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Control-Force Inputs Obtained from Pilots and Nonpilots (Flight Attendants): Comparison with Established Handbook Distributions of Performance

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CONTROL-FORCE INPUTS OBTAINED FROM PILOTS AND NONPILOTS (FLIGHT ATTENDANTS): COMPARISON WITH ESTABLISHED HANDBOOK DISTRIBUTIONS OF PERFORMANCE

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Earlier reports in this series (Beringer, 2006-2008) have reported the force that pilots and nonpilots could exert on flight controls. This paper presents a comparison of some well-known tables of human strength with the values from recent samples of women and men pilots and nonpilots in an attempt to determine how closely those distributions fit tabled distributions of human strength. Findings suggest that some other samples may be used to approximate the difficult-to-sample Part 121 female pilots if the data are treated properly. Specifically, yoke-activation tasks for the female pilots could be reasonably well approximated by fractional performance values of male pilots. It was also determined that some older data obtained from a narrower sample of participants (both in age and gender) were not especially good for estimating present performance of the more diverse population of present-day certified pilots. Percentile values are provided for the lower values of the sampled groups.

Previous publications have reviewed the Code of Federal Regulations [14CFR, Parts 25.143(c) and 23.143(c)] that specify the maximum forces the test pilot can experience in the flight controls during the testing required for certification of an aircraft (Beringer, 2006) and presented some preliminary data comparing the abilities of current pilots and nonpilots with both the values contained in the regulations and with documented abilities of earlier-sampled populations (Beringer, Ball, & Haworth, 2007). The primary emphasis was on determining what proportion of the samples could produce forces at or above those allowed by the CFR in manual control systems (those data will be referenced as Sample 1). A further sample (Sample 2) of pilots and nonpilots from a Part 121 (scheduled commercial carrier) operator was preliminarily reported by Beringer (2008), detailing data for 35 additional individuals. That paper discussed how the application of force on a single manipuland or control was greatly reduced when the operator was required to apply force with both a hand and a foot simultaneously, and presented data regarding the force that could be applied to both rotary and pushbutton seatbelt releases. The purposes of the present article are to (1) trace the sources of often-used anthopometric data, (2) compare data from these sources with some of the recently collected data, and (3) to determine to what extent samples other than Part 121 female pilots can be used to estimate performance of that group, whether they be of male pilots or of nonpilots, given that performance of the female population is likely to be the limiting factor for how many individuals will be able to perform force-exertion tasks at any given level.

Popular Anthropometric Data and Their Sources

Many sources of anthropometric data have been generated in the last 50 years, and a large proportion of those were formed prior to 1980. If we examine the sources, we will find that many date anywhere from 25 to 50 years ago. For example, the tabled values found in CFR Part 23.143(c) and CFR Part 25.143(c) are believed to have been derived from data for 5th to 95th percentile males applying for military service between 1955 and 1957, collected at Wright-Patterson AFB (personal communication, Dr. Richard Jones). This recollection appears to be supported by references in Morgan, Chapanis, Cook, and Lund (1963) (reprinted in Van Cott & Kinkaide [1972]) to the source of the strength data relevant to flight controls reported therein as “Unpublished data, Anthropology Branch, Aerospace Medical Research Laboratories.” Additionally, two sets of data summarized in Van Cott and Kinkaide (Table 11-107, Maximal static leg thrust exerted on a fixed pedal by seated males) present data from Rees and Graham (1952) (sample of 20 men) and Rohmert (1966) (sample of 60 men). The summaries in the Van Cott and Kinkaide edition of the handbook were based upon 194 references from the 1950s up through the publication date, thus representing a comprehensive sample of the data collected to that date. Moving forward chronologically, the popular HumanScale 4 (Diffrient, Tilley, & Harman, 1981) dates back 27 years, and the NASA Anthropometric Source Book predates that by 3 years (1978). While it is true that there are some compilations of data with more recent dates, they are just that: compilations of data from earlier studies and assessments.

