REALISTIC CAPACITY LIMITS FOR MARINE PASSENGER SAFETY: ADULT BODY WEIGHT DISTRIBUTIONS IN THE UNITED STATES

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Transportation and lift systems usually incorporate maximum capacity specifications for design, testing, and operation. Whether maximum capacity is specified directly in kilograms, or indirectly as maximum number of adults, user safety depends on accurate and logical relationships between system specifications and the upper limits of body weight distributions in the user population. This study utilizes recent data from the National Health and Nutrition Examination Survey (NHANES) and bootstrap methodology to establish meaningful weight capacity limits for small (10 person) marine craft, concluding that the average adult weight of 75 kg used to establish capacity limits for small marine craft in several ISO standards is far too low to represent contemporary US adults. This study indicates that a randomly selected group of 10 adult males will exceed the 750 kg capacity 97.6% of the time, and a group of 5 adult males and 5 adult females will exceed the 750 kg capacity 80.1% of the time. In fact, this study suggests that a design and testing assumption of 97.5 kg per adult (975 kg for 10 people) is needed to ensure that groups of 10 adult males (the worst case for small craft design) are within capacity limits 95% of the time.

Most transportation and lift systems incorporate maximum capacity specifications for design, testing, and operation in order to ensure the safety of their human occupants. Sometimes maximum capacity limits are specified directly as total pounds or kilograms (in elevators, for example), and sometimes limits are specified indirectly as maximum number of passengers (in marine craft, for example). However, whether maximum capacity is specified directly or indirectly, the safety of users depends on an accurate and logical relationship between system specifications and the upper limits of body weight distributions in the user population.

It's no secret that the average body weight in U.S. populations has increased dramatically in recent decades. In the interval between the National Health Examination Survey I (1960-1962) and the most recent National Health and Nutrition Examination Survey (1999-2002), the average weight of US males (aged 20-74 years) increased 11.2 kg and females increased 11.0 kg (Ogden et al., 2004). These relatively rapid shifts in body weight distributions create a particular challenge for establishing maximum capacity safety limits for transportation & lift systems which may be in service for several decades, and may also be designed and tested using weight distributions that may be significantly outdated to begin with.

Findings from a recent accident investigation in the UK (Marine Accident Investigation Board, 2004) highlight the potential impact of outdated body weight statistics on marine craft safety, and provided the impetus for the US study reported here. The accident involved capsizing of a 10 passenger rental boat, *Breakaway 5*, on the River Bure in the Norfolk Broads, with the loss of one life. Ten people were on the boat when it capsized: 2 adult males, 2 adult females, and 6 teenagers or young adults ranging between 57 kg and 108 kg in weight. The total weight of the ten people in *Breakaway 5* was 845kg. MAIB investigation found the *Breakaway 5* capsizing to be the result of both the total weight in the boat, and the distribution of that weight in the boat.

As European safety directives governing the maximum capacity and stability of small marine craft are derived from relevant international

standards (ISO 14946: 2001; ISO 12217-1: 2002) that assume an average adult weight of 75 kg, and as a Breakaway 5 class vessel with the equivalent of 10 people aboard weighing a total of 750 kg subsequently passed stability testing in accordance with ISO 12217-1, the MAIB concluded that review of the body weight assumptions inherent in the international standards was required. UK statistics provided to the MAIB by QinetiQ (a company formed when the UK Ministry of Defence privatized many of its research functions) indicated that random samples of 5 males and 5 females would be expected to exceed the assumed standard total of 750 kg some 27% of the time, and that random samples of 10 males would be expected to exceed 750 kg in total weight 87% of the time (MAIB, 2004: Figure 8). Both UK results indicated a need to revise the body weight assumptions underlying international standards, and the author was subsequently contacted by the Convener of ISO TC 188 Working Group 22, Small Craft Stability, for comment on a proposed new weight average of 85 kg per adult (Andrew Blyth, personal communication, August 11, 2005).

As it is widely believed that Americans are heavier than European populations, the purpose of this study is to provide comparable weight statistics for groups of 10 randomly selected US adults.

