Injury Risk Functions for 5th Percentile Females: Ankle Inversion and Eversion

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Abstract Females are more likely to sustain lower extremity injuries than males. Many injury risk functions (IRFs) for females are derived from scaled male data. Biomechanical differences between males and females in the lower extremity are known, but little is known about how these differences affect the applicability of scaling between the sexes. Twenty matched pair small female PMHS legs were tested by applying inversion and eversion of the ankle, matching a condition previously tested on males and larger females. For the new dataset, half the specimens were barefoot and the remainder were shod. The goal of this study was to generate IRFs for ankle inversion and eversion from a combined dataset of male and female PMHS tests to determine the extent to which sex, scaling, and the presence of a shoe affect the prediction of ankle injury tolerance. Results suggest that sex-specific IRFs exhibit greater predictive ability than those developed with scaled male and female data combined. Scaling inversion and eversion moment was found to misconstrue the measured data, even within the same sex. Therefore, IRFs for each sex (no specific anthropometry) are recommended. Absence or presence of a shoe was a significant predictor of injury tolerance and the presented IRFs take both conditions into account.

Keywords ankle biomechanics, injury risk functions, female, scaling, sex differences

I. INTRODUCTION

Females are more susceptible to injury compared with male drivers in comparable automotive crashes and have a higher incidence of lower limb injury [1-4]. This increased injury risk for females was reiterated in an analysis of frontal crashes in NASS-CDS for more recent field data (1998-2014) [5]. Even after controlling for delta-V, age, height, weight, and vehicle model year, Forman et al found that females are at a higher risk of sustaining both AIS2+ and AIS 3+ injury than males, with the largest injury risk discrepancy between the sexes occurring in the lower extremity, particularly in the ankle [5]. Despite this injury risk discrepancy in field data between the sexes, many lower extremity female ATD injury risk functions are based on scaled male PMHS injury data [6-7]. This scaling technique (equal-stress equal-velocity scaling) normalizes subject response based on mass ratio between the subjects assuming the constant ratio of density and modulus of elasticity, as well as requiring an assumption of geometric similarity between the scaled objects [8]. In other words, to apply this technique to test responses, scaled specimens should have similar material properties to that of a target population and have similar geometric characteristics that remain in a consistent proportion to each other regardless of overall size. However, significant biomechanical differences between males and females suggest that both of these underlying assumptions are violated when applying scaling across the sexes.

Material property differences have been observed between the sexes in the bones, ligaments, and tendons. A nanoindentation study using a viscoelastic model of bone showed that female bone had a significantly greater relaxation time constant than male bone, indicative of slower creep and relaxation times for female bone [9]. In addition, females have been shown to have lower bone volumetric density, and different bony geometry and structure at different skeletal sites for all ages, especially post-menopause [10]. Failure testing of cadaveric ACLs demonstrated female ACLs had 8.3% lower strain to failure, 14.3% lower stress at failure, 9.43% lower strain energy density at failure, and 22.49% lower modulus of elasticity than males [11]. Similarly, a failure study of ligaments of the ankle showed that the male ligaments exhibited significantly higher yield and ultimate force values than those obtained from females, suggesting that sex differences in ligament material properties are not isolated to the ACL, but likely exist throughout the body [12]. Female tendons also have lower elastic modulus and a lower rate of new connective tissue formation, and this difference is exacerbated at higher estradiol levels [13]. These differences in material properties provide a possible causal relationship to

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corroborate the findings of studies that have shown, in general, that females have increased joint laxity and physiologic range of motion compared to males, which could contribute to differences in loading across joints and injury tolerance between sexes [14-16].

In addition to material property differences, skeletal geometry is different between the sexes, especially alignment in the lower extremity resulting from differences in the male and female pelvis [17]. Nguyen and Shultz used clinical measures to study the differences in static lower extremity alignment and determined that college-aged females, on average, have greater anterior pelvic tilt, greater thigh internal rotation, greater knee valgus orientation, and greater genu recurvatum [18]. Little research has been done on sex differences in the foot and ankle, with only a few studies examining external foot clinical measurements [19-20]. These studies have shown significant differences in the sexes in scaled foot breadth, scaled foot length, calf height, plantar arch height, ankle circumference, calf circumference, ankle height, medial malleolus height, first metatarsal height, instep circumference, ankle length, outside ball of foot length, and bimalleolar breadth (all normalized either by height or foot length) [20]. Recently, a study examining morphometrics of the talus demonstrated that talus depth, width, cross sectional area, radius and strength were significantly different between males and females, even when all measures were normalized by height [21]. Given these material property and geometric differences between the sexes, scaling is likely not a reliable procedure to predict injury tolerance across the sexes; however, scaling has never been well-examined for its effectiveness if predicting injury across the sexes. It is possible that the reliance on scaling male data to predict female injury over predicts female injury tolerance, and contributes to females being at greater risk of injury in a crash.

Further, the effect of the presence or absence of a shoe on injury while in an automotive crash event has not been well studied. For axial loading through the heel, studies have found that a shod condition affects ankle kinematics for PMHS and decreases the tibia/fibula force response measured in ATDs [22-24]. Several sports biomechanics analyses have showed that shoes have an effect on ankle and knee injuries, but similar effects in an automotive crash loading environment have not been researched [25-26].

While several previous studies have used PMHS to determine ankle inversion and eversion response and injury tolerance, there is no set of data that includes either males or females of significantly different size (height and weight) that can be used to validate or refine the assumptions that would be necessary to apply these scaling techniques to the ankle either across or within a sex [27-31]. Therefore, the goals of this study are to (1) generate small female ankle inversion and eversion data that can be combined with previous larger male and female data, and (2) to generate IRFs for ankle inversion and eversion from a combined dataset of male and female PMHS tests to determine the extent to which sex, scaling, and the presence of a shoe affect the prediction of ankle injury tolerance.

II. METHODS

In order to determine effects of sex, scaling, and shod or barefoot condition on injury prediction for ankle inversion or eversion loading, small female PMHS legs (half barefoot, half shod) were tested applying either inversion or eversion of the ankle. These tests were designed to have comparable boundary and loading conditions to the study by Funk et al., who performed inversion/eversion tests on ankles from mid-sized male and mid-sized male size female PMHS to simulate loading that may occur in a car crash [31]. Multiple IRFs were developed using the combined dataset comprised of the new small female tests, and the Funk et al. tests. Several IRF forms were examined including lumping all data into a combined model (controlling for potential confounders with model variables), and stratifying the dataset by sex, presence/absence of a shoe, and loading direction. IRFs were also developed with scaled and non-scaled (measured) data.