Although tables of values are, in many cases, simply reprinted/repeated from earlier sources, some have been modified. Ahlstrom and Longo (2003) took the table of arm, hand, and thumb-finger strength (5th percentile male data), Figure 23, from MIL-STD-1472F and reduced all of the contained values to 80% of their original values, presenting it as their Exhibit 14.5.2.1 (page 14-44). The justification, presented on page 14-43 of the document, was: "Since the experimental conditions used to collect the source data yielded maximum possible exertion values for young men, these values are were [*sic*] too high for design purpose. For design, one does not want to deliberately or consistently require maximum exertions. Thus these source values were reduced by 20% before applying them as design criteria." While it is certainly reasonable to expect a downward shift of the distribution of applicable forces with an increased age range (see Stoll et al., 2002, for strength loss as a function of aging), no specific rationale is given for the choice of precisely 20% as the reduction factor. Thus, we have recommended force-application levels for design purposes that are a fractional proportion of earlier tabled values, but without a clear tie of the amount of the reduction to a specific empirically defined reduction factor. While it might be possible that one could take Stoll's data providing profiles of strength loss by age, make an assessment of the distribution of ages in the target population, and then rectify the original data for young men by that factor, this will not be attempted here. Table 1 is partially derived from Beringer (2008; Table 4) and depicts the sample sizes and age ranges for the various groups in each sample that will be compared with extant data.

Table 1. Sample compositions showing group, sample size, median age, and age range. Groups of fewer than 4 individuals have been omitted. Data from Karim are included, as raw data from that study were used to generate percentiles in Figure 2.

			Age		
Sample	**Group**	**n**	**Mean**	**Median**	**Range**
Karim et al. (1972)	Female Part 91 pilots	25	35.4	34	18 to 58
Beringer Sample 1	Male Part 121 pilots	32	49.7	49.5	38 to 58
	Female Part 91 pilots	12	45.7	48.1	21 to 64
	Female nonpilots	12	49.5	50.5	17 to 71
Beringer Sample 2	Female Part 121 pilots	11	40.8	39	32 to 54
	Male Part 121 pilots	6	39.5	38.5	32 to 52
	Female nonpilots (flight attendants)	10	39.9	38.5	24 to 57
	Male nonpilots (flight attendants)	6	32.5	34	22 to 47

COMPARISONS WITH TABLED DATA

Depending upon how much of the population one wishes to accommodate, one may choose one of the lower percentile values from the known tables of human strength. Frequently these tables will present the 5th, 50th, and 95th percentile values. Some, however (i.e., Diffrient et al., 1981), present the 2.5th as the low point, with overlapping distributions for men and women portrayed with two common sets of values (weak men and average women in one; average men and strong women in the other). While it would be possible to thus provide for success of either 97.5% of 95% of the subpopulation from the pilot group (women), the overall success for all pilots would be higher than either of those values due to higher force-application success rates by the men at those same levels. The following figure (Figure 1) provides tabled data for yoke-force input by samples of men pilots and nonpilots. Some sources did not contain

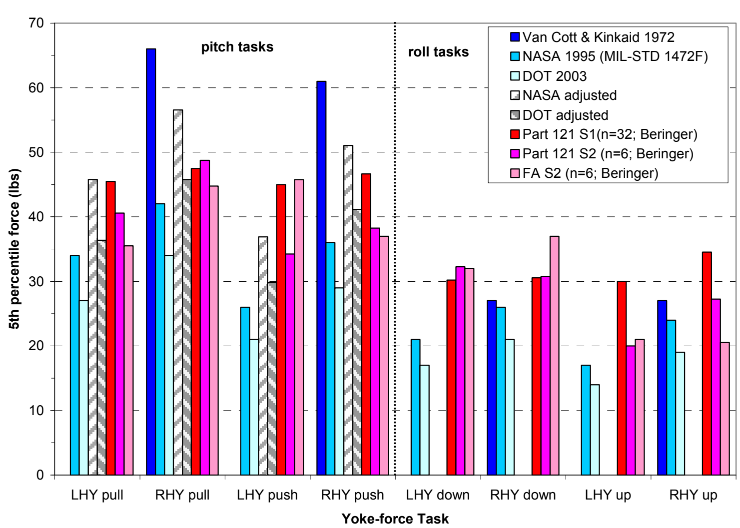

Figure 1. 5th percentile tabled force values and recent samples for men.

the data for yoke-force application, and a derivation factor had to be determined. For example, the Laubach chapter in the NASA source book (1978) presented data for force exertion on a vertical handgrip in various locations near a seated operator, but none of them were a close enough match to the position of the vertical part of the control. However, two of the sources contained data that appeared to be a location match for side-stick data, and the data from Van Cott and Kinkade contained both yoke-push/pull data and side-stick-push/pull data for appropriate elbow angles. Multiplication factors were determined for deriving applied yoke force from applied side-stick force (left-hand push, stick to yoke, 1.3469; left-hand pull, stick to yoke, 1.4186), and the data in Figure 1 labeled as "adjusted" are the resulting values.

