# The lack of sex and age diversity in neck biomechanical data.

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## ABSTRACT

*Female and elderly individuals are at greater risk than male and young individuals for neck injury in otherwise equivalent automotive collisions. Developing safety technologies to protect all occupants requires high quality data from a wide range of biomechanical test subjects. Here we sought to quantify the demographic characteristics of the volunteers and post-mortem human subjects (PMHSs) used to create the available biomechanical data for the human neck during impacts. A systematic literature and database search was conducted to identify kinematic data that could be used to characterize the neck response to inertial loading or direct head/body impacts. We compiled the sex and age for 626 volunteers and 110 PMHSs exposed to 5,431 impacts extracted from 63 published studies and three databases, and then compared the distributions of these parameters to reference data drawn from the neck-injured, fatally-injured, and general populations. We found that the neck biomechanical data were biased toward males, the volunteer data were younger, and the PMHS data were older than the reference populations. Increasing the diversity of these parameters in future studies is vital for filling the gaps in the current neck biomechanical data and will provide critical data to address existing inequities in automotive and other safety technologies.*

## INTRODUCTION

Injuries to the head and neck are some of the most catastrophic consequences of motor vehicle collisions. Over the past seven decades, improvements in roads, vehicles, safety equipment, safety regulations, and enforcement have significantly reduced the injury, morbidity, and mortality burden associated with head and neck injuries. Despite these considerable achievements, many injury prevention approaches, including the computational models and anthropometric test devices (ATDs) used to design and evaluate safety equipment, have focused on the adult male occupant (Linder and Svensson, 2019). There are considerable field data showing that female and elderly individuals are at greater risk of serious and fatal injuries than adult males in similar severity collisions (Evans and Gerrish, 2001; Bédard et al., 2002; Hill and Boyle, 2006; Zhu et al., 2006; Bose, Segui-Gomez and Crandall, 2011; Carter et al., 2014).

Underlying kinematic differences between males and females have been established. In volunteer studies, females exhibit higher magnitude head accelerations in both frontal and rear-end collisions (Siegmund et al., 1997; van den Kroonenberg et al., 1998). In rear impacts females also exhibit greater forward rebound and larger intersegmental motion between adjacent vertebrae in the cervical spine (Ono et al., 2006).

Sex differences in external neck morphology and anatomical differences in the cervical spine between males and females have also been established. The vertebral anatomy, curvature, head mass, neck strength, neck muscle morphometry, and neck muscle activation patterns have all been shown to differ between males and females (Siegmund et al., 1997; Kamibayashi and Richmond, 1998; Matsumoto et al., 1998; Klinich et al., 2004; Stemper et al., 2008; Vasavada, Danaraj and Siegmund, 2008; Sato et al., 2017).

It is clear that sex and age affect occupant kinematics and neck injury mechanics, and that injury prevention devices such as restraint systems, airbags, and head restraints, which are primarily designed for adult males, are not as effective for females and elderly occupants. An important first step in addressing this inequity in injury prevention design is to understand the diversity — or lack of diversity — in the baseline biomechanical data being used to motivate these designs. Therefore, we sought to quantify the distributions of sex and age for volunteer and PMHS tests that make up the available neck biomechanical data and to compare the distributions of these parameters to reference data drawn from the neck-injured, fatally-injured, and general populations.

## METHODS

A systematic search was performed for published studies that contained kinematic data for the head and torso in response to inertial loading and direct head and body impacts, and from which the neck response could be estimated. Five databases (PubMed, Web of Science Core Collection, Compendex Engineering Village, SportDiscus, and SAE Mobilus) were searched in June/July 2020 with no restrictions on year or language of publication. The search terms reflected the eligibility criteria, including keywords targeting human subjects and cadavers, head, neck and torso kinematics, and impact loading. Studies extracted from relevant review articles were also added to the results of these searches.