Inversion and Eversion PMHS Experimental Testing

Twenty matched pair, small female PMHS (age 62.0 ± 6.5 years, height 159.0 ± 5.0 cm, weight 48.9 ±6.1 kg) lower extremities were selected to be tested under a dynamic inversion or eversion loading condition. Anthropometry information for all tested PMHS can be found in Table 1, below. All PMHS were obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by the Center for Applied Biomechanics and an institutional review board at the University of Virginia. Subjects were confirmed to be free of infectious diseases (HIV, Hepatitis A and C), and stored in a freezer (-15°C) until 48 hours before preparation. Additionally, all PMHS received a computed tomography (CT) scan prior to testing to determine preexisting injury or anatomic anomalies. From the CT scans, three of the specimens (878 R and L and 863 R) were found to have os naviculare, or an accessory navicular bone. These specimens were still included in testing, given that this is a common anatomical irregularity (between 20% and 28% of the total population), with females being more likely to have an accessory navicular bones than males [32-33].

TABLE I
SMALL FEMALE INVERSION/EVERSION TEST MATRIX

Test Number	Subject	Age (years)	Subject Height (cm)	Subject Mass (kg)	Test Condition
1	859 - R	71	162.6	54.0	Inversion – Barefoot
2	859 - L	71	162.6	54.0	Eversion – Barefoot
3	862 - R	61	157.5	54.4	Inversion – Barefoot
4	862 - L	61	157.5	54.4	Eversion – Barefoot
5	878 - R	64	162.6	59.0	Inversion – Barefoot
6	878 - L	64	162.6	59.0	Eversion – Barefoot
7	879 - R	62	160.0	49.0	Eversion – Barefoot
8	879 - L	62	160.0	49.0	Inversion – Barefoot
9	809 - R	59	149.9	47.6	Eversion – Barefoot
10	809 - L	59	149.9	47.6	Inversion – Barefoot
11	864 - R	66	165.1	43.1	Eversion – Shod
12	864 - L	66	165.1	43.1	Inversion – Shod
13	856 - R	60	152.4	39.9	Eversion – Shod
14	856 - L	60	152.4	39.9	Inversion - Shod
15	866 - R	53	154.9	41.3	Eversion - Shod
16	866 - L	53	154.9	41.3	Inversion - Shod
17	881 - R	70	165.1	46.3	Inversion - Shod
18	881 - L	70	165.1	46.3	Eversion - Shod
19	863 - R	64	162.6	54.4	Inversion - Shod
20	871 - L	44	157.5	54.4	Eversion - Shod

Specimen preparation for testing including potting the proximal tibia, rigidly affixing motion tracking plates to the tibia, calcaneus, talus, and second and third metatarsals, and attaching both a strain gage (C2A-06-062WW-350, Micro-Measurements, Raleigh, NC, USA) and acoustic sensor (Mitras Nano-30, Physical Acoustics, Princeton, NJ, USA) to the surface of the bone of the distal tibia and fibula, superior to the malleoli (where injuries were expected to occur). A tri-axis array of accelerometers (7264B-500, Endevco, Orange County, CA) and angular rate sensors (ARS-8K, Diversified Technical Systems, Seal Beach, CA, USA) was also attached to each calcaneus just prior to testing. To pot each specimen, the knee joint was disarticulated and soft tissue of the proximal tibia was removed. The tibia was then positioned in the potting cup such that the mid-tibia ridge was perpendicular to the bottom of the potting cup, which ensured the tibia was parallel (0 ± 1.7 degrees) to the ground during testing. The proximal tibia was then secured within a rigid mounting using screws, and potting material (Bondo Body Filler, 3M, Maplewood, MN, USA) was placed around the tibia. Throughout the entire procedure, care was taken to preserve the integrity of the fibula, ensuring a natural relative motion between the tibia and fibula. Prior to preparation of each specimen, a second CT scan was taken to help determine locations and orientations of all instrumentation relative to an anatomic coordinate system, and served as a confirmation that no injuries were induced during preparation.

Ten of the specimens were tested with a shoe (shod) and the other ten subjects were tested barefoot. Shoes used were women's low heel, dress, black, oxford shoe with standardized design by the Unites Stated Military Standard (MIL SPEC, MIL-S-21711E), which is the shoe designated for use with the Hybrid III 5th percentile female ATD. The test matrix (Table 1) was constructed such that each matched pair had one leg tested in eversion and the other in inversion, but both specimens of the same matched pair would be tested in either the shod or barefoot condition. With these conditions, the rest of the test matrix was randomised, so that inversion, eversion, barefoot, and shod conditions varied across the left and right lower extremities.

A test apparatus was designed to accomplish matched test conditions to those described by Funk et al (2002). The apparatus (Figure 1a) incorporates an adjustable foot block that is free to rotate about an offset, fixed vertical axis and mounted on a rotational pedestal similar to those used in previous studies [30-31]. While Funk et al's test series never exceeded a rotation of 56 degrees, some specimens in the study were uninjured, so the Dr. Steffan Datentechnik (DSD) controller parameters were adjusted so the footplate would rotate up to 70 degrees at an angular velocity of 1000 deg/s, in the hopes of attaining injury data from all specimens.

The potting cup for each PMHS was attached to a tower (right hand side of Figure 1a and 1b), which was rigid and had no motion throughout the tests. A spring attached on the tower side of the apparatus used to apply an axial load of 2000 N to each specimen just prior to testing; this axial load was selected as it was one of the conditions tested by Funk et al [31]. The footplate was adjusted so that the center of rotation of the apparatus corresponded with the anatomic center of rotation for inversion/eversion motion. This anatomic location was determined to be sixty percent of the distance between the average of the distance between the lateral malleolus and the ground (when the foot was planted on the ground) and the medial malleolus and the ground (when the foot was in the same position). This measurement as the inversion/eversion joint center was confirmed on each specimen's CT scan prior to testing. Each foot was attached to the footplate using five sliding blocks (2 on medial side, 2 on lateral side, one at the heel), which were compressed into the flesh, and a cable tie around the midfoot was added as an extra precaution to prevent motion, seen in Figure 1c. The apparatus was designed so a leg could be positioned with the toes pointing up (Figure 1a) or down (Figure 1b) in order to accomplish the any combination of the test conditions in the randomised test matrix for right and left feet. Six-axis load cells (3868TF, Humanetics, Plymouth, MI, USA) were attached between the footplate and the rotating pedestal, and the potting cup and spring enclosure. Additionally, tri-axis array of accelerometers (7264B-500, Endevco, Orange County, CA) and angular rate sensors (ARS-8K, Diversified Technical Systems, Seal Beach, CA, USA) were attached to the rotating footplate, and the stationary tower.