Relating data for female pilots to other samples/populations

Given that it is difficult to obtain large samples of women Part 121 pilots due to (1) their comparatively small number relative to men Part 121 pilots and (2) their unavailability due to flight operations being conducted, an attractive alternative would be to use more accessible samples that could somehow be related to the target population. The most obvious choice would be another sample of women with demographics, other than piloting, that were similar. Thus, let us first look at how the 5th percentile values for the four recent samples, pilots and nonpilots, compared amongst themselves and with percentile values derived from the raw data for women pilots in Karim et al. (1972) data (Figure 2). One can see a relative consistency across the samples from the Beringer assessments, with a relatively small but consistent difference, excepting in sample 2 yoke push, in favor of the pilot participants. However, the values from Karim et al. are considerably larger for the yoke push and pull tasks when compared with the other four samples. Aileron (yoke rotation) forces appear to be comparable. One contributing factor for this differential may be that Karim used a hard wooden seat on the test platform that may have allowed participants to use it as a brace more effectively than the padded Cessna seat used in the Beringer assessments. That the flight attendants' force performances (Women FA) were lowest on the hand-up aileron-roll tasks and lower than their own hand-down performances is consistent with other data showing a reduction in the applicable force for hand-up tasks, as compared with hand-down tasks. Otherwise, all recent samples appeared to be relatively close in their 5th percentile levels of yoke-force application.

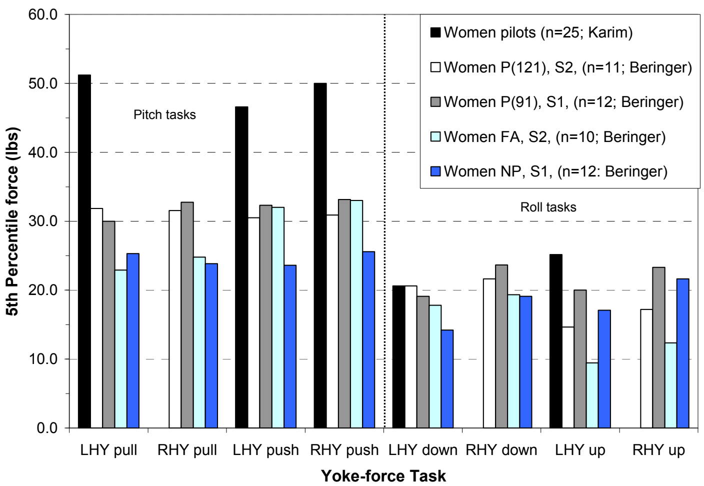

Figure 2. Comparison of recent women pilot samples' calculated percentiles with those derived from Karim et al. (1972).

Humanscale 4 (Diffrient et al., 1981), as mentioned earlier, presents its summarized low-end force data for the 2.5th percentile rather than the 5th percentile and, as such, comparisons with performance data had to be reported separately from the other sources reporting 5th percentile data. Figure 3 depicts the 2.5th percentile Sample 2 data for women and those from Humanscale. The data in Humanscale for the conditions closest to the yoke-manipulation task being investigated consistently underestimate the women's values from the sample by an average of 32.6% for the pitch axis and 35% for the roll axis.

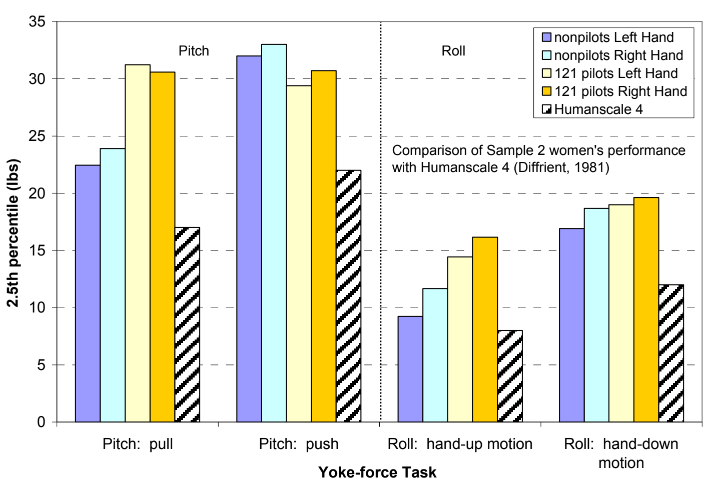

Figure 3. Comparison of women's 2.5th percentile data from Sample 2 with those from Humanscale 4.