MATERIALS AND METHODS

Study Samples

The most authoritative resource for US Civilian height and weight distributions are the National Health and Nutrition Examination Surveys (NHANES) conducted by the National Center for Health Statistics (NCHS). For this study, we have downloaded data from the NCHS website for the survey periods 1999-2002 (National Center for Health Statistics, 2002, 2004), and generated male and female study samples with sex-specific demographic (age/race) distributions matching those of the US Federal Census 2000 (U.S. Census Bureau, 2001). Only subjects aged 18-65 years with valid weight data were utilized in this study, resulting in initial sample sizes of N=3,779 males and N=3,412 females.

Because NHANES samples subjects equally across age and sex strata, statistical analyses of NHANES data are not representative of the US Civilian population unless subjects are weighted or sampled in proportion to actual US demographic distributions. To arrive at study samples whose demographic distributions are reflective of US Civilians aged 18-65 yrs for the year 2000, we have used stratified (age/race) random sampling of the male and female NHANES data with probabilities of selection determined by the relative frequencies of the sampling cells in Census 2000 and number of subjects available in the comparable sampling cells for the NHANES 1999-2002 reference data. These pseudorandom study samples were generated from the NHANES 1999-2002 reference data using the Stata 9.0 command *sample* (StataCorp, 2005).

Ten pseudorandom samples of US civilian males and ten pseudorandom samples of US civilian females were created for this study, each with sample sizes of n=1779 males and n=1568 females respectively, the largest subsets permitted by the mathematical relationships between relative frequencies of people in the sampling cells for Census 2000 and relative numbers of subjects in the sampling cells for NHANES 1999-2002.

Statistical Approach

Because body weight distributions are usually skewed right (Sokal & Rohlf, 1981: 117), a non-parametric statistical approach is preferable to one that assumes a normal (Gaussian) distribution. Bootstrapping (Efron and Tibshirani, 1998; Manly, 1997) is a commonly used method for empirically defining the distributions of statistics when their actual distributions are unknown or do not conform to a known theoretical distribution. In this project bootstrapping has the added validity of avoiding assumptions inherent in large sample statistics so that we may establish the distribution of interest using repeated samples of a small group of people (10 adults), which is most relevant to the small marine craft problem.

The distribution of interest here is the total weight of 10 randomly sampled U.S. adults, and what we would like to know is the probability that the 10 adults' total weight exceeds 750 kg, the

expected weight of 10 adults assumed in ISO 14946 and ISO 12217-1 standards. In addition, assuming that a large percentage of samples fall above 750 kg in total weight, we would like to know the total weight below which 95% of our samples fall, which may be a more realistic value for safety related design, testing, and operational standards. Note that simply knowing the 95th percentile of body weight will not provide a realistic basis for design because it is highly unlikely that 10 passengers boarding together would each equal or exceed the population 95th percentile for weight.

In this project, we repeatedly drew groups of 10 randomly selected subjects from each study sample, totaled the group's weight, and saved the group's total for further analysis. Because larger sample sizes are required to estimate probabilities in the tail of a statistic's distribution, we utilized 10,000 replications for each of the ten previously generated study samples (Manly, 1997), resulting in a total of 100,000 bootstrap replications for each of three passenger conditions: 10 Males, 5 Males and 5 Females, and 10 Females. These bootstrap routines were executed using Stata 9.0 *bootstrap* (StataCorp, 2005).

RESULTS AND DISCUSSION

For randomly selected samples of 10 US adults between the ages of 18 and 65, and based on 100,000 total replications for each sampling condition, the following total statistics were obtained.

Table 1. Probability of 10 US adults exceeding ten passenger capacity limits based on 75 kg and 85 kg averages for body weight

Sample Condition	P >750 kg	P >850 kg
10 Males	.9764	.5583
5 Males, 5 Females	.8008	.2174
10 Females	.4450	.0552

It is clear from Table 1 that use of a 75kg average adult weight in establishing capacity limits for small marine craft is unrealistically low for today's US adult population. The probability that a party of 10 adults will exceed the 750kg total capacity assumed in ISO stability standards is at lowest, 44% (all females) and at highest 98% (all males). Equally mixed parties of 10 would be expected to exceed the assumed total weight capacity of 750 kg 80% of the time. These results clearly support the MAIB's conclusion based on UK data that the 75 kg assumption underlying ISO standards for small marine craft capacities is unrealistic. Even using the suggested new standard of 85 kg per adult, US parties of 10 would be expected to exceed the 850 kg limit for mixed parties 22% of the time and for all male parties 56% of the time.

