# Exploring the effects of sex and size on dynamic tibia properties

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***Abstract*** Pedestrian road traffic injuries are a global concern with incidences ranging from 20–50 million each year. To support equitable and applicable research into pedestrian injuries, experimental studies must incorporate female and male samples of various ages and sizes. The objective of this study was to examine relationships between tibial biomechanical properties and sex, body size, and bone size to evaluate the role of each in understanding tibia response and identifying lower extremity injury thresholds, with a particular emphasis on the interaction between sex and size. Fifty-nine tibiae were impacted in a 6 m/s lateral-medial 4-point bending scenario to replicate a pedestrian-MVC impact to the leg. Overall, tibia structural properties were not significantly different between sexes in a dynamic 6 m/s blunt leg impact. No meaningful relationships between tibia structural properties and sex were observed. Trends demonstrated that dynamic tibia properties have more significant relationships with bone size than body size, when separated by sex. In localized loading (e.g., impact to pedestrian leg) bone size has stronger relationships with structural properties than body size. While this study was unable to conclusively identify variables contributing to variance in tibial response, the foundation for future research has been established.

***Keywords*** pedestrian injuries, leg injury, tibia fracture, structural properties, sex differences

## I. INTRODUCTION

Pedestrian road traffic injuries are a global concern with incidences of injured pedestrians in the global adult population estimated to be 17,683,004 in 2019 [1]. The rank order of Disability-Adjusted Life Year (DALY) for the 10 leading causes of the global burden disease highlights the worldwide health threat of pedestrian injuries, with road traffic injuries ranked at #9 in 1990 and at #3 in 2020 [2]. Health, economic, and societal burdens are directly linked to pedestrian road traffic injuries [2]. Age and lower socioeconomic status have been identified as high-risk factors for pedestrians involved in motor vehicle crashes [2]. Previous studies have shown that average lifetime costs per adult pedestrian impacted by a motor vehicle range from US$2,892–$902,089 for MAIS 1–5 injuries, excluding fatalities [3]. In the USA, injured pedestrians consistently represent 2–3% of total road traffic injuries from 2011–2020 [4]. In 2020, 18,213 females and 22,545 males were injured in US pedestrian-motor vehicle crashes (MVC) [4]. Adults, analyzed in five-year age intervals from 21–80+ years, represented 2–3% of all road traffic injuries in 2020 in the USA [4]. While research has identified specific populations at increased risk, global data demonstrate that adult females and males are injured in pedestrian road traffic incidents (Fig. 1). However, females are not equally represented in experimental biomechanical literature. This is due to foundational assumptions that females are small and males are midsize or large. Therefore, most experimental data are collected on males and simply scaled to “female” based on size-assumptions. It remains unknown if scaling from male to female, or large to small, is appropriate globally (whole body) or locally (per body region). Which highlights the question of whether there is a need for increased female vs male data or size variation data (small vs large) to provide equitable and applicable research in pedestrian injuries and severity risk across populations.

Across multiple studies conducted globally, lower extremity injuries in adult pedestrian impacts are either the most common or second most common injury [2,5-7]. In a review of pedestrian and crash data in four countries (USA, Germany, Japan, and Australia), a previous study found that leg injuries accounted for 32.6% of pedestrian

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AIS2+ injuries [6]. A French study [8] determined that when pedestrians were impacted at <30km/h, lower limb injuries were the second highest AIS2+ injury (32%) in the sample of males and females (0–90 years old). Saadè *et al* [9] found that lower limb injuries were the most frequently injured body region in pedestrian-MVC and specifically, the tibia was the most frequent AIS3+ injury. Additionally, tibia fractures are the most common injury in lateral pedestrian-bumper impacts [10,11]. While lower extremity injuries alone are not likely contributing to pedestrian fatalities, these injuries are associated with high costs (health, economic, and societal) and can lead to long-term disabilities [2]. More specifically, midshaft tibial fractures are associated with increased difficulty in treatments, increased healing durations, and increased risk in developing complications [6,12].

As incidents of pedestrian road traffic injuries continue to rise worldwide and the population of injured pedestrians includes both males and females, there is a critical need for research regarding lower extremity injuries in pedestrian-MVC loading events. The objective of this study was to examine relationships between tibial biomechanical properties and sex, body size, and bone size to evaluate the role of each in understanding tibia response, with a particular emphasis on the interaction between sex and size.

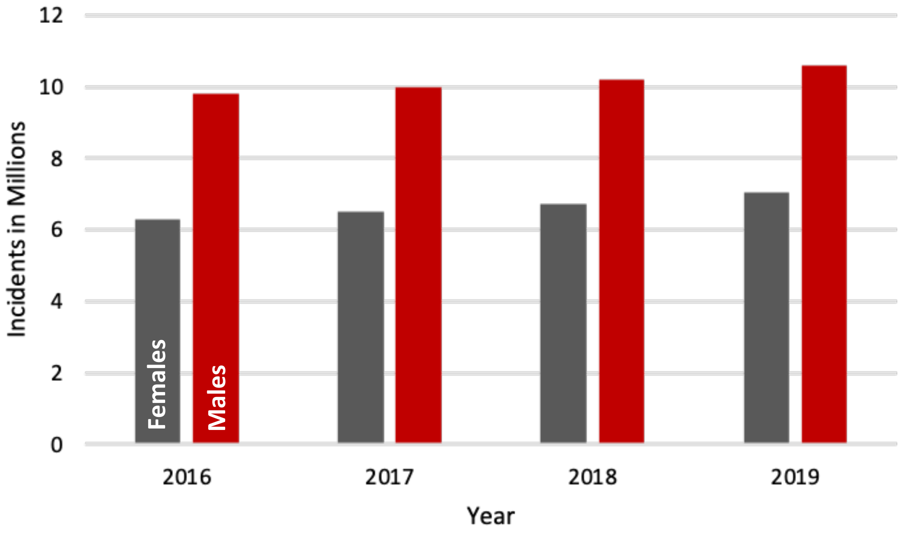

Fig. 1. Global mean incidences of pedestrian road injuries in adults (20+ years) by sex and age [1].

## II. METHODS

### *Experimental Testing*

Fifty-nine tibiae (females, n=30; males, n=29) from an age-matched sample (p=0.130) (29–102 years) (Fig. 2) were ethically obtained through The Ohio State University Body Donation Program, Columbus, Ohio, USA, following compliance protocols established by research ethics advisory committees. All tibiae were screened prior to selection to determine the presence of any pre-existing trauma. Tibiae with any observed trauma to the diaphysis were excluded from this study. Prior to testing, all soft tissue was removed, except for the periosteum, and pre-test imaging was conducted. For more details regarding sample preparation and pre-test data collection, see [13]. The proximal and distal ends of the tibiae were rigidly potted at the 20% and 80% sites, determined based on the total length of the tibia without the medial malleolus (tibia length). All tibiae were experimentally loaded in a controlled 4-point bending scenario in a lateral-medial direction at 6 m/s (21.6 km/h) (Fig. 3). All tibiae were impacted at the 40% and 60% sites, calculated using tibia length, simultaneously, and were loaded to failure. This dynamic loading rate is intended to represent an impact to the pedestrian leg by a vehicle bumper. For more details regarding experimental design and boundary conditions, see [13].

