Skeletal Site and Method-dependent Variability of Bone Mineral Density in Injury Biomechanics Research

Zachary A. Haverfield, Randee L. Hunter, Kathryn L. Loftis, Amanda M. Agnew

Abstract Bone mineral density (BMD) is often used for injury prediction and fracture risk evaluation. This study aims to determine the breadth and depth of BMD utilization in injury biomechanics research and evaluate the appropriateness of these approaches by assessing BMD sensitivity and variability throughout the human body. A scoping review was conducted examining post-mortem human subject (PMHS) experimental studies that utilized dual-energy x-ray absorptiometry (DXA) and/or quantitative computed tomography (QCT) for bone quality assessment. Subsequently, areal BMD (aBMD) and volumetric BMD (vBMD) of 76 male PMHS were assessed throughout the body using DXA and QCT. Results indicated that methods and applications of BMD in injury biomechanics are largely inconsistent, and that only 40% of studies assessed bone quality with injurious PMHS testing. aBMD differed between almost every skeletal site ($p<0.05$) and, similarly, vBMD was different between most sites ($p<0.05$). Further, no singular measure from DXA or QCT represented global BMD throughout the body. Few relationships in BMD were found between DXA and QCT ($p<0.05$) at comparable sites. Variability in bone quality assessment methods may limit comparability of data within the field. Overall, assessing BMD for PMHS biomechanical testing requires standardized methods and comprehensive understanding of variability between/within skeletal elements of interest.

Keywords Bone quality assessment, CT, DXA, Imaging, Skeletal fracture

I. INTRODUCTION

In the field of injury biomechanics, skeletal fractures are commonly assessed to inform injury mitigation efforts and safety standards. Further, indicators of skeletal health associated with risk of fracture and severity can be utilized to identify at-risk populations and explain injury outcomes. Bone mineral density (BMD) is a common assessment of skeletal health [1] and is quantified with radiographic imaging modalities that measure the amount of radiation passing through bone [2]. BMD is utilized in both injury biomechanics research and in clinical practice to assess fracture risk, bone quality, and overall skeletal health. Specifically, BMD in injury biomechanics is often quantified in post-mortem human subjects (PMHS) for selection criteria for a study and/or to discern the likelihood of sustaining an injury in experimental testing. Although clinical methods of bone quality assessment have been standardized, the field of injury biomechanics has not identified a consistent method of bone quality assessment despite the importance of accurately interpreting fractures to inform injury risk. Additionally, no identified research has broadly summarized the variation in current methods and applications of bone quality assessment in injury biomechanics, which may limit the comparability of data within the field.

Although the standard clinical method to quantify BMD is conducted using dual-energy x-ray absorptiometry (DXA), growing evidence has demonstrated that fracture risk increases independently of T-score categorizations of skeletal health [3–5]. Specifically, errors result from the two-dimensional nature of DXA, which allows superimposed skeletal, non-skeletal, and hyperdense structures to be measured simultaneously with the region of interest, skewing resulting areal BMD (aBMD) values [6]. Further, age-related changes to the skeleton, such as osteoarthritic bone growth, may exacerbate these inherent errors, potentially inflating measures of aBMD used to define bone quality and fracture risk [7][8]. To avoid these errors, quantitative computed tomography (QCT) provides three-dimensional visualization and quantification of bone quality using volumetric BMD (vBMD) [9][10]. QCT methodologies can differentiate distinct skeletal envelopes, such as trabecular and cortical bone, to be assessed individually. Methods such as QCT that increase the sensitivity of BMD are not clinically utilized as often as DXA due to increased irradiation [11]. However, this issue does not apply to PMHS, and QCT may improve bone

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quality assessment in injury biomechanics that aid fracture risk predictions and interpretations of injury.

Using varying imaging modalities to quantify BMD may result in differential designations of skeletal health and fracture risk even within an individual. To further confound this, assumptions of homogenous bone quality across the body are likely inaccurate. For instance, trabecular BMD has been shown to vary across the human body [12], which may be a result of the heterogeneous mechanical loading environments differentially influencing functional adaptation of skeletal elements. In addition to differences in BMD between skeletal elements, previous work demonstrated that BMD varies significantly even within a single bone [13–15]. Accounting for inherent intra-skeletal variation is therefore essential for accurately identifying at-risk populations and quantifying injury risk at specific skeletal sites of interest.

The use of BMD in experimental PMHS injury biomechanics may vary within the field, limiting comparability of results due to inconsistencies in assessment techniques. Further, additional research is needed to determine the extent to which BMD varies throughout the body and between common imaging modalities, which could impact PMHS selection criteria, injury assessment outcomes, and explanations of injury severity. Thus, the purpose of this study is twofold: 1. conduct a scoping review to summarize the current methodologies for quantifying BMD and its applications in injury biomechanics; and 2. quantify BMD in a PMHS sample using both DXA and QCT to determine the extent of variability throughout the body and between methods.

II. METHODS

Review of Literature

A scoping review referencing practices from PRISMA guidelines [16] was conducted to gauge the extent of consistency in methods and utilization of bone quality assessment/BMD within the field of injury biomechanics. Ten prominent sources were selected to search for literature pertaining to experimental PMHS testing from the years 2000–2021 to evaluate comparable and modern imaging technologies. Article sources included: *Annals of Biomedical Engineering, Enhanced Safety of Vehicles (ESV), International Research Council on Biomechanics of Injury (IRCOBI), International Journal of Transportation, Journal of Biomechanics, Journal of Biomechanical Engineering, Journal of the Mechanical Behavior of Biomedical Materials, Society of Automotive Engineers (SAE)* publications, *Stapp Car Crash Journal*, and *Traffic Injury Prevention.*

Scopus (Elsevier) and Google Scholar were used to identify articles with initial search terms that included “post-mortem human subject”, “post-mortem human surrogate”, “PMHS”, “injury”, “experimental testing”, and “sled testing”. A primary screening of the articles was conducted to remove duplicates from searches. All resulting articles were secondarily screened to ensure they met the following inclusion criteria: 1. the article presented primary experimental PMHS testing; 2. PMHS testing directly assessed or reported skeletal injury; and 3. experimental testing of PMHS was not limited to isolated anatomical components. Once screened, each article was evaluated for its inclusion of DXA and/or CT (also termed QCT), the utilization of BMD and/or T-scores (defined as *bone quality* data), anatomical region of interest, and associations of bone quality data with injury findings.