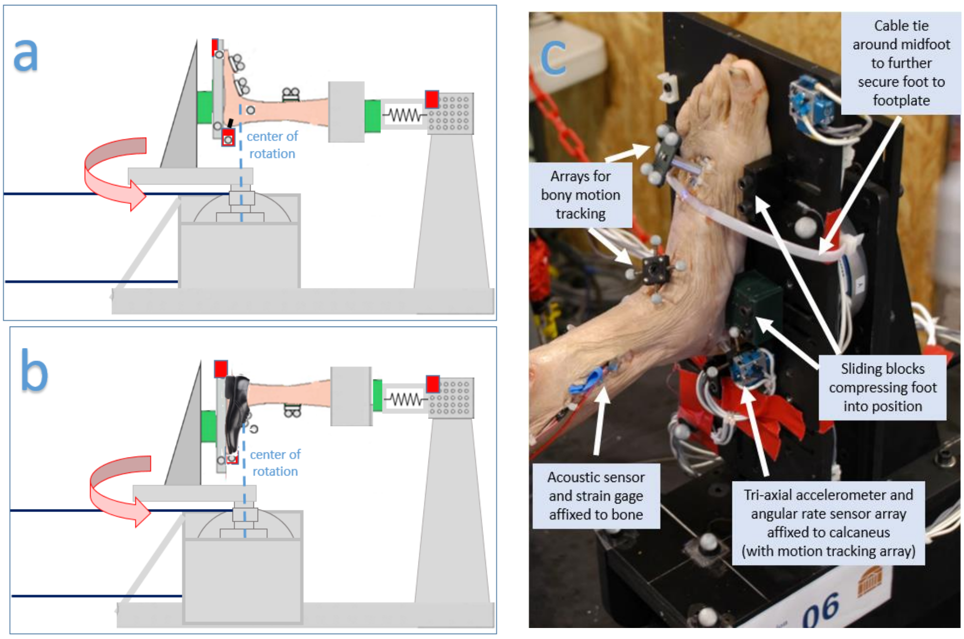

Fig. 1. The designed test apparatus with a barefoot test condition with the toes pointing up (a), the same test fixture in a different configuration so the specimen can be inverted to rotate in a different direction with the MIL-Spec (b), and a picture of one of the testes specimens, with instrumentation and hardware depicting how the specimen is affixed to the footplate (c).

Following testing, a third CT scan was performed for each specimen, followed by a dissection to determine injury type and location. A foot and ankle orthopedic surgeon, certified by the American Board of Orthopaedic Surgery, performed dissections and classified injuries. Then, moments about the subtalar joint were calculated at each time step for each PMHS test, using the same equations and coordinate systems as described by Funk et al [31]. In this test series, force and moment inputs to the moment calculations were determined from the inertially compensated response from the footplate load cell, whereas Funk et al used implanted tibia and fibula load cells in his moment calculations. Time of initial injury was determined using a combination of data from the acoustic sensors, strain gages, and kinematic response of the calcaneus recorded by the tri-axial accelerometer and angular rate sensor package. In order to have confidence that an abrupt change in strain measurement, acoustic output, or kinematic output actually corresponded to injury, a criterion was created that required changes in at least two of these three metrics at the same time to determine injury. If this criterion was not met, the exact time of injury for each specimen was considered unknown and the maximum value of the moment calculated throughout the test was used as a "left censored" data point, in which the injury occurred at some unknown time before the maximum loading input applied by the test. For the tests where the exact time could be determined, the calculated moment at the time of injury was used for IRF development as an "accurate" data point. For tests where no injury was sustained, the maximum subtalar moment throughout the test was used as a "right censored" data point, in which it is unknown how much more moment would be required to generate an injury.

Injury Risk Function Development

Previous inversion/eversion PMHS tests were analyzed to determine which datasets could be combined with the new test data for the formation of injury risk functions. In order to tease out the effects of sex, anthropometry, and barefoot or shod condition with higher statistical power, all tests selected for inclusion had the same boundary and loading conditions. Therefore, inclusion criteria for new inversion/eversion IRF development included a dynamic test condition, neutral (0 degrees) flexion angle of the ankle during loading, similar axial preload (~2000 N), and the boundary condition of the foot (calcaneus fixed). Data from previous inversion/eversion PMHS test conditions can be found in Table 2, and the data highlighted in the table was the only additional data incorporated in injury risk function development for this study.

In addition to the measured data from Funk et al and the current study, all data were also scaled using equal-mass equal-velocity scaling to match the anthropometry of the 5th percentile female and the 50th percentile male [8]. Standing height and total mass were used to develop scale factors for all data, as these were the only anthropometry metrics included for all specimens in Funk et al's report. Scaled targets for height and weight for the 5th percentile female were 151.3 cm and 46.9 kg, and scaled targets for height and weight for the 50th percentile male were 175.2 cm and 74.4 kg [34]. All data used for the development of all of the IRFs reported in this paper are presented in the Appendices (measured and scaled, male and female, small female and 50th percentile male-sized females, and barefoot and shod condition). Often, an Abbreviated Injury Scale (AIS) level has been used to develop IRF in the past, but it was not used to define "injury" and "no injury" in this test series. Rather any soft or hard tissue injury in the small female PMHS or Funk et al's PMHS tests were considered "injury" for this analysis.