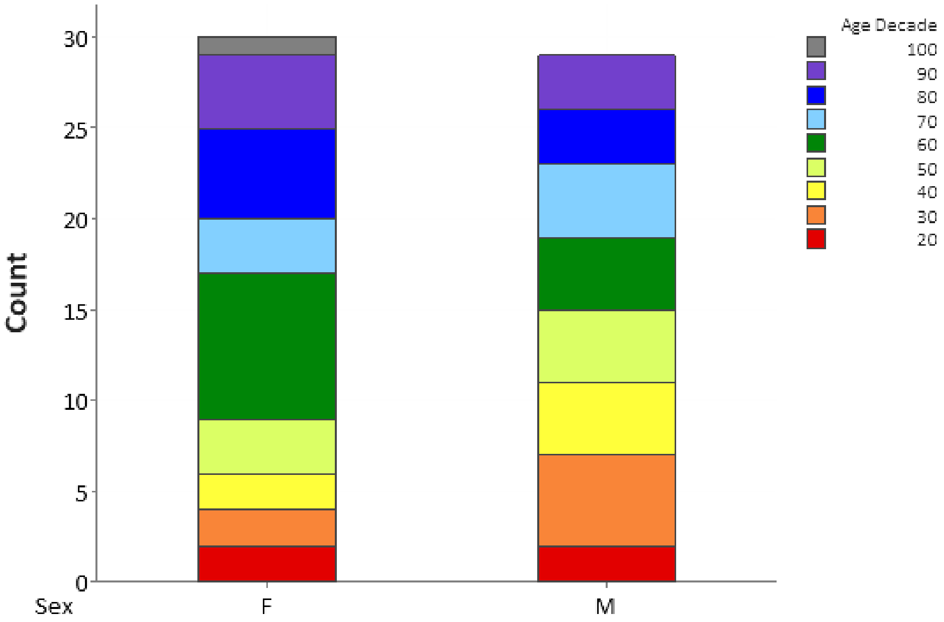

Fig. 2. Sample demographics by sex and age (decade).

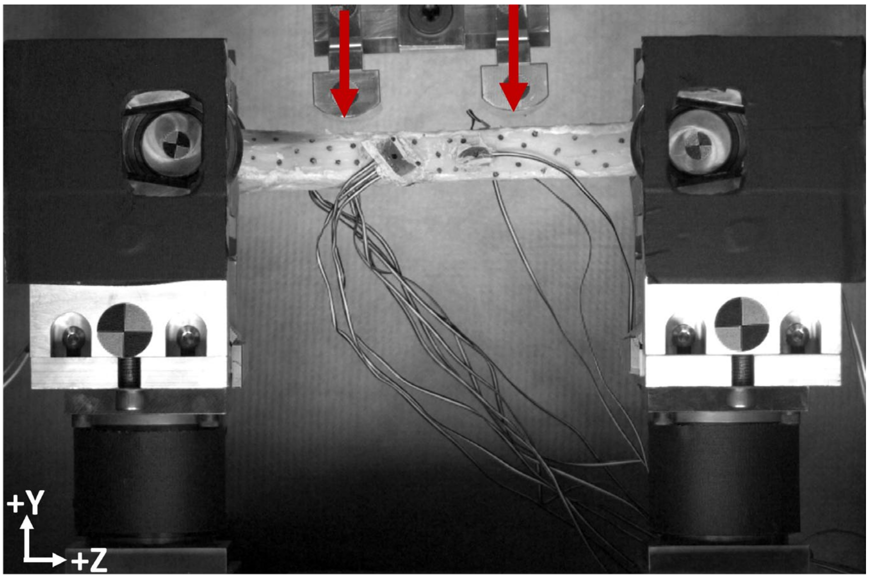

Fig. 3. Exemplar of a right tibia in testing fixture. Red arrow indicates direction of impact (lateral-medial).

### *Data Processing and Analyses*

Definitions of body size, tibia size, and tibia structural property variables utilized in this study are provided in Table I. The SAE J211 anatomical coordinate system was utilized, where positive X was anterior, positive Y was lateral for the right tibia and medial for the left tibia, and positive Z was inferior [14]. Force data were collected at 100,000 Hz. Displacement data were collected at 20,000 Hz and filtered using CFC 180. Independent samples t-tests were utilized to evaluate sex differences in all independent and dependent variables. All variables were tested for normality and linear regressions were employed to evaluate relationships between tibia structural properties and body and bone size variables. ANCOVA analyses were utilized to investigate the effects of the primary independent size variable, with sex as the covariate, to evaluate whether females and males demonstrated different relationships when both sexes had significant relationships with the same structural property within the same analysis. One-way ANOVA and Tukey's Honest Significant Difference (HSD) analyses were used to test for significant differences between structural properties and body size categories. All statistical analyses were performed using Minitab 18 Statistical Software [15] and the significance level for all analyses was α=0.05.

TABLE I
VARIABLES AND DEFINITIONS

| Variable and unit | Definition and/or Formula |
|---|---|
| *Body Size* | |
| Stature (cm) | Subject height measured postmortem |
| Weight (kg) | Subject weight measured postmortem |
| Body Mass Index (BMI) | kg/m$^2$ |
| *Bone Size* | |
| Tibia Length (mm) | Distance from lateral condyle to distal articular surface, excludes medial malleolus |
| Medial-Lateral Diameter (mm) | Width of tibial diaphysis (medial surface to lateral surface) at the site of the nutrient foramen |
| *Tibia Structural Properties* | |
| Peak Force (N) | Sum of absolute maximum force in Y from each load cell |
| Peak Displacement (mm) | Maximum displacement in Y |
| Structural Stiffness* (N/mm) | Slope of 20–80% of linear portion of F-D curve |
| Energy (N*mm) | Total area under the F-D curve to peak force |
| Peak Bending Momentɫ (Nm) | Peak reaction force multiplied by the distance between the impact point (40% or 60%) and the center of rotation at the corresponding, based on load cell and impact point, end of the tibia |

*Referred to as "stiffness" for the remainder of this paper
ɫReferred to as "bending moment" for the remainder of this paper

## III. RESULTS

No significant departure from normality was observed in any of the variables (p>0.057). One possible outlier was detected, using a Grubbs' test, in energy but was determined to be a valid value and was therefore not excluded from analyses. Pearson's correlation was conducted to determine which independent variables were correlated (Fig. 4). In pairwise Pearson's correlations the following significant correlations were found: stature and weight (r=0.49, p<0.001), stature and tibia length (r=0.83, p<0.001), stature and M-L diameter (r=0.62, p<0.001); weight and BMI (r=0.87, p<0.001), weight and tibia length (r=0.34, p=0.007), weight and M-L diameter (r=0.29, p=0.023); and tibia length and M-L diameter (r=0.57, p<0.001). Descriptive statistics and independent sample t-test results are provided in Table II. Age was not significantly different between females and males in this sample and was not further analyzed within the scope of this study. Significant differences (p<0.005) between sexes were observed in the following variables: body size (stature and weight), bone size (tibia length and medial-lateral diameter), and structural properties (energy and bending moment). As expected, females were smaller than males in both body and bone size. The lack of significant differences in structural properties between sexes was unexpected. Females demonstrated smaller mean values in peak force, peak displacement, energy, and bending moment than males. However, females had a higher mean stiffness than males. Females demonstrated greater variation in peak displacement, stiffness, and energy values than males. The minimum and maximum values in peak displacement and energy were both within the female sample. Despite no significant differences in peak force, peak displacement, and stiffness between sexes; overall, females tended to demonstrate smaller structural property means.

TABLE II
DESCRIPTIVE STATISTICS BY SEX AND INDEPENDENT-SAMPLES T-TEST RESULTS

| Variable (unit) | Sex‡ | Minimum | Maximum | Mean | SD | p-value* |
|---|---|---|---|---|---|---|
| Age (years) | F | 29 | 102 | 68 | 21.1 | 0.130 |
| | M | 24 | 96 | 59 | 21.8 | |
| *Independent Variables* | | | | | | |
| Stature (cm) | F | 149.8 | 180.3 | 163.0 | 7.6 | **<0.001** |
| | M | 160.0 | 190.5 | 177.3 | 7.7 | |
| Weight (kg) | F | 37.4 | 110.2 | 55.6 | 14.6 | **<0.001** |
| | M | 35.8 | 96.1 | 70.9 | 13.7 | |
| BMI ($kg/m^2$) | F | 13.5 | 33.9 | 20.8 | 4.7 | 0.148 |
| | M | 11.0 | 32.7 | 22.6 | 4.5 | |
| Tibia Length (mm) | F | 296 | 397 | 354 | 22 | **<0.001** |
| | M | 343 | 423 | 387 | 20 | |
| M-L Diameter (mm) | F | 20 | 28 | 23 | 1.8 | **<0.001** |
| | M | 21 | 30 | 26 | 2.1 | |
| *Dependent Variables* | | | | | | |
| Peak Force (N) | F | 8159 | 22461 | 15293 | 3734 | 0.131 |
| | M | 8014 | 25596 | 16735 | 3493 | |
| Peak Displacement (mm) | F | 1.7 | 4.9 | 3.3 | 0.7 | 0.502 |
| | M | 2.3 | 4.6 | 3.4 | 0.5 | |
| Stiffness (N/mm) | F | 3811 | 20115 | 10054 | 3487 | 0.586 |
| | M | 3036 | 17563 | 9571 | 3298 | |
| Energy (N*mm) | F | 8506 | 35633 | 19119 | 5531 | **0.005** |
| | M | 9918 | 30489 | 23078 | 4894 | |
| Bending Moment (Nm) | F | 349.0 | 937.1 | 637.7 | 127.8 | **<0.001** |
| | M | 422.0 | 1188.9 | 777.0 | 146.6 | |