Following the screening process, accepted articles were assessed using the classification questions outlined in Fig. 1. All information was organized in Microsoft Excel (v2018) and evaluated for data frequency relative to each classification question and category of the identified imaging modality.

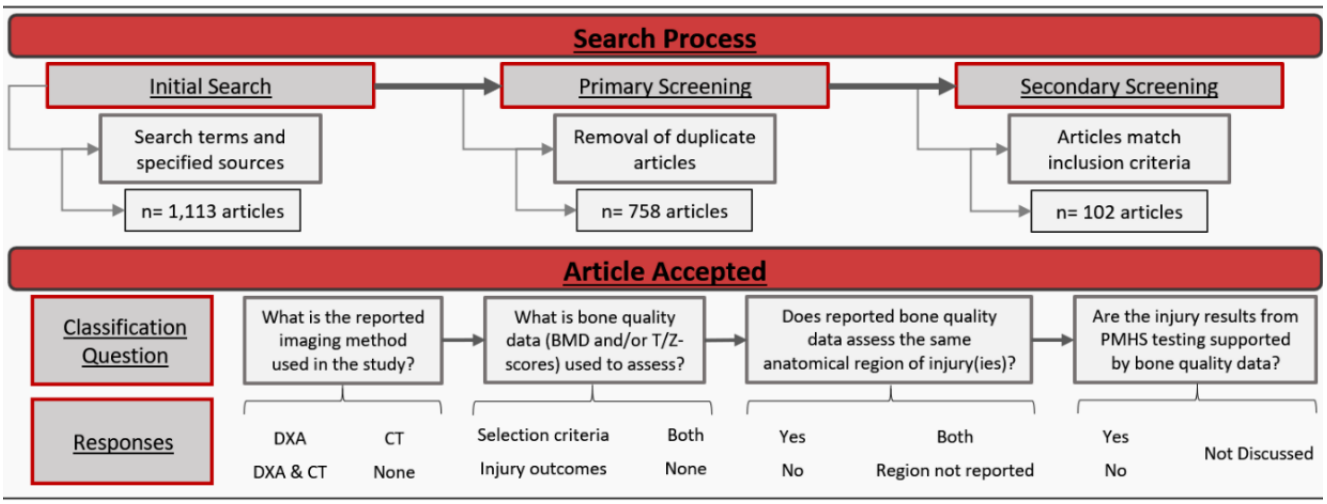

Fig. 1. Scoping review article classification

BMD Collection

Seventy-six male PMHS ranging in age from 24 to 102 years (62 ± 14.5) were included for analysis of imaging data previously collected in the Injury Biomechanics Research Center (Columbus, OH, USA). A DXA scan was conducted using a General Electric Lunar Prodigy scanner at consistent acquisition parameters. Standard clinical sites and protocols defined by the World Health Organization [1] were used to obtain areal bone mineral density (aBMD) from the L2-L4 region (mean) in the lumbar spine, the left femoral neck (Fem-N), the ultra-distal radius (Rad-UD), and the 33% of the total length from the distal radius (Rad-33). Following the DXA scan, a whole-body clinical CT scan was performed on each subject that included INTable™ phantom rods of known density throughout the length of the body. CT scan acquisition parameters were consistent with a 512 x 512 matrix, slice thickness of 0.6 mm, 120 kVp, and a reference 250 mAs. Due to the retrospective nature of the study, scan reconstruction diameters ranged from 500 mm to 650 mm. Volumes of interest (VOIs) were created using OsiriX MD imaging software (v.12.0.02) from the left humerus, radius, femoral neck, femur, tibia, and calcaneus, as well as the lumbar spine. Further, multiple VOIs along the length of the bone, or at different vertebral levels, were obtained from the femur, radius, lumbar spine, and tibia (Table I). All VOIs consisted of five slices in the axial plane, except for the femoral neck, which included three coronal slices for accurate visualization.

VOIs from each skeletal element were further segmented to assess different tissue compartments, including trabecular (Tb), cortical (Ct), and Total (combined Tb and Ct) bone, resulting in 23 separate VOIs for each PMHS (Table I). Due to the influence of non-skeletal tissues in HU quantification of bone [12][17][18], in addition to blunt VOI segmentation (Fig. 2), a Hounsfield unit (HU) threshold specific to each tissue type was applied to the VOI to exclude non-skeletal tissue voxels. HU thresholds were derived from the literature as follows: Tb bone: 150-660 HU, Ct bone: 661-3000 HU, and Total bone: 150-3000 HU [19–21]. The femoral neck Ct bone was further divided into the superior (Sup) and inferior (Inf) cortices for individual analysis to quantify potential intra-element variation between the cortices. After thresholding and segmentation, a mean HU value from each 5/3 slice VOI was obtained. To calculate vBMD, a custom, validated MATLAB code was used to obtain HU from each of the three phantom rods in the same CT slices as those isolated for each VOI. Phantom rod HU values were plotted against their known densities with a linear fit to create site-specific HU to vBMD calibration curves for each PMHS.

For primary BMD data collected in this study, repeated measures mixed model ANOVAs with *post-hoc* Tukey tests were utilized to identify differences in BMD values between skeletal sites using Minitab 18 statistical software. Further, linear regressions were conducted to determine if BMD from one site was able to predict BMD at another for both aBMD and vBMD (Tb, Ct, and Total bone). Finally, Pearson correlations were used to assess relationships between aBMD and total vBMD, and linear regressions were used to determine if aBMD could predict total vBMD at comparable skeletal sites. Statistical significance for all tests was set *a priori* at $p<0.05$.

TABLE I
VOIS ASSESSED FOR VBMD

Skeletal Element	Site(s)*	Abbreviation(s)	Skeletal Tissue Type(s)†
Humerus	50%	Hum-50	Ct
Radius	4%	Rad-4	Tb, Total
Radius	30%, 50%	Rad-30, Rad-50	Ct
2nd-4th Lumbar spine	Mid	L2, L3, L4	Tb, Total
Femoral Neck	Mid	Fem-N	Tb, Total, Ct (Inf, Sup)
Femur	50%	Fem-50	Ct
Tibia	4%	Tib-4	Tb, Total
Tibia	38%, 50%, 66%	Tib-38, Tib-50, Tib-66	Ct
Calcaneus	Mid	Calc	Tb, Total

*Sites obtained within the axial plane are defined at either a percentage of total length relative to the distal end or from the axial midpoint (mid) (50%) of the skeletal element. The femoral neck site was defined at the coronal midpoint (mid) (50%) of the skeletal element.
†Ct = cortical bone, Tb = trabecular bone, Inf = inferior cortex, Sup = superior cortex.