TABLE 2
PREVIOUS PMHS INVERSION/EVERSION STUDIES

Study	Dynamic or Quasi-Static	# PMHS Tests (M/F)	Ankle Flexion Angle (deg)	Axial Load (N)	Foot Boundary Condition
Begeman et al 1993 [27]	Quasi-static	18 (13/5)	-13, 0, 13	270-1300	Foot Fixed
Petit et al 1996 [28]	Quasi - Static	12 (N/A)	0	400 N tension to Achilles	Calcaneus Fixed
Parenteau et al 1998 [29]	Quasi - Static	16 (11/5)	0	0	Foot Fixed
Jaffredo et al 2000 [30]	Dynamic	12 (8/4)	0	0	Foot Fixed
Funk et al 2002 [31]	Dynamic	13 (9/4)	0	0-500	Fixed Calcaneus
Funk et al 2002 [31]	Dynamic	11 (6/5)	0	1460 – 2633	Fixed Calcaneus
Funk et al 2002 [31]	Dynamic	11 (6/5)	30	1549-3208	Fixed Calcaneus

Once the final dataset was determined, all IRF models were developed using survival analysis using the statistical software R version 3.4.4 (R Foundation, Vienna, Austria). In this case, survival analysis is an attractive option over other potential methods (e.g., traditional logistic regression) because it allows for the use of data of mixed censoring. In the combined injury dataset from this test and Funk et al's tests, both accurate and left and right censored data are present. In its mathematical formulation, survival analysis can account for the varying levels of uncertainty inherent to exact vs. censored data, allowing us to combine data of mixed censoring into one injury risk function, whereas traditional logistic regression cannot [37]. For a few of Funk et al's tests, the same specimen was tested more than once. This is problematic because is unknown whether the first impact weakened the subject, and including repeated tests weighs one individual's response more heavily when creating a population injury risk function. Unlike Funk et al's analyses, the data from PMHS subjected to repeated tests were treated as "interval-censored" in which the injury is assumed to have occurred somewhere between the maximum moment in the initial test and the injury moment determined in the final test, as suggested by McMurray et al [35]. Data type (censoring) for each test can also be found in the Appendices.

The development of injury risk functions via survival analysis is described in detail in three previous studies, and these recommendations were followed for the development of IRF for this study [35-37]. Several IRF forms were examined including lumping all data into a combined model (controlling for potential confounders with model variables), and stratifying the dataset by sex, presence/absence of a shoe, and loading direction. IRFs were also developed for scaled and non-scaled data for both the 5th percentile female and the 50th percentile male. Different potential distributions were considered (log-logistic, log-normal, and Weibull distribution), and their predictive ability was evaluated based on model p-value tests. Survival analysis was performed on the distribution with the best predictive capability compared to the measured injury data to form IRF.

III. RESULTS

PMHS Experimental Testing Results

For the tested small female PMHS, results from the post-test CT scans and dissection showed that seven out of the twenty specimens were uninjured (injury data can be found in Appendix Table 1), while the remainder sustained either soft tissue or bony injury. Of the seven uninjured specimens, five were tested in the barefoot condition, while only two were shod. Furthermore, barefoot and shod condition seem to have an effect on injury pattern: barefoot specimens only sustained bony fracture, whereas tested shod specimens sustained a combination of bony and soft tissue injuries. Comparing to Funk et al's dataset, injury type and pattern do not seem to differ between the sexes or within females of two different anthropometries. Bimalloelar fractures (or fractures of both the distal tibia and fibula) were the most common injury pattern across both the test conditions, with four specimens in this test series (two barefoot, two shod) sustaining this combination of injuries. The six specimens that sustained bimalleolar fractures (in this test series and in Funk et al's dataset) had the lowest mid-tibia bone mineral density (BMD) of all the tested specimens. The three specimens that sustained bimalleolar fractures in this test series had increased acoustic output and decreases in bone strain at to the same time for sensors on both the lateral and medial sides. The presence of os naviculare did not affect injury type, moment, or timing. The average and standard deviation for moment at failure for accurate data only for small female in this test series (inversion: -41.5±5.65 Nm; eversion: 64.2±25.2 Nm) and all female, in this test series and Funk's test series (inversion: -74.5± 12.5 Nm; eversion: 39±0 Nm) were similar given the large deviation in the data, and were lower than failure moments for all male data (inversion: -81.3± 25.2 Nm; eversion: 194±44Nm). Average failure moment and standard deviation for all male and female data (scaled and measured) are reported for inversion and eversion in Figure 2, below.

In the measured data, the average inversion failure moment is lower than the average eversion failure moment in all of the test datasets, similar to results found by previous studies [27-31]. Also, eversion moment has greater variance in measured data, with less difference between males and females compared to inversion failure moment. The standard deviation for all measured datasets is high, and, in general, scaling to a specific anthropometry does not seem to decrease the variance. In several cases, the scaled variance is larger than the variance from original measured dataset. Scaling by total mass and scaling by height often yielded different average values when attempting to predict the same response (up to 74.2% difference). Using all male or female data to predict a failure moment for the same anthropometry also yielded different average responses. In attempts to predict the injury moment for the 5th percentile female, most average inversion and eversion moment predicted using male data was higher than the average measured small female data. Measured small female eversion data yielded an average failure moment around 64 Nm, but using only female data (both smaller and larger female) to predict 5th percentile response yielded an average of either 52 or 60 Nm (20.7% or 6.5% difference, respectively), which seem reasonable given the average and deviation of the measured small female data. However, using only male data to predict the same response yielded an injury moment of 139.6 or

85.1 Nm (74.2% or 28.3% difference, respectively), and both predictions fall outside of the standard deviation of the small female measured data. Conversely, when attempting to predict 50th percentile male failure moment, using female data consistently underpredicted the average failure moment compared to the measured male data and the scaled male data.