‡Females (F) n=30, Males (M) n=29

*Significant p-values are **bold**

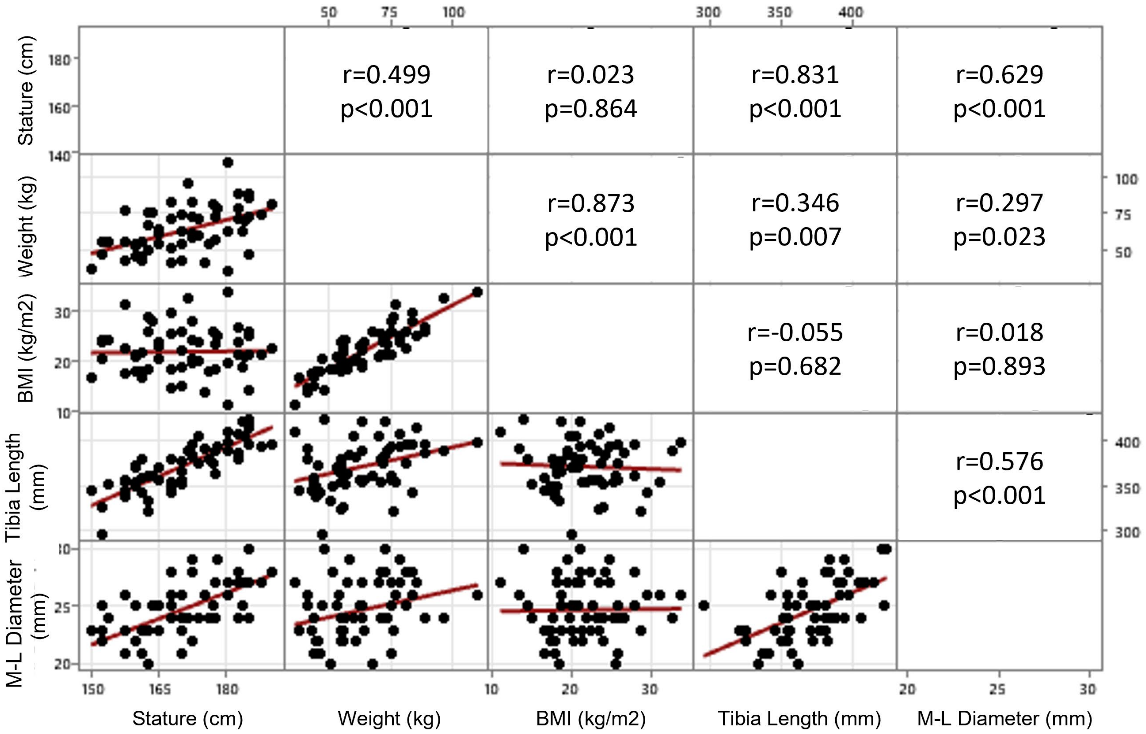

Fig 4. Correlation matrix of independent variables. Pearson's correlation with 95% CI.

Statistical analyses were performed on the whole sample and then the sample was separated into sex-specific subsamples for further analyses (Tables III and IV, Figs. 5–6). Significant relationships were observed in the combined sample as well as both sex-specific samples between structural property and body and bone size variables. In the combined sample, bending moment demonstrated significant relationships with all body size variables and M-L diameter, peak force and energy demonstrated significant relationships with body size variables, and peak displacement and stiffness demonstrated significant relationships with bone size variables (Table III). More specifically, bending moment had significant relationships with stature ($p<0.001$), weight ($p<0.001$), BMI ($p=0.023$), and M-L diameter ($p=0.001$). While significant, the variance in bending moment could not strongly be explained by the independent variables ($R^2<22.60\%$). Peak force had significant relationships with weight ($p=0.010$) and BMI ($p=.003$); however, both relationships were weak ($R^2<14.54\%$) (Table III). Energy demonstrated a single significant relationship with BMI ($p=0.018$) and peak displacement and stiffness were both found to have significant relationships with tibia length ($p<0.004$) (Table III). However, as with bending moment and peak force, all significant relationships were weak and none of the variance in the analyzed tibia structural properties can be explained by the body or bone size variables in the combined sample.

TABLE III
REGRESSION ANALYSES OF STRUCTURAL PROPERTIES VS. BODY AND BONE SIZE IN COMBINED SAMPLE‡

| Dependent Variables | Independent Variables | $R^2$ (%) | p-value* |
|---|---|---|---|
| | *Body Size* | | |
| Peak Force | Stature | 0.84 | 0.490 |
| Peak Displacement | | 6.29 | 0.055 |
| Stiffness | | 2.14 | 0.269 |
| Energy | | 11.02 | **0.010** |
| Bending Moment | | 20.49 | **<0.001** |
| Peak Force | Weight | 13.50 | **0.004** |
| Peak Displacement | | 0.28 | 0.690 |
| Stiffness | | 2.17 | 0.266 |
| Energy | | 18.03 | **0.001** |
| Bending Moment | | 22.60 | **<0.001** |
| Peak Force | BMI | 14.54 | **0.003** |
| Peak Displacement | | 0.92 | 0.470 |
| Stiffness | | 6.33 | 0.055 |
| Energy | | 9.38 | **0.018** |
| Bending Moment | | 8.74 | **0.023** |
| | *Bone Size* | | |
| Peak Force | Tibia Length | 2.29 | 0.252 |
| Peak Displacement | | 15.27 | **0.002** |
| Stiffness | | 13.75 | **0.004** |
| Energy | | 2.64 | 0.219 |
| Bending Moment | | 4.80 | 0.096 |
| Peak Force | M-L Diameter | 3.84 | 0.137 |
| Peak Displacement | | 1.68 | 0.328 |
| Stiffness | | 0.00 | 0.969 |
| Energy | | 3.66 | 0.147 |
| Bending Moment | | 16.90 | **0.001** |

*Significant p-values are **bold**

‡Regression equations are provided in Table AI, Appendix

Different relationships between tibia structural properties and body (Table IV) and bone (Table V) size were observed in the sex-specific samples versus the combined sample. When evaluating relationships between structural properties and body size, no significant relationships were observed in the male sample (Table IV). In the female sample, significant relationships were observed between the following variables, bending moment with weight (p=0.005) and BMI (p=0.025), peak force with weight (p=0.030) and BMI (p=0.021), and stiffness with BMI (p=0.040). Significant relationships between structural properties and bone size variables were observed in both the female and male samples (Table V). Specifically, peak displacement and stiffness demonstrated significant relationships with tibia length in females (p<0.028) and males (p<0.032) (Table V). Additionally, only the male sample demonstrated a significant relationship with peak force and tibia length (p=0.022) (Table V). No significant relationships between structural properties and M-L diameter were observed in the sex-specific samples.