Prediction of women's averages from men's

The use of data for males as a baseline can take two forms. First, one can assess the present state of male performance and compare it with tabled values for males, as shown in Figure 1. If the fit were good, then one could use tabled values to represent current men's performance. Alternately, one could just use the new data for males and bias it accordingly. There are existing recommendations as to how to bias the men's data to represent performance expected from the women. For example, Ahlstrom & Longo (2003), in their section 14.5.2.3 (page 14-46) recommend the following reductions of the men's values to apply them to women: "a. For upper extremities, females strength is 56.5% of men. b. For lower extremities, female strength is 64.2% of men. c. For trunk extremities, female strength is 66.0% of men." NASA (1995) presents similar data in that publication's Figure 4.9.3-5, but presents both means and ranges for the differences in total body strength, upper extremities strength, lower extremities strength, trunk strength, and dynamic strength. The three values recommended in Ahlstrom et al. appear to be reproduced directly from the NASA document. Upon closer examination, all of these data appear to have been derived from Laubach (1976; page 85). Other sources have presented the general rule-of-thumb value as 67% (sometimes simply represented as "two-thirds"), undoubtedly derived from Laubach's mean difference for dynamic strength characteristics.

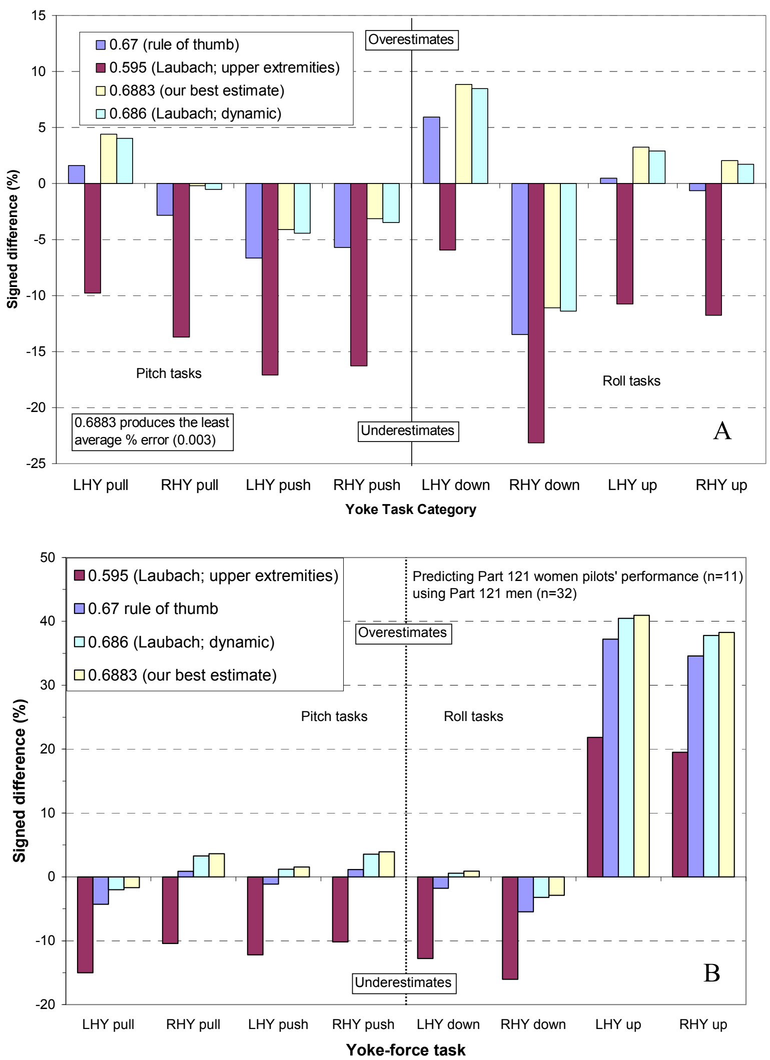

Figure 4. Estimation of Part 91 (A) and Part 121 (B) women pilots' 5th percentile performances as fractional portions of Part 121 male pilots' 5th percentile performances.

