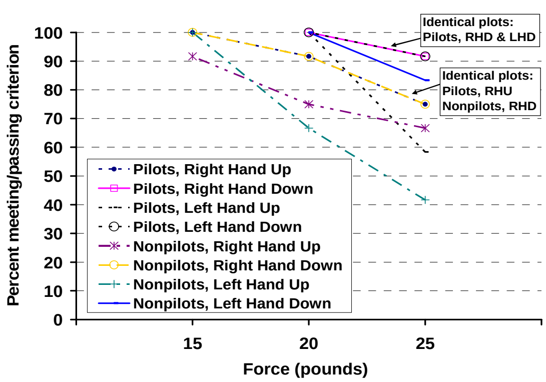

Figure 4. Percentage of "meet-or-exceed" outcomes by population, task, and force level for roll (aileron) input.

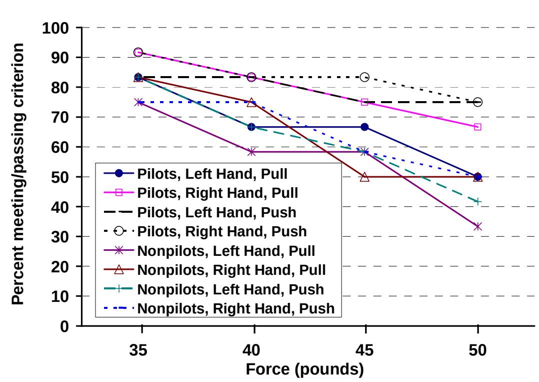

Figure 5. Percentage of "meet-or-exceed" outcomes by population, task, and force level for pitch input.

Two-Handed Input

Two-handed roll-input data are available for only 6 of the female Part 91 pilots and for all of the male Part 121 pilots. The meets-or-exceeds percentages are presented in Table 4 for both clockwise and counter-clockwise inputs. While the female sample is far too small to allow us to draw any conclusions, it appears that the present criterion can be met by a fair percentage of the sample, with small changes in the criterion increasing that percentage. A larger sample with a wider demographic range is required for definitive statements to be made. Of the Part 121 male pilots, only one exhibited performance on one task (CW) that was less than the 50 lb. tabled value.

Table 4. Percentage of meets-or-exceeds criterion outcomes for 6 female GA pilots and 32 male Part 121 pilots, two-handed input, by force level and direction of input.

		Force Criterion (lbs.)			
Pilot type	**Input Direction**	**35**	**40**	**45**	**50**
Female Part 91	Clockwise	100	100	100	67
	C-Clockwise	100	100	67	67
Male Part 121	Clockwise	100	97	97	97
	C-Clockwise	100	100	100	100

Multi-Axis or Multi-Control Inputs

It should be noted that the present force-input criteria are specified for each axis of each control independently. However, performance changes when multiple controls or control axes must be activated simultaneously (Schopper at al., 1987). This type of task was included in the second phase of the data collection. Thus, data for only 5 female GA pilots (one of the 6 for whom data were obtained did not follow instructions for this task and her data were not included) and 32 male Part 121 pilots are available and means for both separate and simultaneous control activation are shown in Figure 6. The task was described to the participants as a situation where they were piloting a twin-engine aircraft and had lost the right engine, resulting in adverse yaw to the right and dropping of the right wing (without significant pitch change). They were instructed to exert as much force as possible, via the same procedure as used before, with their left foot and with their left hand in the down or counterclockwise direction.

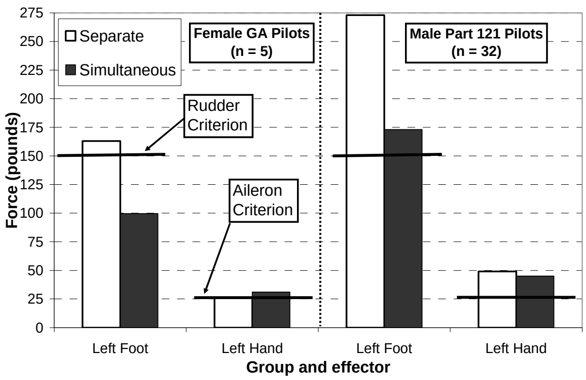

Figure 6. Mean force inputs, in lbs., for left foot and hand, in both separate and simultaneous control activation for female Part 91 and male Part 121 pilots.

The data show the expected decrease from separate to conjoint force application but only for the rudder-pedal input. For the female GA pilots, what was an above-criterion input when done singly became a below-criterion input, on average, when two control inputs were required simultaneously. The men Part 121 pilots, on average, maintained their inputs above the tabled values, despite the significant decrease in rudder input force (paired t; $p<.00001$). While these mean data are generally consistent with the findings of Schopper et al. (1987), they are misleading without looking at the percentages of the population that met or exceeded the tabled levels. These data are presented in Table 5.

Thus, none of the female GA pilots in the small sample could meet the tabled rudder level (150 lb) when exerting force on the yoke in a dimension orthogonal to that of rudder force application. That is to say, pulling (pitch up) on the stationary yoke would have aided the foot-force task, but this task was designed to (1) represent the real-world circumstance of a failed right engine and (2) prevent coupling/aiding achievable by opposing one force application with another to increase force applied to both controls.

Table 5. Percentages of meets-or-exceeds outcomes for the two-input task by control dimension and pilot type.

	Control Dimension	
Pilot Type	**Aileron**	**Rudder**
Female Part 91	80	0
Male Part 121	90	78

Additional data were collected on subjective prolonged-force-application judgments pilots, but space limitations prevent a full discussion of those findings here. Suffice it to say that the levels judged to be acceptable for long-term application were significantly lower than the initial force inputs, on average, and are shown in Table 6. The average values exceeded, in all cases, the tabled values in the CFR for "prolonged application." However, these were subjective levels selected by the participants during the application of force to the controls and should thus be viewed with skepticism until a force application time-history empirical study can be completed to determine actual time/force limitations in performance.

Table 6. Mean force values chosen by participants as "comfortable" for sustained application by control input dimension and sample.

	Single axis			Both hands	Multi-axis	
Pilot type	Pitch	Roll	Yaw	Roll	Roll	Yaw
Female Part 91	18	10	69	17	11	53
Male Part 121	27	12	101	22	13	73
Tabled	*10*	*5*	*20*		*5*	*20*

Conclusions

The primary intent of these initial phases of inquiry was to determine if there were segments of the populations of interest that might not be able to achieve the levels of force input that could conceivably be required, given the present criteria in the CFR. While it is clear, as was expected, that some percentage of the population of female pilots may not be able to exert forces comparable to the criterion, the small size of that preliminary sample prevents any firm conclusions from being drawn about what the actual percentages in that population might be or how the present sample will ultimately compare with the other databases mentioned in this paper. Data for the male Part 121 pilots indicates they are capable, for the most part, of exerting forces at or above the tabled values. A larger sample of female pilots is being collected that should allow better determination of their population parameters and suitable recommendations regarding the present CFR values.

Acknowledgments

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