TABLE IV

REGRESSION ANALYSES OF STRUCTURAL PROPERTIES VS. BODY SIZE BY SEX AND RESULTS‡

| Dependent Variables | Independent Variables | Sample* | $R^2$ (%) | p-value* |
|---|---|---|---|---|
| Peak Force | Stature | Females | 0.10 | 0.869 |
| | | Males | 2.72 | 0.392 |
| Peak Displacement | | Females | 4.18 | 0.278 |
| | | Males | 12.69 | 0.058 |
| Stiffness | | Females | 1.87 | 0.471 |
| | | Males | 1.67 | 0.504 |
| Energy† | | Females | 6.00 | 0.192 |
| | | Males | 0.01 | 0.956 |
| Bending Moment† | | Females | 8.84 | 0.111 |
| | | Males | 1.97 | 0.468 |
| Peak Force† | Weight | **Females** | 15.66 | **0.030** |
| | | Males | 4.96 | 0.246 |
| Peak Displacement | | Females | 0.09 | 0.873 |
| | | Males | 0.60 | 0.689 |
| Stiffness | | Females | 9.05 | 0.106 |
| | | Males | 1.01 | 0.604 |
| Energy† | | Females | 7.28 | 0.149 |
| | | Males | 12.55 | 0.059 |
| Bending Moment† | | **Females** | 25.14 | **0.005** |
| | | Males | 2.60 | 0.403 |
| Peak Force† | BMI | **Females** | 17.64 | **0.021** |
| | | Males | 8.05 | 0.136 |
| Peak Displacement | | Females | 1.93 | 0.464 |
| | | Males | 0.67 | 0.673 |
| Stiffness | | **Females** | 14.18 | **0.040** |
| | | Males | 2.23 | 0.439 |
| Energy† | | Females | 3.82 | 0.301 |
| | | Males | 11.46 | 0.072 |
| Bending Moment† | | **Females** | 16.74 | **0.025** |
| | | Males | 0.62 | 0.684 |

*Significant p-values and sample are **bold**

†Significant relationships observed in the combined sample

‡Regression equations are provided in Table AII, Appendix

TABLE V

REGRESSION ANALYSES OF STRUCTURAL PROPERTIES VS BONE SIZE BY SEX AND RESULTS‡

| Dependent Variables | Independent Variables | Sample* | $R^2$ (%) | p-value* |
|---|---|---|---|---|
| Peak Force | Tibia Length | Females | 8.23 | 0.124 |
| | | **Males** | 17.85 | **0.022** |
| Peak Displacement† | | **Females** | 20.24 | **0.013** |
| | | **Males** | 15.93 | **0.032** |
| Stiffness† | | **Females** | 16.15 | **0.028** |
| | | **Males** | 18.06 | **0.022** |
| Energy | | Females | 0.01 | 0.962 |
| | | Males | 2.49 | 0.414 |
| Bending Moment | | Females | 0.12 | 0.856 |
| | | Males | 3.93 | 0.302 |
| Peak Force | M-L Diameter | Females | 3.46 | 0.325 |
| | | Males | 0.01 | 0.964 |
| Peak Displacement | | Females | 0.10 | 0.868 |
| | | Males | 7.05 | 0.164 |
| Stiffness | | Females | 0.87 | 0.624 |
| | | Males | 0.01 | 0.964 |
| Energy | | Females | 0.16 | 0.833 |
| | | Males | 0.17 | 0.831 |
| Bending Moment† | | Females | 2.69 | 0.387 |
| | | Males | 4.00 | 0.298 |

*Significant p-values and sample are **bolded**

†Significant relationships observed in the combined sample

‡Regression equations provided in Table AII

ANCOVA analyses were conducted when both female and male samples demonstrated significant relationships between the same structural property within the same analysis (e.g., peak displacement and tibia length) (Table VI). In the ANCOVA analyses, sex was designated as the covariate to investigate the effects of the primary independent size variable and to evaluate whether females and males demonstrated different relationships with structural properties and body or bone size. ANCOVA results demonstrated no significant differences between sexes for the selected analyses in which females and males displayed significant relationships independently (p>0.771).

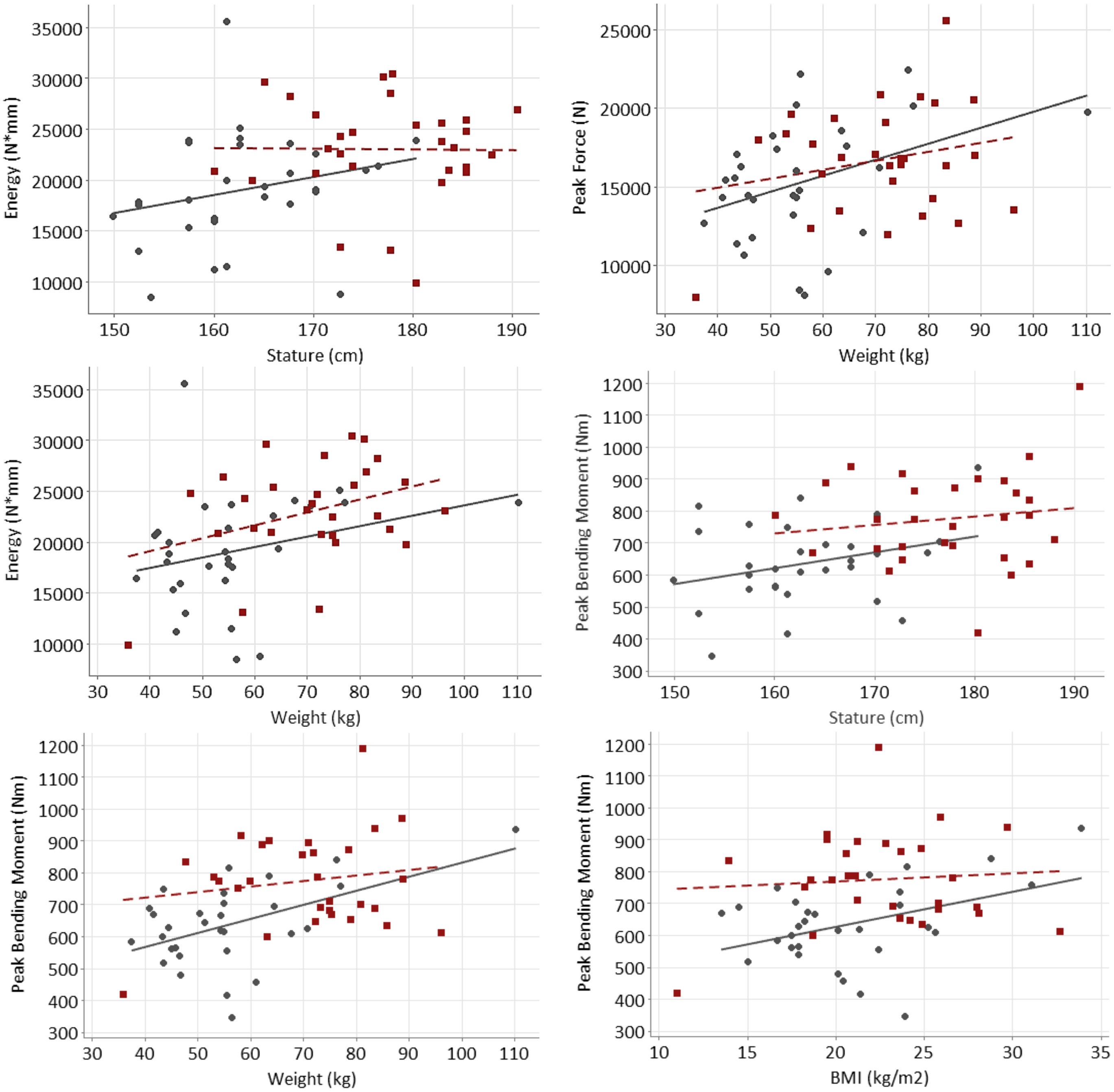

Fig. 5. Scatterplots and linear regressions of significant structural properties and body size relationships. Exemplar graphs include relationships that were significant in either the combined sample and/or the sex-specific samples (females = gray, males = red).