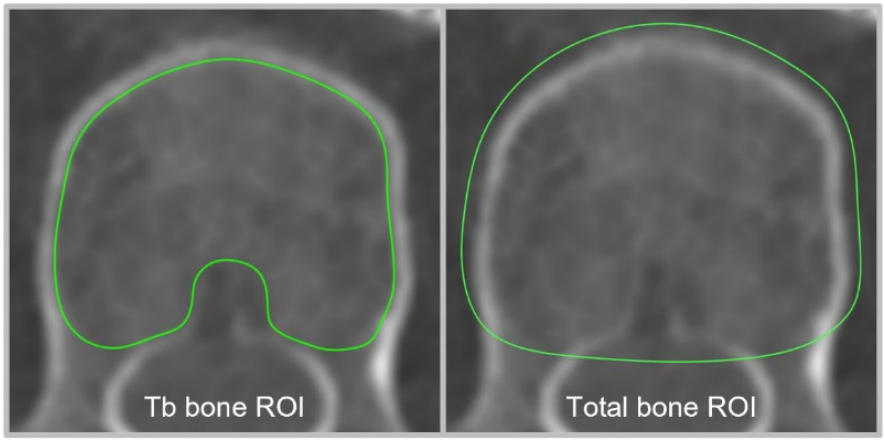

Fig. 2. Example lumbar blunt segmentation between Trabecular (Tb) (left) and Total bone (right)

III. RESULTS

Scoping Review

Between the years 2000 and 2021, a total of 102 articles met the inclusion criteria of primary injurious PMHS experimental testing and were published in the designated sources. Bone quality assessment using DXA and/or CT was used in 40.2% (n=41/102) of the included studies, while 59.8% (n=61/102) of the experimental PMHS studies did not utilize imaging modalities to assess bone quality. Of the articles that utilized DXA and/or CT, 82.9% (n=34/41) of the studies collected data from only DXA, 9.8% (n=4/41) from only CT, and 7.3% (n=3/41) used both DXA and CT to collect bone quality data (Fig. 3).

Literature from the scoping review that used DXA and/or CT to collect BMD, T-scores, or Z-scores (n=41) demonstrated variability in the utilization, anatomical location, and explanation of injury outcomes (Fig. 3). A notable finding demonstrated that 65.9% (n=27/41) of bone quality data were collected either from anatomical regions outside of the reported location(s) of injury, or the anatomical region was not specified at all. Though BMD was reported, one of the 41 studies did not utilize or mention the purpose of collecting BMD and was not included in subsequent analysis. Further, 57.5% (23/40) studies utilized BMD only for PMHS selection criteria, and of those, fifteen (65.2%) selected PMHS using BMD values from anatomical sites outside of the targeted region of interest for injury. Of the studies that used BMD data to explain injuries from a different anatomical region, 80.8% (n=21/26) did not discuss or report any relationships between bone quality and injury outcomes. A total of 13 articles discussed bone quality data in relation to PMHS injuries, with nine using DXA and four using DXA and/or CT. Findings from this review demonstrated that 77.8% (n=7/9) of the articles that only used DXA found *no* relationships between BMD and injury outcomes. In contrast, 100% (n=4) of the studies that used CT alone or in conjunction with DXA reported that injuries were associated or aligned with expectations from BMD.