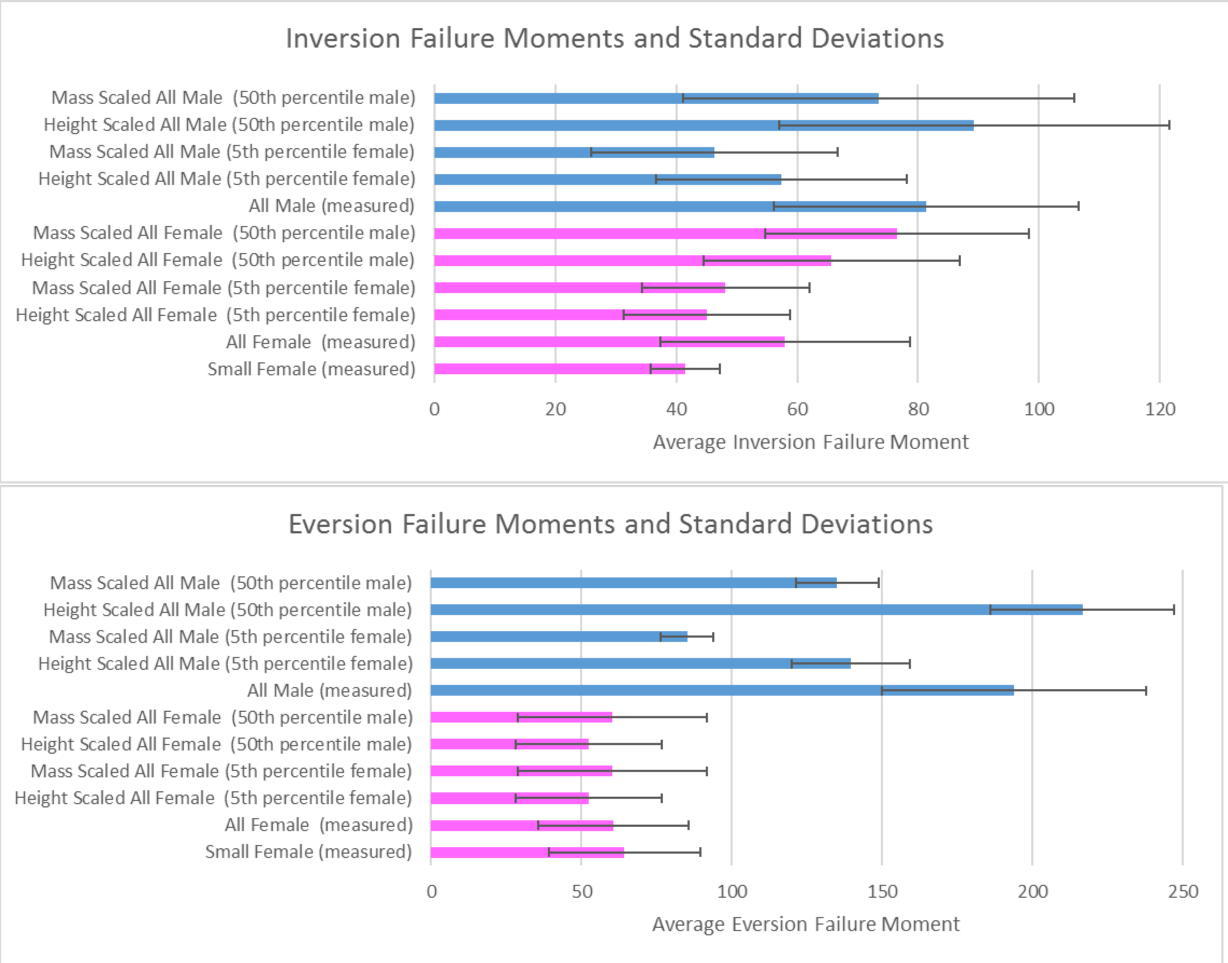

Fig. 2. Magnitude of average inversion (top) and eversion (bottom) failure moments and their respective standard deviations. Pink data is female source data (the data is either measured or scaled as indicated by the vertical axis), and blue data is male (again, either measured or scaled as described by the vertical axis).

Injury Risk Function Development Results

Survival analysis using a multivariate Weibull model ($\chi 2 = 3.35$, p=0.65) had best model predictive capabilities with respect to the measured data compared to log-normal ($\chi 2 = 1.32$, p=0.93) and log-logistic distributions ($\chi 2 = 1.67$, p=0.89). Initially, specimen age, height, mass, BMD, sex, loading direction, and barefoot or shod condition were used as predictor variables in the analysis. While none of these factors were statistically significant for the measured data, sex, direction of loading, and barefoot and shod condition were kept in the model. Sex was maintained as a covariate as it had the strongest correlation with the exact failure moment data (r= 0.596; note that mass strongly correlated to sex in this dataset); this correlation indicates the potential for sex to become significant with additional data to increase power. Although direction and barefoot or shod condition were only weakly correlated with exact failure moment (r=0.196, r=-0.103, respectively), they were kept in the model as they were variables of interest for this study. Using these three covariates (male=1, female=0, eversion=1, inversion=0, shod=1, barefoot=0), the multivariate Weibull survival model ($\chi 2 = 1.16$, p=0.76) again had the best fit of the data in comparison to log-normal ($\chi 2 = 0.12$, p=0.99) and log-logistic ($\chi 2 = 0.17$, p=0.98) survival models. From this, the closed-form moment survivor function was obtained, and then the probability of injury function was calculated for the IRF. All IRF for this study have the form described below, where M is the failure moment (the main predictor variable), and β_i represent the coefficients estimated for the failure model, and X_i represent the covariates in the analysis.

$$P(injury) = 1 - e^{-coeff} \quad [1]$$
$$coeff = \{Me^{-\alpha}\}^{1/scale} \quad [2]$$
$$\alpha = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \quad [3]$$

Coefficients and fit evaluation for the measured data model can be found in Table 3, below. Note that the IRF uses the magnitude of inversion and eversion moment (all values are positive) in its formulation.

TABLE 3
SURVIVAL MODEL COEFFICIENTS FOR IRF CREATED WITH MEASURED DATA (N=29)

Parameter	scale	Intercept (β_0)	Load Direction (β_1)	Sex (β_2)	Shod/Barefoot (β_3)
Coefficients	0.594	4.817	0.200	-0.257	-0.255
Std. Error		0.240	0.280	0.355	0.323
P value		2.26e-29	0.474	0.468	0.431
Log-likelihood: -85.5, ChiSq=1.16; model P value = 0.76					
*note: X_1 inversion=0, eversion=1, X_2 female=0, male=1; X_3 barefoot=0, shod=1;					

The same analysis was repeated for all of the scaled data. The Weibull model best characterized the moment response of the scaled PMHS data and predictor from the measured IRF were used. Coefficients for the scaled IRF using all data (male and female, from this test series and Funk et al's test series) for the 5th percentile female anthropometry and the 50th percentile male anthropometry can be found in Tables 4, below.