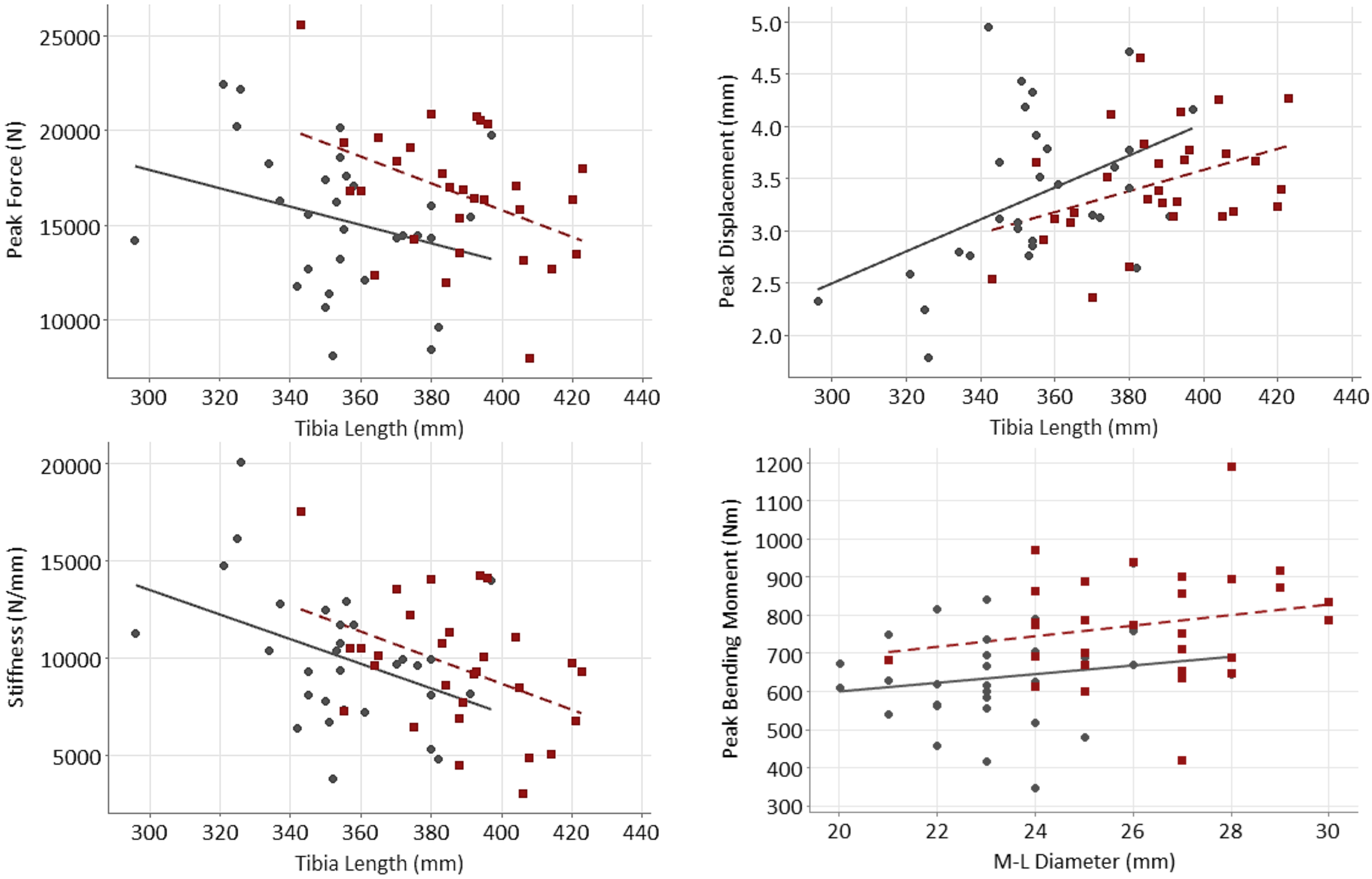

Fig. 6. Scatterplots and linear regressions of significant structural properties and bone size relationships. Exemplar graphs include relationships that were significant in either the combined sample and/or the sex-specific samples (females = gray, males = red).

To assess the effect of body size in the context of common ATD and HBM sizes, three distinct categories representing the 5th, 50th, and 95th percentiles [16] were used to create subsamples based on stature alone (Table VI). Weight was not able to be used for inclusion because it would have restricted the sample sizes too much for analysis, but is reported for each category, nonetheless. Sex was not considered in these subsamples, and the only inclusion criteria was stature, resulting in small, midsize, and large body size categories, independent of sex. One-way ANOVA tests were performed to evaluate whether structural properties significantly varied between body size categories (Table VII, Figs. A1–A5). Significant relationships were observed between body sizes with energy ($R^2$=20.42, p=0.033) and bending moment ($R^2$=23.51, p=0.018). Tukey HSD analyses demonstrated that the significant differences in both energy and bending moment were observed between the small and large body size categories (Table VII).

TABLE VI

BODY SIZE CATEGORIES

| Body Size Category | Percentile | Sample Stature (cm) | Sample* Weight (kg) | Female (n) | Male (n) |
|---|---|---|---|---|---|
| Small | 5th ± 5 | 149.8–157.4 | 37.4–77.1 | 9 | 0 |
| Midsize | 50th ± 2.5 | 171.4–178.0 | 41.5–96.1 | 3 | 10 |
| Large | 95th ± 2.5 | 182.8–190.5 | 47.6–88.9 | 0 | 11 |

*Weight was not considered for body size categorization

TABLE VII
ANOVA AND TUKEY HSD ANALYSES AND RESULTS

| Tibia Structural Properties | Body Size Category* | Mean | $R^2$ (%) | p-value* |
|---|---|---|---|---|
| Peak Force (N) | Small | 16054 | 4.47 | 0.504 |
| | Midsize | 15283 | | |
| | Large | 16924 | | |
| Peak Displacement (mm) | Small | 2.9 | 16.29 | 0.069 |
| | Midsize | 3.5 | | |
| | Large | 3.6 | | |
| Stiffness (N/mm) | Small | 11200 | 9.37 | 0.229 |
| | Midsize | 8463 | | |
| | Large | 9832 | | |
| Energy (N*mm) | **Small** | 17172 | 20.42 | **0.033** |
| | Midsize | 21793 | | |
| | **Large** | 23265 | | |
| Bending Moment (Nm) | **Small** | 613 | 23.51 | **0.018** |
| | Midsize | 721 | | |
| | **Large** | 811 | | |

*Significant p-values and body size categories are **bold**

Relationships between structural properties and independent variables were examined for each body size category to inform on whether size scaling is appropriate. The only significant relationship found was in the small category between peak displacement and tibia length ($R^2$=50.58%, p=0.032) (Fig. 7).

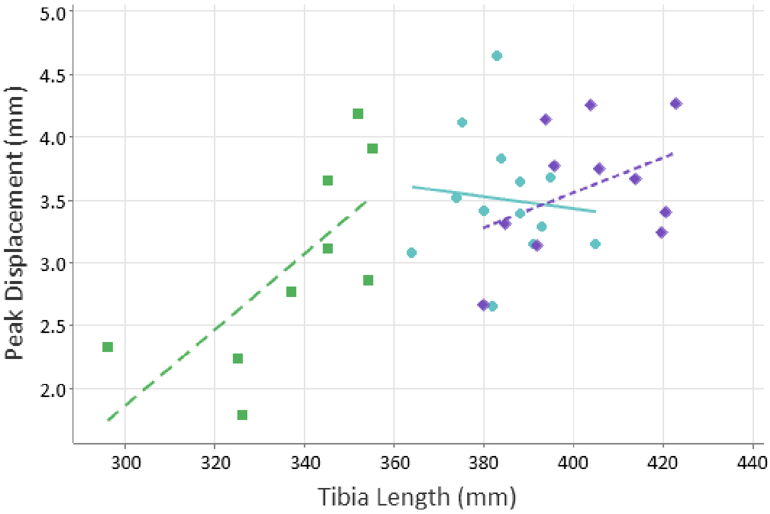

Fig. 7. Scatterplot of peak displacement and tibia length by body size categories with regression lines by size category: small (green squares), midsize (blue circles), and large (purple diamonds).