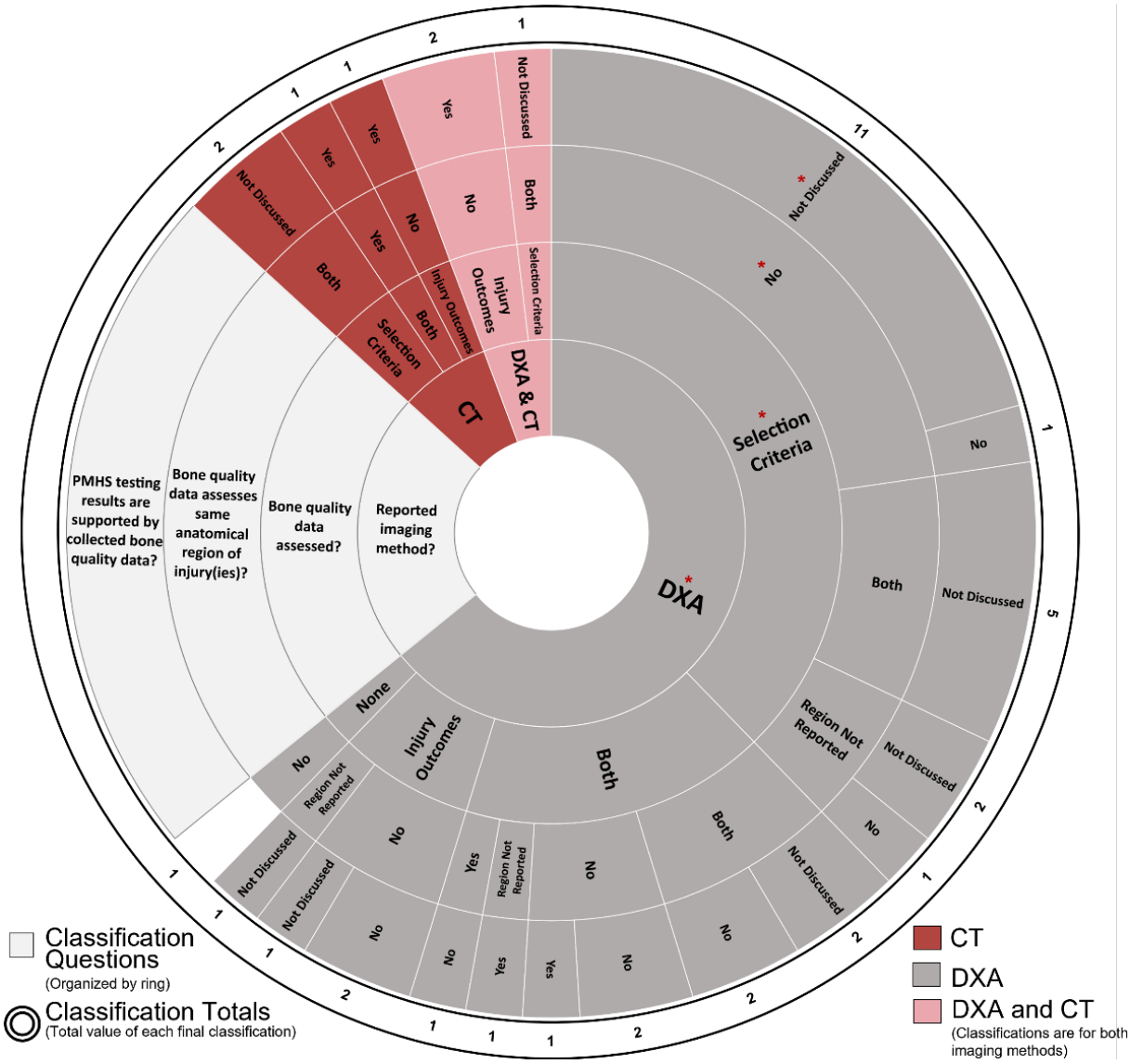

Fig. 1. Imaging articles summary (n=41 out of 102). Example*: 11 studies used DXA for PMHS selection criteria, data were not from the same injury region(s), and were not discussed in relation to injuries.

aBMD

Descriptive statistics for primary DXA aBMD data are presented in Table A.I. aBMD was significantly different between all skeletal sites (ANOVA, p<0.001), except for the Fem-N compared to Rad-33 (p=0.518) (Table II). Linear regressions further demonstrated that aBMD from one site was able to predict aBMD at all other sites (p<0.035), except for L2-L4 to Rad-33 (p=0.479) (Table II). However, only small amounts of variation were explained between sites as R^2 values did not exceed 22.8%, thus, relationships were generally weak (Fig. 4).

TABLE II
RESULTS OF ABMD SITE COMPARISONS

Skeletal Sites		N	*Post-hoc* Tukey	Linear Regression	
			p-value	R^2 (%)	p-value
L2-L4	*Fem-N*	75	**<0.001**	5.9	**0.035**
L2-L4	*Rad-UD*	67	**<0.001**	12.3	**0.004**
L2-L4	*Rad-33*	67	**<0.001**	0.8	0.479
Fem-N	*Rad-UD*	67	**<0.001**	13.1	**0.003**
Fem-N	*Rad-33*	67	0.518	7.3	**0.027**
Rad-UD	*Rad-33*	67	**<0.001**	22.8	**<0.001**

Bold = statistically significant

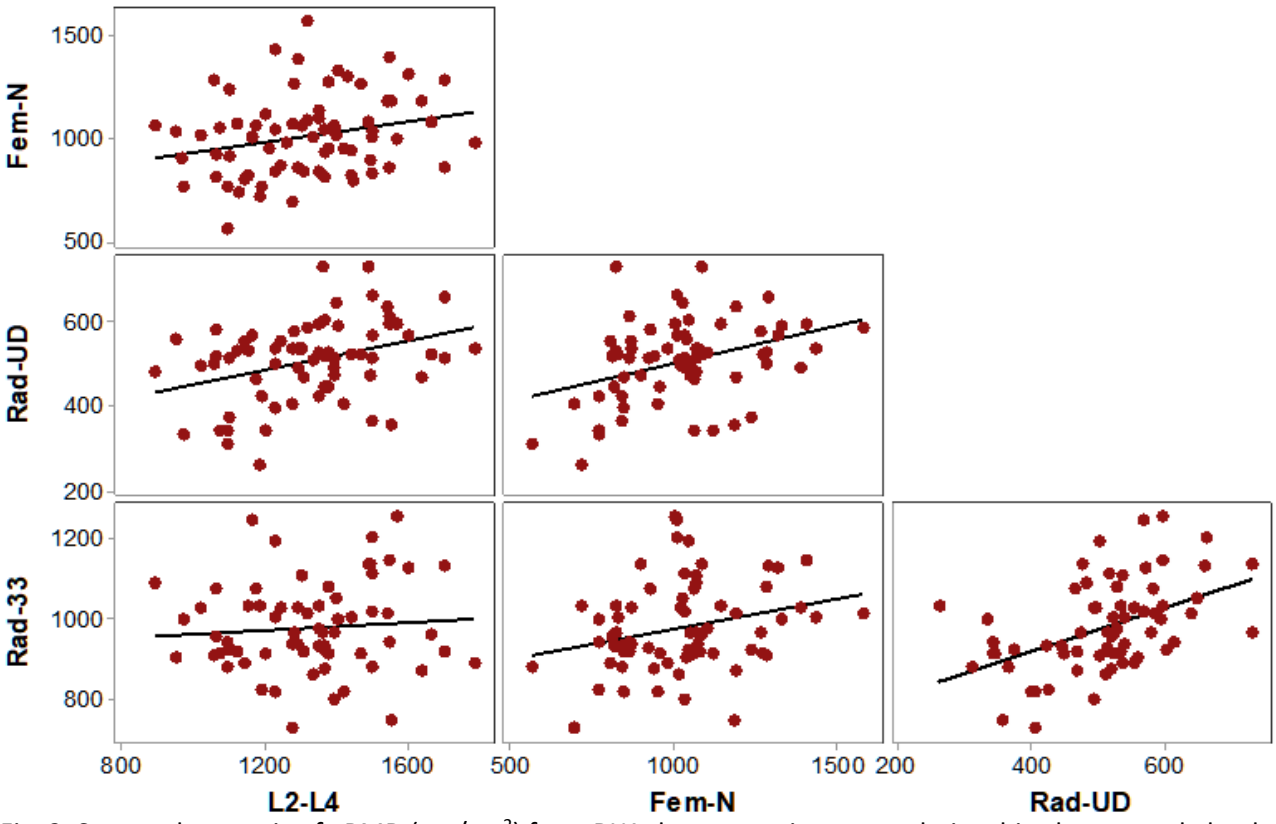

Fig. 2. Scatterplot matrix of aBMD (mg/cm^2) from DXA demonstrating poor relationships between skeletal sites

vBMD

Descriptive statistics for Trabecular (Tb) and Total vBMD are displayed in Table A.II. Significant variation in Tb vBMD was identified throughout the body (ANOVA, $p<0.001$) (Fig. 5, Table III). *Post-hoc* site-specific comparisons demonstrated that Fem-N Tb vBMD was significantly larger than Tb vBMD at all other sites ($p<0.001$). Tb vBMD was not different between lumbar spine sites ($p>0.188$). However, while Tb vBMD from L2 and L3 were significantly smaller than both the distal tibia and radius sites ($p<0.05$), L4 Tb vBMD was significantly smaller than the distal tibia ($p=0.025$) but not the distal radius ($p=0.530$). Tb vBMD from each skeletal site successfully predicted Tb vBMD at all other sites ($p<0.016$) (Table III). However, when Tb vBMD from one skeletal region (e.g., the lumbar spine) was used to predict Tb vBMD at another (e.g., the tibia), R^2 values ranged from only 7.5% to 37.5% (Fig. 6, Table III).