A sample Web of Science search is as follows:
#1 TS = (Volunteer* OR "In Vivo" OR Cadaver* OR "Ex Vivo" OR PMHS)
#2 TS = (head)
#3 TS = (sled OR "crash test*" OR impact*)
#4 TS = (acceleration* OR displacement*)
#4 AND #3 AND #2 AND #1

Studies from the search results were first compiled and deduplicated using Legacy RefWorks (ProQuest, Ann Arbor, MI). Author GB screened the titles and abstracts based on preset criteria (Table 1) and then performed a full-text review on the relevant subset to identify eligible studies containing the desired data using Covidence (Melbourne, Australia). Author PAC reviewed studies whose inclusion/exclusion was ambiguous. For eligible studies, we then determined if the kinematic data were available in the publication, appendix, supplementary material, by contacting the authors, or searching biomechanics databases (e.g., National Biodynamics Laboratory, Air

Force Biodynamic, and NHTSA Biomechanics databases). We then extracted the sex and age for all volunteers and cadavers from each test within the included studies. These characteristics were compared to reference data for automotive neck injuries (NASS-CDS), automotive fatalities (FARS), and the general population (US Census Bureau, USCB).

*Table 1. Study Eligibility Criteria*

| Inclusion Criteria | Exclusion Criteria |
|---|---|
| ● Test volunteer or cadaver subjects with or without helmets.<br>● Measure primary data on time history accelerations or displacements of both the human head and base of the neck or upper thorax (C6 - T4 range).<br>● Involve accelerating the head by means of inertial loading or direct head or body impact. | ● Solely use subjects who have undergone spinal surgery, have apparent or induced injuries, have been otherwise altered, or exhibit extreme spine pathologies.<br>● Involve modifying the kinematics of the head and neck through additional impacts (airbags, steering wheels, head restraints) or other factors.<br>● Poor methodology or insufficient detail to assess the quality of the methods used to obtain and modify data (requires the agreement of two reviewers). |

From the NASS-CDS data, we extracted all cases from 1993 to 2015 with cervical spine injuries (Region 6, Structures 02, 50 and 59 based on the 1998 Abbreviated Injury Scale) for light vehicles (Body types 1 to 49) and all types of crashes. For each unique individual (n=25,889), we extracted the maximum Abbreviated Injury Scale (AIS) score for their cervical spine injury, as well as their sex and age. Individuals were removed from the dataset if their sex was unknown (n = 9) or if their age was unreported (n = 4).The data were then grouped into three datasets based on injury severity: AIS1+, AIS2+, and AIS3+ injuries. Injuries of unknown severity (coded as AIS 7 in NASS) were included in the AIS1+ group but removed from AIS2+ and AIS3+ groups.

From the FARS data, we queried the Fatality and Injury Reporting System Tool (FIRST) to extract the sex and age of all drivers and occupants who died in motor vehicle crashes from 2005 to 2019.

From the census data, we extracted the estimated 2017 US population for females and males at each year of age between 0 and 100 years (USCB, 2019). All individuals over 100 years old were pooled into the 100-year category.

Datasets for age were created for the number of volunteer tests, PMHS tests, AIS1+ injured individuals, AIS2+ injured individuals, AIS3+ injured individuals, fatalities, and people in the general population. We focused our analysis on the number of volunteer and PMHS tests rather than the number of volunteers or cadavers because each test yielded a unique set of data. As a result, a volunteer or cadaver could appear multiple times in the datasets. The medians for the male and female data were computed using all of the data within a dataset. Dispersion within each of the datasets was quantified using the interquartile range (IQR).

## RESULTS

Our search yielded 2,249 unique studies, of which 417 studies were relevant to our goals, 91 of the 417 relevant studies measured the kinematic variables we sought, and 63 of these studies presented or otherwise allowed access to their data (Figure 1). The 63 studies contained 626 unique volunteers exposed to 5,229 tests and 110 unique PMHSs exposed to 202 tests (see Supplemental Materials for the 63 included articles).