## IV. DISCUSSION

Female biomechanical data are lacking for vehicle occupants and vulnerable road users [17-20]. This is in part due to previous regulations and research predominantly concentrated on mid-size adult males [17-20], which has led to disparate treatment in regards to vehicle safety based on sex [17,19,21]. In other words, research and analytical resources (e.g., Anthropomorphic Test Devices [ATDs] and Human Body Models [HBMs]) and established injury thresholds are predominately based on scaled midsize male data. Whether or not these scaled data, and ultimately the resultant tools (i.e., ATDs, HBMs), appropriately represent females or smaller individuals has not been unequivocally demonstrated across applications. This study provides experimental data from a large sample size (n=59), inclusive of both sexes, from a range of body sizes, and across the adult lifespan to contribute to closing this gap. These data were collected from controlled, experimental tests conducted to replicate pedestrian leg impacts at real-world dynamic loading rates (6 m/s). Pedestrian lower extremities are most frequently impacted from the side and result in responses and injuries different than those of motor vehicle occupants [6]. The tibia is the most frequently injured element in pedestrian-bumper impacts [11], which is one of the most common types of non-fatal pedestrian-MVCs [6]. Therefore, this study provides data directly applicable to one of the most vulnerable road user populations, adult pedestrians, and provides fundamental data for female pedestrians, in particular.

Overall, body size and bone size variables were significantly different between females and males ($p<0.001$). BMI was not significantly different between sexes, which highlights a possible limitation of this variable. However, these findings are consistent with [22], which demonstrated no differences between females and males in BMI. While BMI is utilized across scientific fields, due to the potentially oversimplified and normalized output, BMI may not capture individual or population differences as well as other specific body proportion variables. In general, the females within this sample demonstrated smaller mean body and bone size measurements than the males. When compared to average body measurements for females and males in the USA, our sample means are representative of the national averages in stature but not weight [23] (Table VIII). This may be a result of sampling bias due to the source of the sample as well as selection criteria.

TABLE VIII
BODY SIZE COMPARISONS BETWEEN USA AVERAGES AND STUDY SAMPLE

| | US Average Body Measurement Data [22] | | Sample Mean Body Measurement Data | |
|---|---|---|---|---|
| | Females | Males | Females | Males |
| Stature (cm) | 163.5 | 175.26 | 163.0 | 177.3 |
| Weight (kg) | 77.4 | 90.6 | 55.6 | 70.9 |

Trends in structural property variables demonstrate females having lower mean values of peak force, peak displacement, energy, and bending moment. However, females demonstrated a higher mean value of stiffness, but not significantly different from male values. Two of the structural property variables, energy and bending moment, were significantly different between females and males ($p<0.005$). The lack of sex differences in other structural properties was unexpected as general assumptions across fields suggest that females respond differently than males and are at increased risk for fracture and higher injury severities. However, these results are consistent with research that has shown that while morphological (size and shape) differences exist between sexes in the tibia, mechanical properties (e.g., stiffness, strength, ductility) are not significantly different between females and males [24]. The authors [24] suggest that higher incidences of stress fractures in females may be the result of female tibiae overloaded due to similar mechanical properties to males but smaller tibiae. Future work will utilize stress calculations to evaluate differences in tibia size categories.

Bending moment data were compared to previous dynamic blunt leg impact studies [25-28] (Tables IX and AII). Due to differences in tissue status, loading mechanism, loading rate, and loading direction, direct comparisons cannot be conducted. However, an overview of mean bending moments from the samples and sex-specific subsamples can provide insight into how differences in loading conditions may result in differences in bending moments and capture variation between females and males. When compared to previous studies, the mean bending moment data from this research are higher than previous research [25-29] (Table X). This variation may be attributed to specimen differences (e.g., sex, age, and geometry) and/or differences in the loading conditions. Trends in female and male mean bending moments were similar between this research and previous studies, where males demonstrated higher bending moments than females. The study with the most similar loading rate is [26], which has the highest bending moments within the previous research. However, there is still a large amount of variation in bending moment values between [26] and the current study, which may be attributed to the difference in loading mechanism (3-point vs 4-point) and loading direction (P-A vs L-M). On-going and future work include conducting similar tests at a different loading rate (2 m/s), different direction (P-A), and in legs. This work may provide a link to compare the current study with previous research.

TABLE IX

SUMMARY OF BENDING MOMENT DATA FROM THE CURRENT AND PREVIOUS STUDIES*

| Reference | Sample (N) | Sex (n) | Loading Mechanism | Loading Rate (m/s) | Loading Direction | Bending Moment (Nm) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Mean | Female Mean | Male Mean |
| [25] | Tibiae (22) | F (3)<br>M (8) | 3-point bending | 2.1–6.9 | L-M, A-P | 300.5 | 272.3 | 308.0 |
| [26] | Legs (12) | F (6)<br>M (6) | 3-point bending | 5.55 | P-A | 408.0 | 369.8 | 446.2 |
| [27] | Tibiae (6) | M (6) | 3-point bending | 1.45 | L-M | 297.3 | NA | 297.3 |
| [28] | Legs (4) | M (4) | 3-point bending | 1.5 | L-M | 362.8 | NA | 362.8 |
| Current Study | Tibiae (59) | F (30)<br>M (29) | 4-point bending | 6 | L-M | 706.2 | 637.7 | 777.0 |

*Quasistatic data not included in this summary

Pairwise Pearson's correlations were utilized to measure the strength and direction of linear relationships between the body and bone size variables (Fig. 4). As expected, stature had a significant positive correlation with weight, tibia length, and M-L diameter. The strongest relationship observed with stature was tibia length, which was not surprising, as tibia length is a known component of stature. In forensic applications, established methods for estimating height utilize tibia length in regression equations [30]. Weight demonstrated significant positive correlations with BMI, tibia length, and M-L diameter, and tibia length was significantly correlated with M-L diameter. Relationships between weight and tibia morphology, specifically at the level of the nutrient foramen, have previously been established [22]. Future work will explore relationships between structural properties and tibia morphology (e.g., cross-sectional geometry, global tibia shape, local tibia shape).

Analyses of the combined sample found 11 significant relationships between structural properties and body and bone size variables (Table III). While strongly correlated, specifically stature and tibia length, differences in relationships between structural properties and body and bone size were observed. Peak displacement and stiffness demonstrated significant relationships with tibia length ($p=0.002$ and $p=0.004$, respectively), and energy and bending moment had a significant relationship with stature ($p=0.010$ and $p<0.001$, respectively). These findings suggest that local size (e.g., tibia length) and global (e.g., body) size variables, while correlated, may provide different insight into loading response in localized, i.e., pedestrian leg-bumper, loading. Similar body size results were observed in relationship to rib structural properties, where body size variables (i.e., stature, weight, and BMI) did not demonstrate any meaningful relationships with any rib properties [31]. While the relationships in the current study reached the level of statistical significance, all $R^2$ values had very little practical meaning (<22.60%), indicating that in the combined sample, neither body or bone size were able to sufficiently explain the variation observed in peak force, peak displacement, stiffness, energy, or bending moment.

Sex-specific subsamples allowed for examination of the effect of sex in relationships between tibial properties and body (Table IV) and bone size (Table V). Different relationships in the sex-specific samples were found to be significant, compared to the results of the combined sample. Significant relationships between structural properties and body size variables were only observed in the female sample between peak force and weight (p=0.030), peak force and BMI (p=0.021), stiffness and BMI (p=0.040), bending moment and weight (p=0.005), and bending moment and BMI (p=0.025). Interestingly, energy was not found to have any significant relationships with any body size variable in either sex-specific sample but demonstrated relationships with all body size variables in the combined sample. Likewise, bending moment demonstrated a significant relationship with M-L diameter in the combined sample, but no significant relationship with either sex-specific sample. This indicates that in those relationships, size, regardless of sex, was a better predictor of response. These same trends were not observed in relationships between structural properties and bone size. Significant relationships were observed in the female and male samples between peak displacement and tibia length and stiffness and tibia length (Table V). Similar results were observed in the combined sample, with significant relationships found between peak displacement and tibia length and stiffness in tibia length. However, the $R^2$ values, while still not significant, are higher in relationships between peak displacement, stiffness, and tibia length in the sex-specific analyses. These stronger relationships suggest that local size (i.e., bone size) may be more important in understanding tibial response than global size (i.e., body size), although there is a relationship between the two. Additionally, while these data are separated by sex, these results may be more indicative of size differences between sexes (tibia length was significantly different between sexes), rather than variation due to sex differences. The male subsample had an additional significant relationship between peak force and tibia length, which was not observed in the female sample nor in the combined sample. Since this relationship is only observed in the male sample, this may support sex-specific effects. While female data are critical in understanding sex-specific responses and injuries, it has yet to be determined whether these differences are simply due to sex or can be attributed to size differences or the interaction of multiple individual-specific variables (e.g., age, sex, body proportions, geometry, microstructure, etc.).