Variability in Total bone vBMD was also identified (ANOVA, $p<0.001$) (Fig. 5) and demonstrated similar trends to Tb bone (Table III). All sites were still significantly smaller than Fem-N Total vBMD ($p<0.001$). However, L2 Total vBMD was significantly smaller than L4 ($p=0.001$), which was not observed for Tb vBMD at these sites. No significant differences were observed in Total vBMD of L2 and L3 compared to the distal radius and tibia ($p>0.209$). However, L4 Total vBMD was significantly larger than Total vBMD from Rad-4 ($p=0.033$) and Tib-4 ($p<0.001$). In contrast to Tb vBMD results, Calc Total vBMD was significantly larger than Total vBMD in L2, L3, L4, Rad-4, and Tib-4 ($p<0.001$). Total vBMD from one skeletal site significantly predicted Total vBMD at all other sites ($p<0.048$), except when using L2 or L3 vBMD to predict Tib-4 or Calc vBMD, as well as Fem-N vBMD to predict Tib-4 vBMD ($p>0.062$) (Table III). Further, using Total vBMD from one skeletal region to predict Total vBMD at another in only significant relationships resulted in R^2 values from 5.2% to 37.3% (Table III), and relationships were generally weak (Fig. 6).

TABLE III
INTER-SITE COMPARISONS FOR TRABECULAR AND TOTAL vBMD

Skeletal Sites		*Post-hoc* Tukey		Linear Regression			
		Trabecular	Total	Trabecular		Total	
		p-value	p-value	R^2 (%)	p-value	R^2 (%)	p-value
Rad-4	*Fem-N*	**<0.001**	**<0.001**	19.2	**<0.001**	17.3	**<0.001**
Rad-4	*Tib-4*	0.825	0.497	22.4	**<0.001**	25.5	**<0.001**
Rad-4	*Calc*	**0.001**	**<0.001**	15.8	**<0.001**	36.2	**<0.001**
L2	*Rad-4*	**0.002**	0.957	13.9	**0.001**	12.0	**0.002**
L2	*L3*	1.000	0.754	44.2	**<0.001**	57.5	**<0.001**
L2	*L4*	0.351	**0.001**	41.0	**<0.001**	50.9	**<0.001**
L2	*Fem-N*	**<0.001**	**<0.001**	11.4	**0.003**	14.4	**0.001**
L2	*Tib-4*	**<0.001**	0.974	10.5	**0.004**	4.6	0.062
L2	*Calc*	1.000	**<0.001**	7.5	**0.016**	3.2	0.123
L3	*Rad-4*	**<0.001**	0.999	37.5	**<0.001**	11.7	**0.003**
L3	*L4*	0.188	0.131	66.2	**<0.001**	57.5	**<0.001**
L3	*Fem-N*	**<0.001**	**<0.001**	25.2	**<0.001**	15.8	**<0.001**
L3	*Tib-4*	**<0.001**	0.209	17.2	**<0.001**	0.8	0.440
L3	*Calc*	1.000	**<0.001**	15.9	**<0.001**	0.3	0.619
L4	*Rad-4*	0.530	**0.033**	29.3	**<0.001**	22.1	**<0.001**
L4	*Fem-N*	**<0.001**	**<0.001**	27.5	**<0.001**	12.5	**0.002**
L4	*Tib-4*	**0.025**	**<0.001**	13.2	**0.001**	9.6	**0.006**
L4	*Calc*	0.292	**<0.001**	16.3	**<0.001**	15.2	**<0.001**
Fem-N	*Tib-4*	**<0.001**	**<0.001**	8.6	**0.010**	0.4	0.585
Fem-N	*Calc*	**<0.001**	**<0.001**	18.5	**<0.001**	5.2	**0.048**
Tib-4	*Calc*	**<0.001**	**<0.001**	14.5	**0.001**	37.3	**<0.001**

N=76 VOIs for each skeletal site. **Bold** = statistically significant.