The largest sample of male Part 121 pilots (32) was used as the basis for prediction, and the data were restricted to tasks that were common to both major sampling efforts to make comparisons direct and straightforward. Figure 4 depicts the percentage of error for the yoke-activation tasks when using various fractions of male average performance for prediction of female Part 91 pilots' performance. Included are Laubach's value for the upper extremities (.595), Laubach's value for dynamic tasks (.686), a general rule of thumb (.67), and our best estimate for minimizing average error across tasks (.6883). Clearly, next to our tailored value, the estimate for dynamics tasks (.686) produces the best average prediction across these specific tasks (0.003 % average error). Across the first six tasks for the female Part 121 pilots, Laubach's factor for dynamic force input (0.57% average error) appeared to be slightly better than our best estimate (0.91 % average error) from the Part 91 pilots' fit when applied to the Part 121 pilots' data. Although the overall error was less using Laubach's upper extremities factor (0.595), it did so at the expense of having none of the estimates accurate to less than 10% error (increasing the error on the first 6 to balance the overestimations on the last two hand-up roll tasks).

Summary of lower percentiles, Samples 1 and 2

Tables 2 and 3 present summaries of the lower percentile values obtained for the participants in both samples, excluding any groups within a sample that consisted of 3 or fewer. These tables are somewhat more conservative than some of the sources (i.e., Karim et al. for pitch tasks), but are not as conservative as others (Humanscale 4). As such, they may be a reasonable compromise for selecting force levels for the activation of aircraft controls that will allow the majority of users to operate them without difficulty. Three cut-off points in the distributions are provided so that the practitioner will have a little more choice (2.5%, 5%, 10%) than that usually afforded by other tables that provide the 50th percentile and one value in each tail.

Table 2. Women's momentary force-application percentiles (lbs) from field data collapsed across samples 1 and 2.

Control	Direction of movement	Hand/foot used	2.5 %		5 %		10 %	
			Pilots	Nonpilots	Pilots	Nonpilots	Pilots	Nonpilots
Yoke	Pull	Left	30.0	22.0	30.1	22.1	31.1	24.2
		Right	29.8	21.6	30.4	23.2	33.8	27.0
	Push	Left	28.7	23.3	29.4	29.2	33.2	32.0
		Right	28.5	25.3	30.6	31.1	31.3	33.0
	Up	Left	14.7	9.5	15.4	10.1	18.4	12.3
		Right	17.4	12.6	19.6	14.2	22.1	18.2
	Down	Left	18.8	16.0	20.0	16.1	20.0	18.0
		Right	18.9	19.1	20.6	20.1	25.8	21.2
Foot Pedal	Push	Left	103.7	52.5	119.8	54.3	127.4	79.2
		Right	112.8	77.4	120.8	85.5	131.2	96.9

Table 3. Men's momentary force-application percentiles (lbs) from field data, collapsed across sample 1 and 2.

Control	Direction of movement	Hand/foot used	2.5 %		5 %		10 %	
			Pilots	Nonpilots	Pilots	Nonpilots	Pilots	Nonpilots
Yoke	Pull	Left	35.7	32.6	39.2	33.2	51.8	34.4
		Right	41.6	33.7	47.1	35.3	51.7	38.6
	Push	Left	40.8	30.0	44.6	31.9	45.7	35.8
		Right	37.8	33.3	44.0	33.6	48.0	34.2
	Up	Left	22.5	20.2	27.3	21.4	32.0	23.8
		Right	26.8	20.3	29.6	20.6	33.8	21.2
	Down	Left	28.7	31.2	29.9	32.4	30.0	34.8
		Right	29.8	36.2	33.4	36.3	35.0	36.6
Foot Pedal	Push	Left	165.0	179.8	174.6	108.5	209.3	182.0
		Right	155.8	177.8	166.1	178.5	181.5	180.0

CONCLUSIONS

The values obtained in this series of samples of pilot and nonpilot performance suggest that some tabled values from the often-referenced sources of anthropometric data may be overestimates of presently obtainable performance for the target groups of interest, male and female pilots engaged in Part 91 (general aviation) and Part 121 (scheduled commercial carrier) operations. It is also apparent that some specific points on the distributions are comparatively higher values than previously documented and suggest stronger performance than previously suggested. As such, it is recommended that one take the conservative approach when using any of these values to set design limits, using the lesser of the collective values or the median of several sources if in doubt. The data also suggest that some predictions of female performance as a fractional measure of male performance can be accurate, whereas other specific tasks may, for various reasons, not be as amenable to estimation. Ultimately, it is recommended that the practitioner carefully examine the conditions surrounding and mechanisms employed in the execution of any force application to controls to determine what may best suit the particular application and, if in doubt, seek additional data specific to the application.

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