TABLE 4
SURVIVAL MODEL COEFFICIENTS FOR IRF CREATED WITH SCALED DATA (N=29)

Scaled Dataset Used	Scale	Intercept (β_0)	Load Direction (β_1)	Sex (β_2)	Shod/Barefoot (β_3)
Mass scaled 5th % coefficients	0.661	4.783	0.108	-0.823	-0.119
Std error		0.284	0.310	0.395	0.359
P value		1.54e-63	0.728	0.037	0.74
Log-likelihood: -84, ChiSq=3.89; model P value = 0.27					
Mass Scaled 50th % coefficients	0.655	5.199	0.131	-0.787	-0.088
Std error		0.265	0.302	0.382	0.348
Pv value		5.20e-86	0.664	0.0395	0.801
Log-likelihood: -90.5, ChiSq=3.89; model P value = 0.28					
Height scaled 5th % coefficients	0.642	4.700	0.0175	-0.440	-0.289
Std error		0.256	0.300	0.381	0.346
Pv value		2.85e-75	0.560	0.248	0.402
Log-likelihood: -83.7, ChiSq=1.61; model P value = 0.66					
Height Scaled 50th % coefficients	0.642	5.140	0.175	-0.440	-0.289
Std error		0.256	0.300	0.381	0.346
Pv value		1.13e-89	0.560	0.248	0.402
Log-likelihood: -89.9, ChiSq=1.61; model P value = 0.66					

Interestingly, the mass scaled data resulted in the model with the highest significance in predicting its source data, and also resulted in statistical significance for the sex covariate. This suggests that if the differences in mass are adjusted for, sex related differences become more distinct. A large population study showed that mass and body mass index accounts for a substantial amount of the variance in bone mineral density for all sites in women (8.9–19.8% of total variance, all $p < 0.01$) and for only weight-bearing sites (femur and spine) in men (2.8–6.9% of total variance, all $p < 0.01$); it further found that change in mass over time is the strongest explanatory factor for variation in BMD among females, but not males [38]. Given these findings, there is clearly a complicated relationship between mass and bone mineral density (which contributes to injury tolerance for hard tissue injuries, and soft tissue injuries such as avulsion fractures), and this relationship seems different between males and females. It is possible when mass between males and females is adjusted for, the difference in the relationship between mass and bone mineral density becomes more distinct, and therefore causes sex to become a statistically significant covariate in the mass scaled model.

IV. Discussion

Experimental: Injuries and Failure Moment

Generally, injuries sustained by small female PMHS had similar patterns to those in the Funk et al study at the same test condition. One exception is that this test series had many more ligament avulsion fractures than those recorded by Funk et al. There could be two reasons for this discrepancy: 1) most PMHS tested in this study were likely post-menopausal, and older females have a much higher rate of osteoporosis than the same age males, or 2) most PMHS who sustained avulsion fractures in this test series were tested in the shod condition, which Funk et al did not test. Similar to this study, the two specimens that sustained bimalleolar fractures in Funk et al's study also had the lowest BMD values of the tested specimens, and these injuries occurred at some of the lowest recorded subtalar moments. This is likely due to the fact that specimens with low BMD are close to failure when the leg is simply axially loaded, and a slight increase in rotation is enough to fail the medial and lateral malleolus very close to the same time. This theory is reinforced by the fact that none of the specimens tested by Funk et al with no axial load sustained bony injury. Therefore, it is likely that axial loading is the primary injury mechanism for bimalleolar fractures. Specimens with better bone quality were much more likely to sustain a single malleolar fracture and/or ligament tears from ankle inversion or eversion, and these injuries occur at a higher ankle moment, even when axial load is applied. In general, the shod condition seems to generate more injuries than the barefoot condition. However, these shod results only apply to the shoe tested (MIL-Spec), and it is likely that different construction of shoe could affect injury tolerance and injury patterns. The average inversion and eversion moments from this test series fall within the standard deviation of inversion and eversion moments measured in Funk et al's test series, reaffirming similar boundary conditions between the two test configurations.

Scaling Analysis and Injury Risk Functions

Scaling average male inversion data to predict small female response generally overestimated failure moment, whereas scaling female data to predict average male response generally underestimated injury moment. Overestimating injury moment is more problematic than underestimating, especially if these overestimations of female injury tolerance are included in regulations to evaluate vehicle crashworthiness; it is possible that this trend of scaled male data overestimating female injury tolerance contributes to females being more susceptible to injury than males in comparable crashes. Further analyses of scaling across the sexes for different body regions and injury mechanisms are required to determine the limitations of scaling, and where it might be useful. For now, given the results of this study, combining male and female data through scaling to predict response at the ankle joint is not recommended.

Looking at the measured injury moment data for small females compared to females the size of mid-sized males, the average injury moments for inversion and eversion injury moment are similar, despite the difference in anthropometry. However, standard deviations for these measured data are large, suggesting individual subject variation has a great effect on injury tolerance. Similar average moment response and large standard deviation between these two female groups suggests that gross anthropometry features, such has height and weight, are less indicative of injury moment than biomechanical properties of each individual (such as soft tissue material properties, bony geometry, joint flexibility, etc.) at a level more localized to the injury. This theory is further supported through the construction of IRFs, in which height and mass were not found to be significant predictor variables using measured or scaled data, and did not correlate well to injury moment. While scaling the injury moment within a single sex (females, in this case) does not change the average moment much, it almost never decreases the standard deviation compared to the original measured dataset. This suggests that scaling with height and weight are not necessary, and might actually misrepresent what is fundamentally contributing to the injury tolerance in the measured data for ankle inversion and eversion. Therefore, directly measured data should be used to incorporate population variation in injury tolerance, which, given the similar average injury moment and large standard deviation between two different female anthropometry groups, will likely apply for most anthropometries.

IRF results for scaled measured data strengthen the recommendation for the use of the measured data; looking at female injury with IRF using measured data, data scaled to a 5th percentile anthropometry and data scaled to a 50th percentile anthropometry are very similar to one another. Therefore, it is suggested that different IRFs should take sex into account, but should not be specific to a gross anthropometry metrics for ankle inversion and eversion injury tolerance. While a barefoot or shod condition was not a statistically significant covariate in the IRF analysis, shod specimens were more likely to sustain injury, and generated different injury patterns than barefoot specimens. The difference footwear has on inversion and eversion injury tolerance and injury pattern demonstrates a need to consider a shod condition in future tests and simulations, given it is likely most occupants wear shoes when in vehicles. The difference in injury pattern and injury incidence in the test series described in this study justifies the need to keep this barefoot and shod predictor variable in the IRF formulation, in the hopes that more shod data will be collected and added to the analysis, and possibly show that a barefoot or shod condition is statistically significant in predicting injury. Given these conditions, the suggested IRF for use in ankle inversion and eversion moment tolerance is detailed in Table 3.