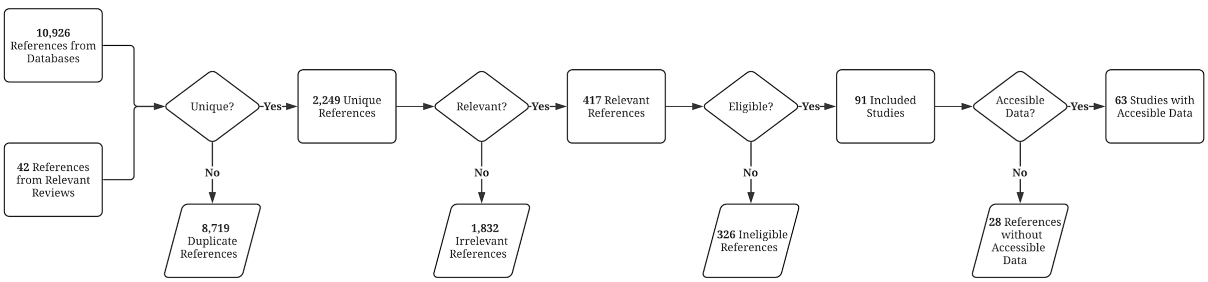


Figure 1. Flowchart showing the number of studies at each stage of the selection process.

About 66% of the volunteer tests and 84% of the PMHS tests were conducted with males (Table 2, also visible in Figures 2 to 5). Both values were higher than the proportion of males in the US population (49%) and in the AIS1+, AIS12+, and AIS13+ neck injury groups (48%, 60%, and 63% respectively), but landed on either side of the proportion of males seen in US automotive fatalities (70%).

Table 2. Sample size (n), median, and interquartile range (IQR) of the age data for the volunteer tests, PMHS tests, AIS1+, AIS2+, and AIS3+ from the NASS data, FARS data, and the US population.

| | Age (years) | | |
|---|---|---|---|
| | n | Median | IQR |

| | | | | |
|---|---|---|---|---|
| Volunteers | Total | 5296 | 26 | 11 |
| | Male | 3544 | 26 | 11 |
| | Female | 1752 | 27 | 7 |
| PMHS | Total | 195 | 65 | 17 |
| | Male | 166 | 65 | 15 |
| | Female | 29 | 72 | 20 |
| AIS1+ | Total | 25859 | 31 | 24 |
| | Male | 12458 | 31 | 23 |
| | Female | 13401 | 32 | 25 |
| AIS2+ | Total | 4410 | 35 | 29 |
| | Male | 2658 | 34 | 26 |
| | Female | 1752 | 38 | 35 |
| AIS3+ | Total | 1985 | 36 | 30 |
| | Male | 1243 | 35 | 26 |
| | Female | 742 | 38 | 36 |
| FARS | Total | 455886 | 39 | 33 |
| | Male | 320917 | 38 | 31 |
| | Female | 134969 | 41 | 38 |
| US Pop. | Total | 324982000 | 38 | 38 |
| | Male | 160044000 | 36 | 37 |
| | Female | 164938000 | 39 | 38 |

The median ages for the PMHS tests were higher than all of the reference datasets, ranging from as little as 26 years older than the FARS data (males) up to 40 years older than the AIS1+ data (females). The youngest female and male PMHSs tested were 46 and 22 years old, respectively. The median ages for the volunteer tests, on the other hand, were lower than all of the reference datasets by a maximum of 14 years relative to the FARS data (females). In addition to differences in the medians, the age-related dispersions (IQRs) of both the volunteer tests and the PMHS tests were less than all of the reference datasets (Table 2). Dispersion was smallest for the female volunteer tests (7 years) and largest for the female fatalities and female population data (38 years). There were no volunteer tests for female children or adolescents (≤17 years old) and the oldest female and male volunteer test subjects were 63 and 65 years old, respectively.

## DISCUSSION

Our goal was to quantify the sex and age of the volunteers and cadavers that comprise the available kinematic data for the human neck and to compare the distributions of these variables to those of the neck-injured, fatally-injured, and general populations. Overall, we found large differences in the sex and age distributions between the biomechanical data and the reference populations.These findings point to an underlying lack of diversity in the biomechanical data being used to understand and ultimately prevent collision-related neck injuries.