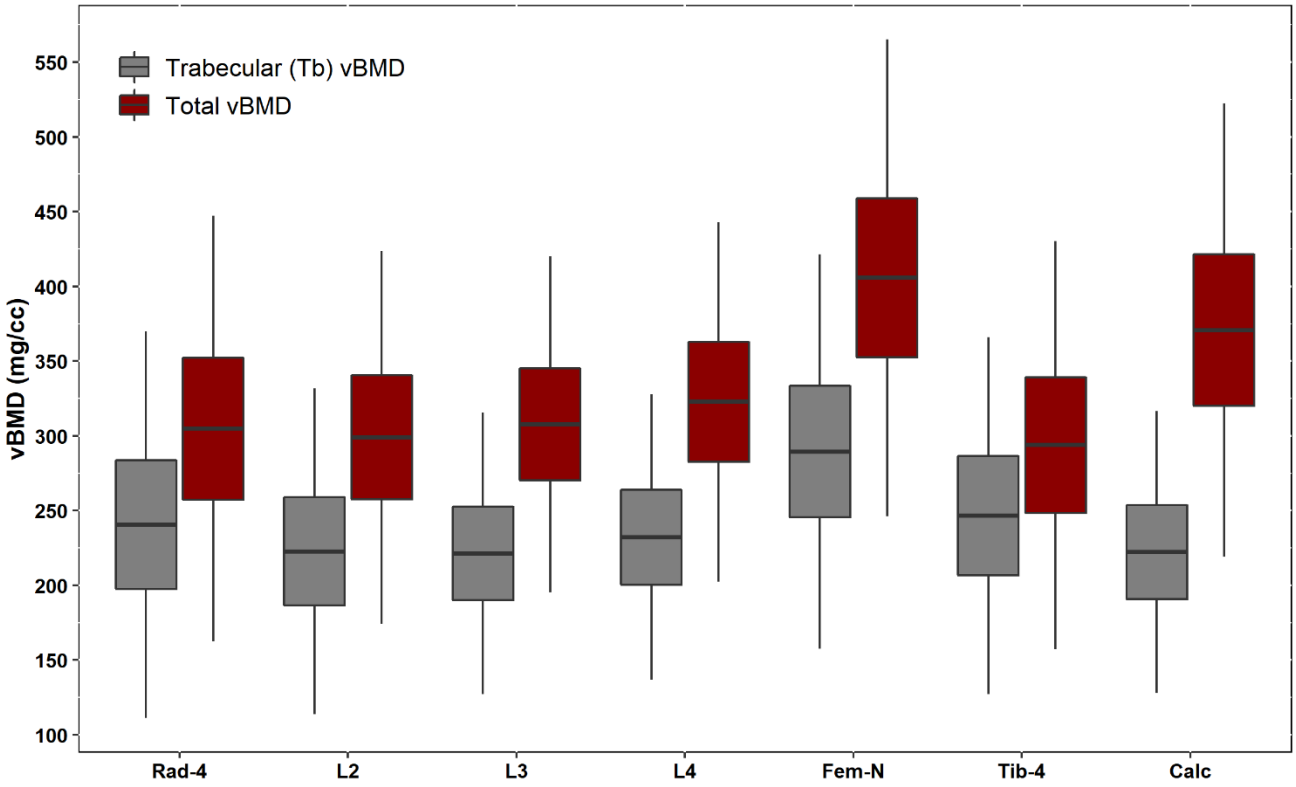

Fig. 3. Boxplot of Trabecular (grey) and Total (red) bone vBMD per skeletal site. Box: ± 1 SD from mean. Whiskers: ± 3 SD from mean.

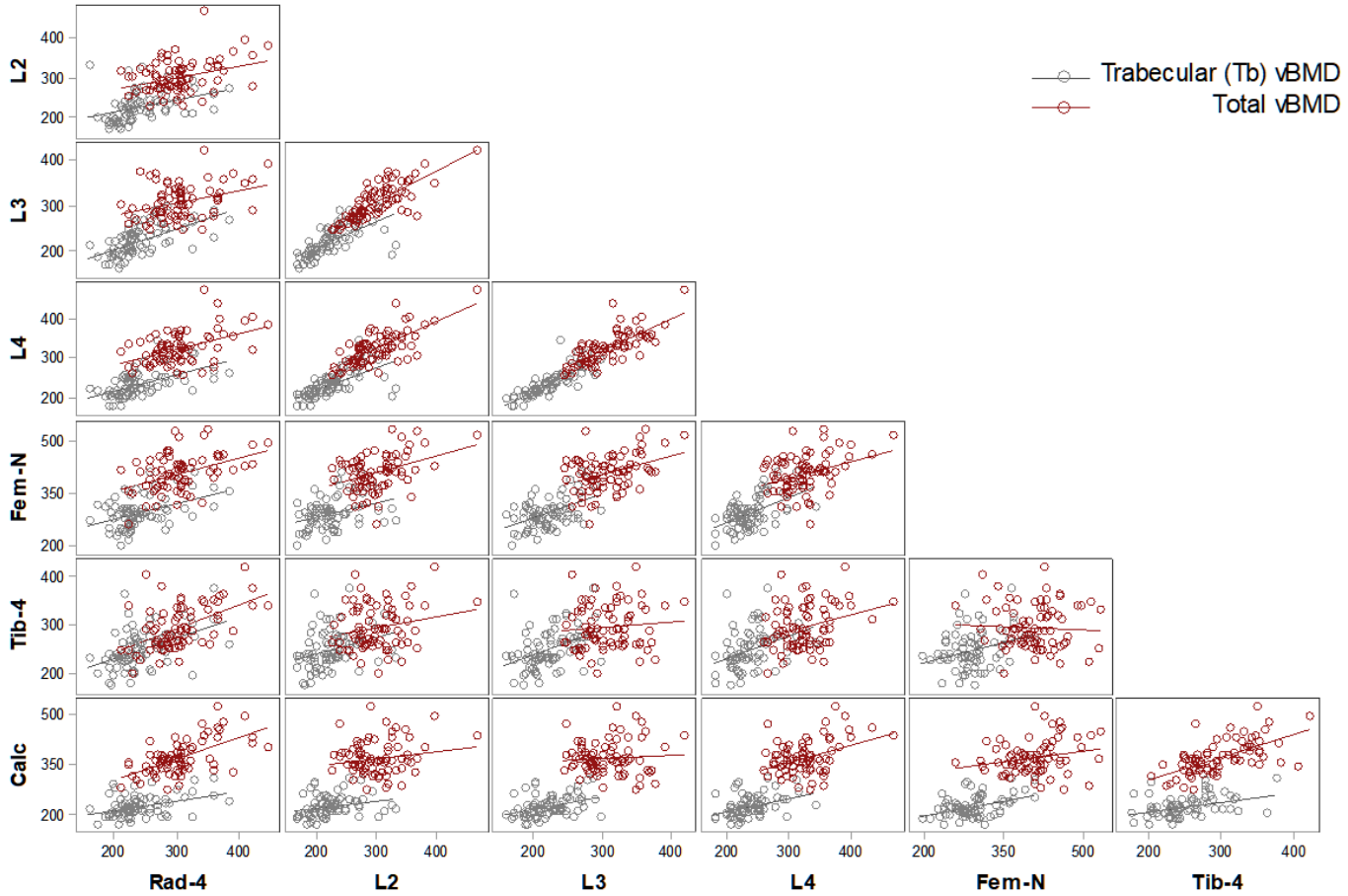

Fig. 4. Scatterplot matrix of Trabecular (grey) and Total (red) bone vBMD (mg/cc) between skeletal sites

Descriptive statistics for Cortical (Ct) vBMD are provided in Table A.III, and *post-hoc* Tukey test results for Ct vBMD are displayed in Table IV. Significant variation in Ct vBMD was identified throughout the body (ANOVA, $p<0.001$). Ct vBMD was different between almost every skeletal site ($p<0.001$), except for Hum-50 with both Rad-50 and Tib-66 ($p>0.055$), as well as Fem-50 with both Tib-38 and Tib-50 ($p>0.732$) (Fig. 7, Table IV). Further, no differences in Ct vBMD were identified within the radius (Rad-50 vs Rad-30, $p=0.905$) or between some locations within the tibia (Tib-50 vs Tib-38, $p=0.954$). However, vBMD at the Tib-66 site was significantly lower than the other tibia sites ($p<0.001$). Ct vBMD of both femoral neck cortices was significantly lower than all other sites ($p<0.001$) (Table IV), and the inferior Fem-N cortex had a significantly higher Ct vBMD compared to the superior cortex ($p<0.001$, Fig. 7). When using Ct vBMD from one skeletal site to predict another (Fig. 8), Fem-N Sup Ct vBMD was unable to predict vBMD in any sites from the radius or tibia ($p>0.068$) (Table IV). While Fem-N Inf Ct vBMD did predict Ct vBMD at all tibia sites ($p<0.04$), it failed to predict Ct vBMD at either radius site ($p>0.076$) (Table IV). Finally, all of these Ct vBMD predictions between skeletal regions with significant relationships resulted in R^2 values ranging from 5.6% to 44.7% (Table IV).