V. CONCLUSIONS

This study has examined the effects that sex, age, height, mass, BMD, scaling, and shod and barefoot conditions have on injury tolerance and development of inversion and eversion IRFs for the ankle, and provides recommendations for ankle inversion and eversion IRFs for use. The study concludes that:

- Female ankle inversion and eversion moment injury tolerance were not significantly higher or lower than male ankle inversion and eversion injury tolerance
- Use of different anthropometric metrics (height and mass) to form scaling factors can greatly change the predicted scaled injury tolerance (up to 74.2% difference) and neither height nor mass was consistently a better metric in predicting injury tolerance
- Scaling male ankle moment injury tolerance data to a female anthropometry using equal-mass equal-velocity scaling typically overpredicts injury tolerance (up to 116.5% error compared to measured data, up to 130.5% error compared to female data scaled to the same anthropometry), whereas scaling female ankle moment injury tolerance data to male anthropometry typically under predicts injury tolerance (up to -68.9% error compared to measured data, up to -55.4% error compared to male data scaled to the same anthropometry)
- Therefore, scaling is not recommended across the sexes for ankle moment injury prediction purposes
- Scaling within a single sex has less of an effect on injury tolerance prediction than scaling across the sexes, however, scaling within a single sex is unnecessary for ankle inversion/eversion failure tolerance because:
  - Scaling often increased the variance from the original dataset, possibly misrepresenting what is fundamentally affecting injury in the original data
  - Similar measured average ankle failure moment were found for two groups of females with different anthropometries (height and mass)
  - IRF results for the measured dataset, 5% scaled dataset, and 50% scaled dataset were similar for all probabilities of injury
- There is large variation in ankle injury moment even for the same sex and the same anthropometry, suggesting individual biomechanical variation at a local level is more important to ankle moment injury tolerance than gross anthropometry metrics
- Therefore, IRF formed with measured data taking sex into account are recommended for ankle inversion/eversion moment for any anthropometry
- The presence of a shoe changes the number of specimens injured and the injury type, but does not change the average failure moment compared to the barefoot specimen
- Bimalleolar fractures are primarily a result of axial loading; for an axial load of 2000N, this injury only occurs in inversion/eversion loading for PMHS with low BMD

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VIII. APPENDICES

APPENDIX TABLE 1
INJURY TYPE AND AIS CODE FOR TESTED SMALL FEMALE PMHS

Test Number	PMHS	Injury Description	AIS Code (2015)
1	859 - R	[No injury]	-
2	859 - L	Closed partial-articular distal tibia fracture, closed fracture line into one joint surface of the talus body	854361.2; 857261.2
3	862 - R	closed partial articular distal tibia fracture; closed isolated lateral malleolus fracure of fibula below ankle joint (Weber A fracture)	854361.2; 854453.2
4	862 - L	closed fracture of the calcaneus into more than two joint surfaces	857371.2
5	878 - R	closed extra-articular medial malleolus fracture; closed isolated lateral malleolus fracure of fibula below ankle joint (Weber A fracture)	854351.2; 854453.2
6	878 - L	closed extra-articular medial malleolus fracture (avulsion fracture, deltoid still intact)	840402.2
7	879 - R	[No injury]	-
8	879 - L	[No injury]	-
9	809 - R	[No injury]	-
10	809 - L	[No injury]	-
11	864 - R	tiny avulsion of partial Calcaneo-fibular ligament (CFL), transverse medial malleolus fracture (extra-articular, closed), talar body fracture (on lateral process, line into one joint surface, closed)	840402.2; 854351.2; 857271.2
12	864 - L	complete avulsion of CFL, subtalar joint opening	840402.2; 877289.1
13	856 - R	distal tibia closed partial-articular fracture, bimalleolar fracture: Weber B	854361.2; 854461.2
14	856 - L	[No injury]	-
15	866 - R	extra articular, closed distal tib fracture, below ankle joint fibula fracture (posterior aspect of distal fibula), Bimalleolar fracture	854351.2; 854453.2
16	866 - L	significant syndesmotic instability, true Weber A distal fibula fracture (closed)	854453.2
17	881 - R	distal fibular avulsion (CFL), slight talar avulsion off talus (PTFL, partial)	840402.2; 840402.2
18	881 - L	[No injury]	-
19	863 - R	tiny avulsion of partial CFL	840402.2
20	871 - L	superficial deltoid injury, complete rupture of deep deltoid, practically an ankle dislocation, small chondral injury (lesion) on lateral talus	877289.1

APPENDIX TABLE 2
DATA USED TO DEVELOP IRF (DIRECTLY MEASURED ONLY)

Source Data	Subject (Sex – ID)	Subtalar Moment Measured (Nm)	Direction of loading	Axial Pre-load (N)	Type of Datapoint
This study	F - 859 - R	-96	Inversion	2000	Right censored
This study	F - 859 - L	36	Eversion	2000	Accurate
This study	F -862 - R	-29	Inversion	2000	Accurate
This study	F - 862 - L	33	Eversion	2000	Accurate
This study	F- 878 - R	-204	Inversion	2000	Left censored
This study	F - 878 - L	79	Eversion	2000	Accurate
This study	F - 879 - R	211	Eversion	2000	Right censored
This study	F - 879 - L	-102	Inversion	2000	Right censored
This study	F - 809 - R	64	Eversion	2000	Right censored
This study	F - 809 - L	-189	Inversion	2000	Right censored
This study	F - 864 - R	62	Eversion	2000	Accurate
This study	F - 864 - L	-54	Inversion	2000	Accurate
This study	F - 856 - R	68	Eversion	2000	Accurate
This study	F - 856 - L	-96	Inversion	2000	Right censored
This study	F - 866 - R	107	Eversion	2000	Accurate
This study	F - 866 - L	-180	Inversion	2000	Left censored
This study	F - 881 - R	-158	Inversion	2000	Left censored
This study	F - 881 - L	185	Eversion	2000	Right censored
This study	F - 863 - R	-120	Inversion	2000	Left censored
This study	F - 871 - L	-184	Inversion	2000	Left censored
Funk 2002	M - 7 - L	-63	Inversion	2467	Accurate
Funk 2002	M - 116 - L	-64	Inversion	2633	Accurate
Funk 2002	M - 146 - R	-117	Inversion	2120	Accurate
Funk 2002	M - 116 - R	150	Eversion	1460	Accurate
Funk 2002	M - 144 - L	46	Eversion	1564	Interval
Funk 2002	M - 144 - L	238	Eversion	2567	Interval
Funk 2002	F - 120 - L	-76	Inversion	2372	Interval
Funk 2002	F - 120 - L	-87	Inversion	2182	Interval
Funk 2002	F - 127 - L	-62	Inversion	1998	Accurate
Funk 2002	F - 120 - R	79	Eversion	1820	Right censored
Funk 2002	F - 114 - R	39	Eversion	1484	Accurate
Funk 2002	M – 530 – L	-35	Inversion	0	Accurate
Funk 2002	M – 532 – L	-22	Inversion	0	Accurate
Funk 2002	F – 533 – L	-24	Inversion	0	Accurate
Funk 2002	M – 9 – L	-23	Inversion	448	Accurate
Funk 2002	M – 8 – L	-15	Inversion	278	Accurate
Funk 2002	F – 127 – R	-25	Inversion	119	Accurate
Funk 2002	M – 530 – R	48	Eversion	0	Accurate
Funk 2002	M – 532 – R	40	Eversion	0	Accurate
Funk 2002	F – 533 – R	23	Eversion	0	Accurate
Funk 2002	M – 10 – R	40	Eversion	413	Accurate
Funk 2002	M – 9 – R	25	Eversion	146	Accurate
Funk 2002	M – 8 – R	66	Eversion	276	Accurate
Funk 2002	F – 114 - L	50	Eversion	94	Accurate