The most obvious difference between the biomechanical and reference datasets is between males and females. There were twice as many male volunteer tests as female volunteer tests and over five times as many male PMHS tests as female PMHS tests. In contrast, there were fewer males than females with neck injuries across the entire range of severities (i.e., AIS1+) and only 1.67 times more males than females when only serious and more severe neck injuries (AIS3+) were considered. Although males were ~2.4 times more likely than females to die in a road crash based on FARS data, this database also captures deaths from non-neck-related trauma and is therefore a poorer reference for the appropriate diversity needed in the neck biomechanical data. Based on these findings, more biomechanical data are needed for females throughout the neck injury spectrum — from whiplash injury to neck fractures.

The age difference we observed between the biomechanical and reference datasets was primarily in the PMHS data. This finding is not surprising given that 75% of deaths in males and 85% of deaths in females occur at over 65 years of age (Shumanty, 2018), making old cadavers more readily available to researchers. Nevertheless, there are established age-related changes in tissue morphology and failure response that potentially confound comparisons between the volunteer and PMHS data (Yukawa et al., 2012; Yoganandan et al., 2018). These differences create problems when combining the geometric, kinematic, and neuromuscular data of young volunteers with the failure data of old cadavers, particularly when creating human body models, developing injury reference values, or designing safety interventions. Another key age-related difference is the absence of volunteer data for female children and adolescents. While injury rates to this population are relatively low, the societal costs of injury to children are high and therefore biomechanical data from male and female subjects are needed to first understand if differences exist and then how to accommodate for them if present.

To interpret our findings, one should consider the different kinds of biomechanical data generated from volunteer and PMHS tests. Volunteers are exposed to lower, often sub-injurious conditions and can yield information related to realistic initial postures, neuromuscular responses, and potential pain measures. Cadavers, on the other hand, are often exposed to injurious loading conditions and can yield information regarding the tolerance to injuries. Given these differing conditions, outcomes, and ethical considerations, volunteer data may be more relevant to less severe neck injuries whereas PMHS data may be more relevant to more severe neck injuries.

Although our findings showed differences in the sex and age of the biomechanical and reference populations, our analysis did not reveal whether the presence or scale of these differences were important. Previously documented morphological (Siegmund et al., 1997; Kamibayashi and Richmond, 1998; Matsumoto et al., 1998; Klinich et al., 2004; Stemper et al., 2008; Vasavada, Danaraj and Siegmund, 2008; Sato et al., 2017) and physiological differences (Ono et al., 2006; Vasavada, Danaraj and Siegmund, 2008) between the male and female neck combined with the different risks for neck injuries in males and females for similar crashes (Carter et al., 2014) suggests that some sex or sex-related variables could be responsible, but our understanding of the complex relationships amongst the many potential variables remains incomplete.

We chose to tabulate volunteer and PMHS tests rather than the individual volunteers and cadavers. While we recognize that multiple tests from a single volunteer/cadaver do not generate independent data, many of the tests were not identical and therefore generated different, though not wholly independent data. From this perspective, our analysis provides an optimistic view of the amount of biomechanical data available for the human neck, and yet it still shows that there are large gaps in the overlap between the biomechanical data, the neck-injured population and the general population. Another limitation of our work is that we did not separate either the biomechanical data or the neck-injured population by loading direction, crash type or injury type. Nevertheless, we recommend that researchers planning to conduct future volunteer and cadaver tests consider these specific factors when they specify the sex, age, and anthropometry distributions of their volunteers and cadavers.

## CONCLUSIONS

We found large differences in the distributions of sex and age between the populations used to generate biomechanical data for the human neck and the neck-injured populations. Based on our findings, we encourage researchers to consider the diversity of their volunteer and cadaver populations in the context of the population at greatest risk for the injury being studied.

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