The sample was then categorized by body size based on stature (Table VII). Weight data were unable to be utilized in conjunction with stature due to sample limitations. Peak force, peak displacement, and stiffness were not significantly different between the small, midsize, or large body size categories (Table VIII). Energy was significantly different between the small and large categories, with the small body size category demonstrating smaller mean energy. A similar trend was observed in bending moment, where the small body size category demonstrated significantly smaller values than the large body size category. In examining the relationships between dependent and independent variables within each body size category, only one significant relationship was observed (peak displacement and tibia length in the small category) (Fig. 7). These analyses revealed a disparity in size variation within this sample. While this is a limitation of this study, it also highlights potential underrepresented populations. Females dominated the small category (females, n=9, males, n=0) while males dominated the large sample (females, n=0; males, n=11). Due to the limitation of sex variation in the small and large categories, these results, while intended to be independent of sex, still maintain a component of variation between females and males and not solely body size differences.

Comparisons of female to male data via independent samples t-tests demonstrated no significant difference in age between sexes (p=0.130). This was expected as this sample was selected to be age-matched between females and males. Age was not further evaluated within the scope of this study to focus on the specific question of whether sex or size are more pivotal in predicting tibial response. While this is a limitation of this study, on-going and future work are analyzing the contributions of age, along with the interactions of sex and size, in explaining the variance in tibial properties. Additionally, frequently utilized tibia injury criteria calculations, such as the Tibia Index, were not calculated in this study due to differences in loading; specifically, the lack of combined bending and compression loading necessary to calculate the Tibia Index. Future research will test a subsample of tibiae in combined loading and comparisons within this research and with previous studies will be conducted. Future work will also incorporate the relationships between structural properties and cross-sectional geometry.

## V. CONCLUSIONS

This study contributes to bridging the gap in experimental research and knowledge of tibial response between populations, specifically females and males. Understanding which variables can predict tibial response is critical in the identification of vulnerable pedestrian populations. Overall, tibia structural properties were not significantly different between females and males in a dynamic 6 m/s blunt leg impact. No meaningful relationships between tibia structural properties and sex were observed. Overall, body size variables had more significant relationships with tibia structural properties than bone size; however, none of these relationships were meaningful. Trends observed within the sex-specific samples demonstrated that females had more significant relationships between tibia structural properties with both body and bone size variables. While this study was unable to conclusively identify variables contributing to variance in tibial response or ultimately determine whether sex, body size, or bone size are the most essential parameters for predicting structural properties, the foundation for future research has been established.

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## VIII. APPENDIX

TABLE AI

REGRESSION EQUATIONS IN COMBINED SAMPLE

| Dependent Variables | Independent Variables | Regression Equation |
|---|---|---|
| Peak Force | Stature | 10581 + 31.88 Stature |
| Peak Displacement | | 0.765 + 0.01548 Stature |
| Stiffness | | 17790 - 46.89 Stature |
| Energy | | -8738 + 175.3 Stature |
| Bending Moment | | -414.6 + 6.591 Stature |
| Peak Force | Weight | 10697 + 84.05 Weight |
| Peak Displacement | | 3.261 + 0.002148 Weight |
| Stiffness | | 7857 + 31.05 Weight |
| Energy | | 11760 + 147.4 Weight |
| Bending Moment | | 418.9 + 4.552 Weight |
| Peak Force | BMI | 9553 + 269.9 BMI |
| Peak Displacement | | 3.684 - 0.01323 BMI |
| Stiffness | | 5894 + 180.6 BMI |
| Energy | | 13203 + 361.9 BMI |
| Bending Moment | | 496.9 + 9.633 BMI |
| Peak Force | Tibia Length | 23640 - 20.60 Tibia Length |
| Peak Displacement | | -0.100 + 0.009431 Tibia Length |
| Stiffness | | 27075 - 46.54 Tibia Length |
| Energy | | 8633 + 33.53 Tibia Length |
| Bending Moment | | 243.5 + 1.248 Tibia Length |
| Peak Force | M-L Diameter | 8900 + 287.6 M-L Diameter |
| Peak Displacement | | 2.564 + 0.03374 M-L Diameter |
| Stiffness | | 9992 - 7.1 M-L Diameter |
| Energy | | 10538 + 426.3 M-L Diameter |
| Bending Moment | | 82.5 + 25.26 M-L Diameter |

TABLE AII

REGRESSION EQUATIONS IN SEX-SPECIFIC SAMPLES

| Dependent Variables | Independent Variables | Sample | Regression Equation |
|---|---|---|---|
| Peak Force | Stature | Females | 12804 + 15.27 Stature |
| | | Males | 29878 - 74.11 Stature |
| Peak Displacement | | Females | 0.076 + 0.02003 Stature |
| | | Males | -0.837 + 0.02420 Stature |
| Stiffness | | Females | 20178 - 62.10 Stature |
| | | Males | 19290 - 54.81 Stature |
| Energy | | Females | -9633 + 176.4 Stature |
| | | Males | 24266 - 6.7 Stature |
| Bending Moment | | Females | -168.7 + 4.946 Stature |
| | | Males | 308.3 + 2.643 Stature |
| Peak Force | Weight | Females | 9653 + 101.5 Weight |
| | | Males | 12701 + 56.90 Weight |
| Peak Displacement | | Females | 3.428 - 0.001568 Weight |
| | | Males | 3.242 + 0.003005 Weight |
| Stiffness | | Females | 6049 + 72.05 Weight |
| | | Males | 7853 + 24.23 Weight |
| Energy | | Females | 13422 + 102.5 Weight |
| | | Males | 14085 + 126.8 Weight |
| Bending Moment | | Females | 393.2 + 4.398 Weight |
| | | Males | 654.4 + 1.730 Weight |
| Peak Force | BMI | Females | 8433 + 329.0 BMI |
| | | Males | 11792 + 218.5 BMI |
| Peak Displacement | | Females | 3.799 - 0.02196 BMI |
| | | Males | 3.671 - 0.00953 BMI |
| Stiffness | | Females | 4309 + 275.6 BMI |
| | | Males | 7112 + 108.7 BMI |
| Energy | | Females | 14388 + 226.9 BMI |
| | | Males | 14812 + 365.3 BMI |
| Bending Moment | | Females | 409.0 + 10.97 BMI |
| | | Males | 719.4 + 2.546 BMI |
| Peak Force | Tibia Length | Females | 32439 - 48.31 Tibia Length |
| | | Males | 44088 - 70.63 Tibia Length |
| Peak Displacement | | Females | 2.075 + 0.01526 Tibia Length |
| | | Males | -0.454 + 0.01009 Tibia Length |
| Stiffness | | Females | 32485 - 63.20 Tibia Length |
| | | Males | 35547 - 67.07 Tibia Length |
| Energy | | Females | 19922 - 2.26 Tibia Length |
| | | Males | 37382 - 36.94 Tibia Length |
| Bending Moment | | Females | 567.0 + 0.199 Tibia Length |
| | | Males | 1316 – 1.391 Tibia Length |
| Peak Force | M-L Diameter | Females | 6562 + 376.3 M-L Diameter |
| | | Males | 16354 + 14.5 M-L Diameter |
| Peak Displacement | | Females | 3.640 – 0.01290 M-L Diameter |
| | | Males | 1.714 + 0.06634 M-L Diameter |
| Stiffness | | Females | 5967 + 176.2 M-L Diameter |
| | | Males | 9212 + 13.7 M-L Diameter |
| Energy | | Females | 21908 - 120.2 M-L Diameter |
| | | Males | 25589 - 95.7 M-L Diameter |
| Bending Moment | | Females | 374.5 + 11.35 M-L Diameter |
| | | Males | 413.2 + 13.86 M-L Diameter |