APPENDIX TABLE 3
DATA USED TO DEVELOP IRF (SCALED TO 5TH PERCENTILE FEMALE)

Source Data	Subject (Sex – ID)	Measured Subtalar Moment (Nm)	Subtalar Moment Scaled by Height (Nm)	Subtalar Moment Scaled by Mass (Nm)	Type of Datapoint
This study	F - 859 - R	-96	-77.34	-83.38	Right censored
This study	F - 859 - L	36	29.00	31.27	Accurate
This study	F -862 - R	-29	-25.71	-25.00	Accurate
This study	F - 862 - L	33	29.25	28.45	Accurate
This study	F- 878 - R	-204	-164.35	-162.16	Left censored
This study	F - 878 - L	79	63.64	62.80	Accurate
This study	F - 879 - R	211	178.42	201.96	Right censored
This study	F - 879 - L	-102	-86.25	-97.63	Right censored
This study	F - 809 - R	64	65.81	63.06	Right censored
This study	F - 809 - L	-189	-194.35	-186.22	Right censored
This study	F - 864 - R	62	47.721	67.47	Accurate
This study	F - 864 - L	-54	-41.56	-58.76	Accurate
This study	F - 856 - R	68	66.54	79.93	Accurate
This study	F - 856 - L	-96	-93.94	-112.84	Right censored
This study	F - 866 - R	107	99.71	121.51	Accurate
This study	F - 866 - L	-180	-167.74	-204.41	Left censored
This study	F - 881 - R	-158	-121.60	-160.05	Left censored
This study	F - 881 - L	185	142.38	187.40	Right censored
This study	F - 863 - R	-120	-96.68	-103.46	Left censored
This study	F - 871 - L	-184	163.11	158.63	Left censored
Funk 2002	M - 7 - L	-63	-35.60	-31.10	Accurate
Funk 2002	M - 116 - L	-64	-51.18	-32.63	Accurate
Funk 2002	M - 146 - R	-117	-85.46	-75.17	Accurate
Funk 2002	M - 116 - R	150	119.96	76.47	Accurate
Funk 2002	M - 144 - L	46	30.77	18.13	Interval
Funk 2002	M - 144 - L	238	159.20	93.8	Interval
Funk 2002	F - 120 - L	-76	-55.51	-44.56	Interval
Funk 2002	F - 120 - L	-87	-63.55	-51.00	Interval
Funk 2002	F - 127 - L	-62	-49.58	-58.16	Accurate
Funk 2002	F - 120 - R	79	57.71	46.31	Right censored
Funk 2002	F - 114 - R	39	31.19	30.49	Accurate

APPENDIX TABLE 4
DATA USED TO DEVELOP IRF (SCALED TO 50TH PERCENTILE MALE)

Source Data	Subject (Sex – ID)	Measured Subtalar Moment (Nm)	Subtalar Moment Scaled by Height (Nm)	Subtalar Moment Scaled by Mass (Nm)	Type of Datapoint
This study	F - 859 - R	-96	-120.153	-132.27	Right censored
This study	F - 859 - L	36	45.06	49.6	Accurate
This study	F -862 - R	-29	-39.94	-39.66	Accurate
This study	F - 862 - L	33	45.45	45.13	Accurate
This study	F- 878 - R	-204	-255.33	-257.25	Left censored
This study	F - 878 - L	79	98.88	99.62	Accurate
This study	F - 879 - R	211	277.17	320.38	Right censored
This study	F - 879 - L	-102	-133.99	-154.87	Right censored
This study	F - 809 - R	64	102.23	100.033	Right censored
This study	F - 809 - L	-189	-301.91	-295.41	Right censored
This study	F - 864 - R	62	74.13	107.03	Accurate
This study	F - 864 - L	-54	-64.56	-93.22	Accurate
This study	F - 856 - R	68	103.37	126.80	Accurate
This study	F - 856 - L	-96	-145.93	-179.01	Right censored
This study	F - 866 - R	107	154.90	192.76	Accurate
This study	F - 866 - L	-180	-260.58	-324.26	Left censored
This study	F - 881 - R	-158	-188.90	-253.89	Left censored
This study	F - 881 - L	185	221.19	297.28	Right censored
This study	F - 863 - R	-120	-150.19	-164.12	Left censored
This study	F - 871 - L	-184	253.40	251.65	Left censored
Funk 2002	M - 7 - L	-63	-55.31	-49.34	Accurate
Funk 2002	M - 116 - L	-64	-79.51	-51.76	Accurate
Funk 2002	M - 146 - R	-117	-132.76	-119.24	Accurate
Funk 2002	M - 116 - R	150	186.36	121.30	Accurate
Funk 2002	M - 144 - L	46	47.80	28.76	Interval
Funk 2002	M - 144 - L	238	247.32	148.80	Interval
Funk 2002	F - 120 - L	-76	-86.24	-70.68	Interval
Funk 2002	F - 120 - L	-87	-98.72	-80.91	Interval
Funk 2002	F - 127 - L	-62	-77.03	-92.26	Accurate
Funk 2002	F - 120 - R	79	89.64	73.47	Right censored
Funk 2002	F - 114 - R	39	48.45	48.36	Accurate