TABLE IV
INTER-SITE COMPARISONS FOR CORTICAL vBMD

Skeletal Sites		*Post-hoc* Tukey	Linear Regression	
		p-value	R^2 (%)	p-value
Hum-50	*Rad-50*	0.055	44.7	**<0.001**
Hum-50	*Rad-30*	**<0.001**	36.6	**<0.001**
Hum-50	*Fem-N Sup*	**<0.001**	8.8	**0.009**
Hum-50	*Fem-N Inf*	**<0.001**	7.4	**0.018**
Hum-50	*Fem-50*	**<0.001**	36.4	**<0.001**
Hum-50	*Tib-66*	0.778	27.2	**<0.001**
Hum-50	*Tib-50*	**<0.001**	12.2	**0.002**
Hum-50	*Tib-38*	**<0.001**	14.1	**0.001**
Rad-50	*Rad-30*	0.905	58.8	**<0.001**
Rad-50	*Fem-N Sup*	**<0.001**	3.5	0.105
Rad-50	*Fem-N Inf*	**<0.001**	4.2	0.076
Rad-50	*Fem-50*	**<0.001**	25.8	**<0.001**
Rad-50	*Tib-66*	**<0.001**	36.0	**<0.001**
Rad-50	*Tib-50*	**<0.001**	32.1	**<0.001**
Rad-50	*Tib-38*	**<0.001**	25.4	**<0.001**
Rad-30	*Fem-N Sup*	**<0.001**	3.2	0.124
Rad-30	*Fem-N Inf*	**<0.001**	4.0	0.083
Rad-30	*Fem-50*	**<0.001**	24.2	**<0.001**
Rad-30	*Tib-66*	**<0.001**	41.8	**<0.001**
Rad-30	*Tib-50*	**<0.001**	33.9	**<0.001**
Rad-30	*Tib-38*	**<0.001**	26.5	**<0.001**
Fem-N Sup	*Fem-N Inf*	**<0.001**	26.0	**<0.001**
Fem-N Sup	*Fem-50*	**<0.001**	13.7	**0.001**
Fem-N Sup	*Tib-66*	**<0.001**	4.1	0.079
Fem-N Sup	*Tib-50*	**<0.001**	4.4	0.068
Fem-N Sup	*Tib-38*	**<0.001**	3.3	0.117
Fem-N Inf	*Fem-50*	**<0.001**	12.1	**0.002**
Fem-N Inf	*Tib-66*	**<0.001**	5.8	**0.037**
Fem-N Inf	*Tib-50*	**<0.001**	6.3	**0.029**
Fem-N Inf	*Tib-38*	**<0.001**	5.6	**0.040**
Fem-50	*Tib-66*	**<0.001**	44.2	**<0.001**
Fem-50	*Tib-50*	0.732	22.5	**<0.001**
Fem-50	*Tib-38*	1.000	22.2	**<0.001**
Tib-66	*Tib-50*	**<0.001**	61.0	**<0.001**
Tib-66	*Tib-38*	**<0.001**	52.4	**<0.001**
Tib-50	*Tib-38*	0.954	60.7	**<0.001**

N=76 VOIs for each skeletal site. **Bold**= statistically significant.