TABLE AIII

PREVIOUS RESEARCH DATA SUMMARY

| Reference | Element | Tissue Status | Sample (N) | Sex (n) | Age (years) | Loading Mechanism | Loading Rate (m/s) | Bending Moment (Nm) | Loading Direction | Subject Sex |
|---|---|---|---|---|---|---|---|---|---|---|
| [25] | Tibia | De-fleshed | 22 | F (3)<br>M (8) | F (43–57)<br>M (54–64) | 3-point bending | 2.1 | 315 | A-P | F |
| | | | | | | | 2.1 | 254 | L-M | F |
| | | | | | | | 2.4 | 246 | A-P | F |
| | | | | | | | 2.4 | 274 | L-M | F |
| | | | | | | | 2.9 | 424 | A-P | M |
| | | | | | | | 2.9 | 431 | L-M | M |
| | | | | | | | 3.2 | 287 | A-P | M |
| | | | | | | | 3.2 | 324 | A-P | M |
| | | | | | | | 3.5 | 326 | A-P | M |
| | | | | | | | 3.5 | 395 | L-M | M |
| | | | | | | | 3.7 | 312 | A-P | M |
| | | | | | | | 3.7 | 237 | L-M | M |
| | | | | | | | 3.7 | 349 | L-M | M |
| | | | | | | | 3.8 | 402 | A-P | M |
| | | | | | | | 3.8 | 264 | L-M | M |
| | | | | | | | 4.2 | 182 | A-P | M |
| | | | | | | | 4.2 | 287 | L-M | M |
| | | | | | | | 4.2 | 224 | L-M | M |
| | | | | | | | 4.7 | - | A-P | F |
| | | | | | | | 6.9 | 176 | A-P | M |
| | | | | | | | Mean | 300.5 | | |
| | | | | | | | Female Mean | 272.3 | | |
| | | | | | | | Male Mean | 308.0 | | |
| [26] | Leg | Fleshed | 12 | F (6)<br>M (6) | F (55–70)<br>M (56–85) | 3-point bending | 5.55 | 239 | P-A | M |
| | | | | | | | | 535 | | F |
| | | | | | | | | 577 | | M |
| | | | | | | | | 458 | | M |
| | | | | | | | | 445 | | M |
| | | | | | | | | 372 | | F |
| | | | | | | | | 259 | | F |
| | | | | | | | | 440 | | F |
| | | | | | | | | 371 | | F |
| | | | | | | | | 424 | | M |
| | | | | | | | | 534 | | M |
| | | | | | | | | 242 | | F |
| | | | | | | | Mean | 408.0 | | |
| | | | | | | | Female Mean | 369.8 | | |
| | | | | | | | Male Mean | 446.2 | | |

| Reference | Element | Tissue Status | Sample (N) | Sex (n) | Age (years) | Loading Mechanism | Loading Rate (m/s) | Bending Moment (Nm) | Loading Direction | Subject Sex |
|---|---|---|---|---|---|---|---|---|---|---|
| [27] | Tibia | De-fleshed | 6 | M (6) | M (44–67) | 3-point bending | 1.45 | 333.8 | L-M | M |
| | | | | | | | | 342.1 | | M |
| | | | | | | | | 251.7 | | M |
| | | | | | | | | 224.7 | | M |
| | | | | | | | | 329.8 | | M |
| | | | | | | | | 301.5 | | M |
| | | | | | | | Mean | 297.3 | | |
| | | | | | | | Male Mean | 297.3 | | |
| [28] | Leg | Fleshed | 4 | M (4) | M (54–69) | 3-point bending | 1.5 | 277 | L-M | M |
| | | | | | | | | 433 | | M |
| | | | | | | | | 259 | | M |
| | | | | | | | | 482 | | M |
| | | | | | | | Mean | 362.8 | | |
| | | | | | | | Male Mean | 362.8 | | |

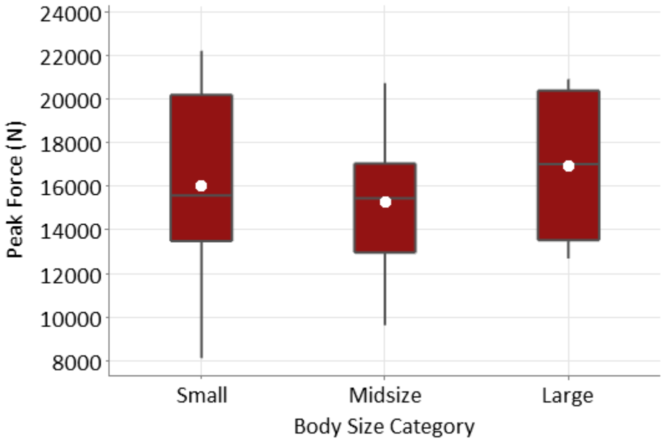

Fig. A1. Boxplot of peak force by body size category. Mean values (white circle).

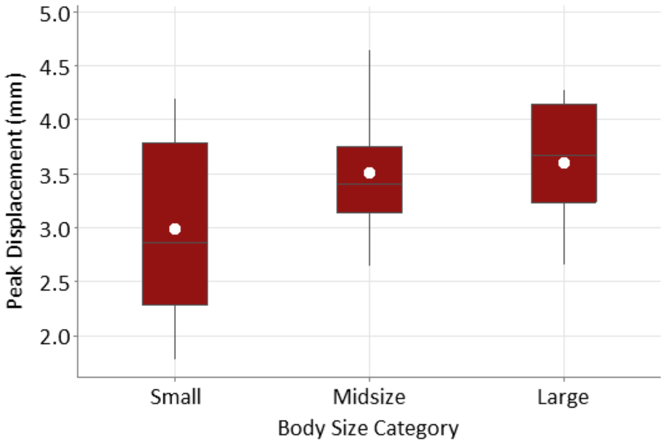

Fig. A2. Boxplot of peak displacement by body size category. Mean values (white circles).

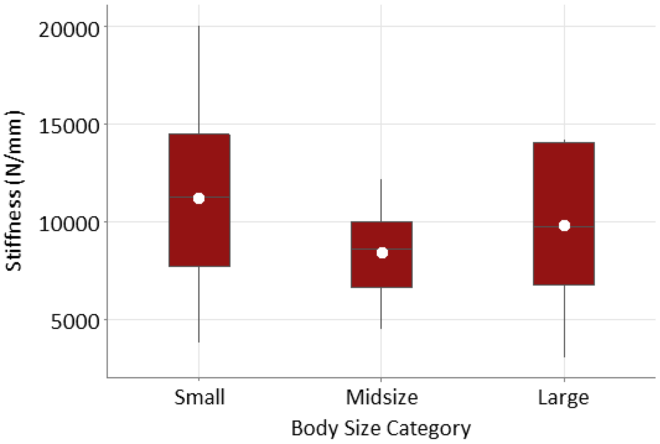

Fig. A3. Boxplot of stiffness by body size category. Mean values (white circles).

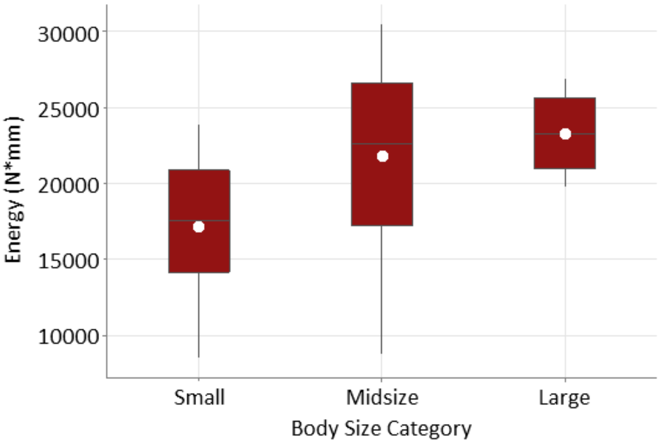

Fig. A4. Boxplot of energy by body size category. Mean values (white circles).

Fig. A5. Boxplot of bending moment by body size category. Mean values (white circles).