Table 2. Total weight (kg) of 10 US adults based on 100,000 trials for each condition

Sample Condition	Mean	95th %ile
10 Males	864.95	974.60
5 Males, 5 Females	804.05	915.70
10 Females	745.11	856.85

In fact, one would prefer to establish maximum capacities for small marine craft using the 95th percentile of total weight for a randomly selected group of 10 men (the worst case scenario), which would be equivalent to an average of 97.5 kg per passenger (see Table 2). Use of a more modest sample condition (5 Males and 5 Females), would result in an assumption of 92 kg per passenger, which, however, would be exceeded on "male bonding" excursions 17 % of the time because the probability of total weight exceeding 920 kg in this study of 100,000 replications of 10 randomly sampled US males is P = .1734.

CONCLUSIONS

The results of this study and that of the UK Marine Accident Investigation Board (2004) clearly support the need to revise assumptions about average adult weight that govern the design, testing, and operation of small marine craft carrying 10 passengers. Moreover, it is likely that international standards governing the maximum capacities of aircraft, larger marine craft, lifts, and other forms of transportation are also using average adult body weights that are too low for safe operation in

today's world. To provide a general basis for addressing this issue, additional bootstrap studies are needed that resample passenger parties of increasingly larger sizes until their results converge on a large sample value.

Finally, it should be mentioned that the bootstrap approach utilized in this study has utility in a variety of potential ergonomic applications where the body dimensions of a group of people must be accommodated as a whole. Designing bench type seating in vehicles and athletic stadiums, for example, could be aided by knowing the statistical distribution of summed shoulder or hip breadths of a randomly drawn group of users.

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REFERENCES

Efron, B. and Tibshirani, R.J. (1998). *An Introduction to the Bootstrap*. London: Chapman and Hall.

ISO 14946. (2001). Small craft – Maximum load capacity. Geneva: International Organization for Standardization.

ISO 12217-1. (2002). Small craft – Stability and buoyancy and categorization – Part 1: Non-sailing boats of hull length greater than or equal to 6 m. Geneva: International Organization for Standardization.

Manly, B.F. (1997). *Randomization, Bootstrap and Monte Carlo Methods in Biology, 2nd edition.* London: Chapman and Hall.

Marine Accident Investigation Branch (MAIB). (2004). Report on the Investigation of the capsize of Breakaway 5, River Bure, Norfolk, 19 July 2003. Report No 2/2004. Retrieved on August 10, 2005: http://www.maib.dft.gov.uk/publications/investigation_reports/2004/breakaway_5.cfm

National Center for Health Statistics. (2002). National Health and Nutrition Examination Survey Data [1999-2000]. Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. Retrieved on June 14, 2004: http://www.cdc.gov/nchs/about/major/nhanes/nhanes99_00.htm

National Center for Health Statistics. (2004). National Health and Nutrition Examination Survey Data [2001-2002]. Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. Retrieved on June 14, 2004: http://www.cdc.gov/nchs/about/major/nhanes/nhanes01-02.htm

Ogden, C.L., Fryar, C.D., Carroll, M.D. and Flegal, K.M. (2004). Mean Body Weight, Height, and Body Mass Index, United States 1960-2002. Advance data from vital and health statistics: no 347. Hyattsville, Maryland: National Center for Health Statistics.

Sokal, R.R. and Rohlf, F.J. (1981). *Biometry.* New York: W.H. Freeman and Co.

StataCorp. (2005). *Stata Statistical Software: Release 9.0*. College Station, TX: Stata Corporation.

U.S. Census Bureau. (2001). Census 2000 Summary File 1 (SF 1) 100-Percent Data. Tables PCT12A - PCT12O. Retrieved on May 23, 2002: http://factfinder.census.gov/