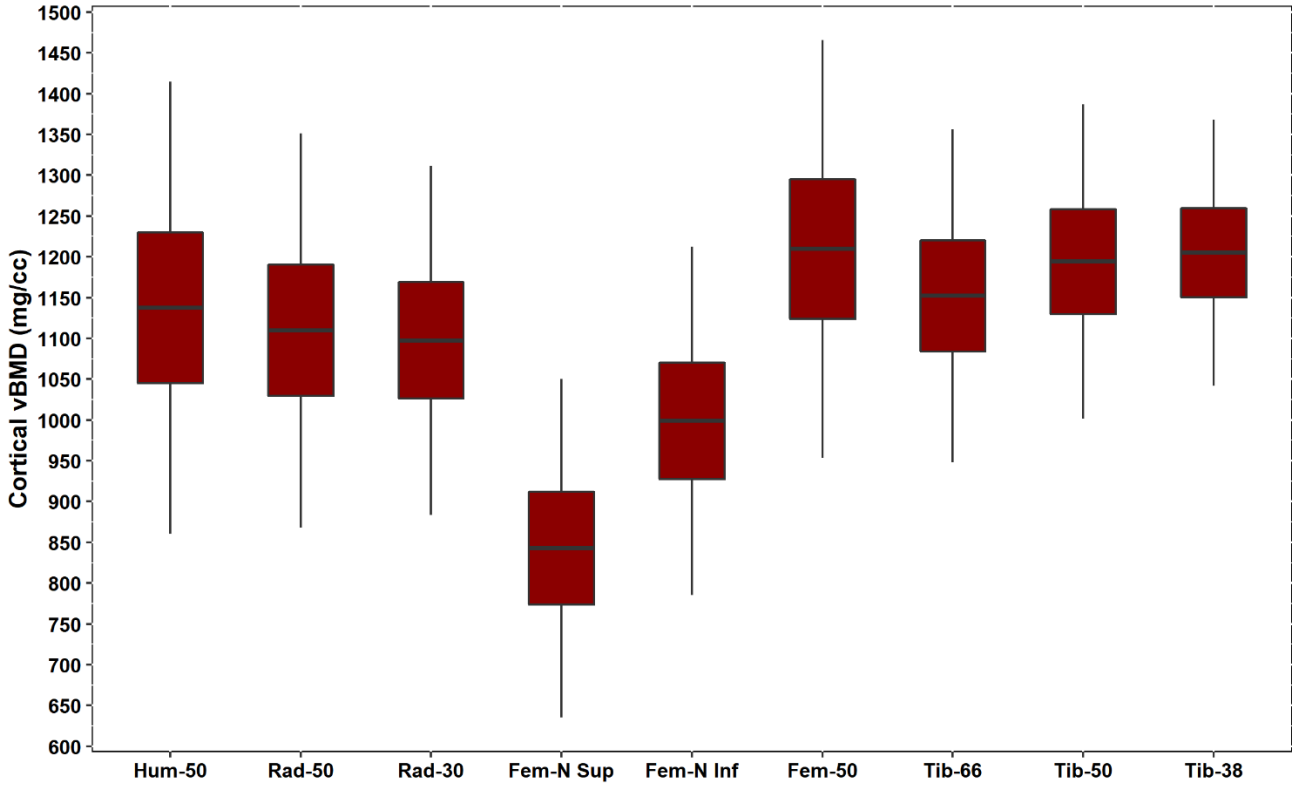

Fig. 5. Boxplot of Cortical bone vBMD per skeletal site. Box: ± 1 SD from mean. Whiskers: ± 3 SD from mean.

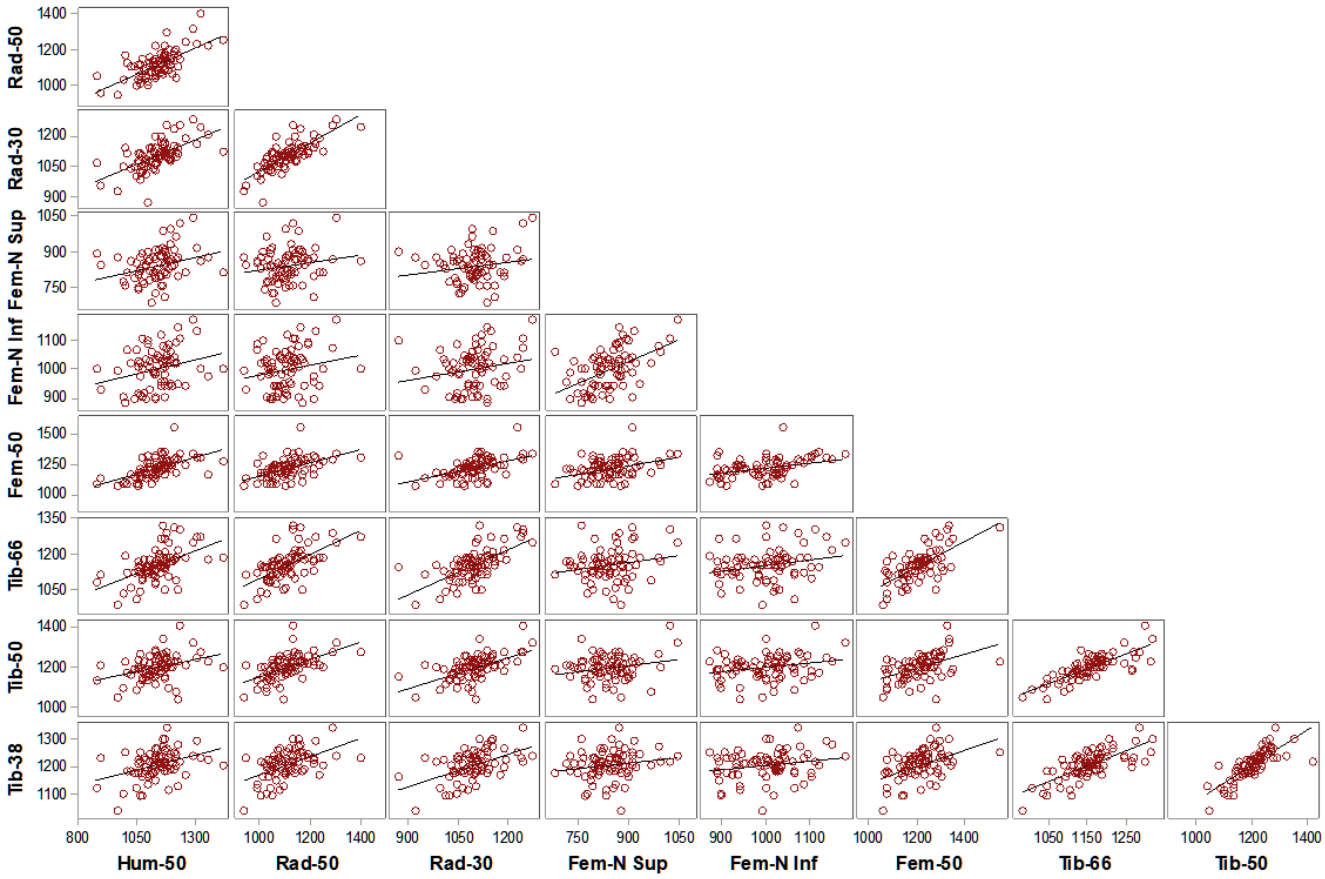

Fig. 6. Scatterplot matrix of Cortical bone vBMD (mg/cc) per skeletal site

aBMD vs vBMD

When assessing BMD calculated from DXA versus QCT, comparable sites were analyzed between the two imaging methodologies (Table V, Fig. 9). Weak positive correlations were found between aBMD and vBMD of the 2nd-4th lumbar vertebrae (R= 0.461, p<0.001) as well as at the radial diaphysis (R= 0.354, p=0.003). However, no relationships were observed in the femoral neck (R=0.035, p=0.767) or the distal radius (R=0.240, p=0.050). Further analyses demonstrated lumbar aBMD could significantly predict and explain 21.3% of variation in lumbar vBMD (p<0.001). Additionally, aBMD quantified from the radial diaphysis explained 12.6% of variation in vBMD at the comparable radius site (p=0.003).

TABLE V
PEARSON CORRELATION (R) AND LINEAR REGRESSION (R^2) RESULTS OF DXA ABMD AND QCT VBMD

DXA Sites	QCT Sites	N	R	R^2	p-value*
L2-L4	*L2-L4 Total*	76	0.461	21.3%	**<0.001**
Fem-N	*Fem-N Total*	75	0.035	0.1%	0.767
Rad-UD	*Rad-4 Total*	67	0.240	5.8%	0.050
Rad-33	*Rad-30 Ct*	67	0.354	12.6%	**0.003**

Bold= statistically significant. *p-value displayed is for correlation *and* regression.

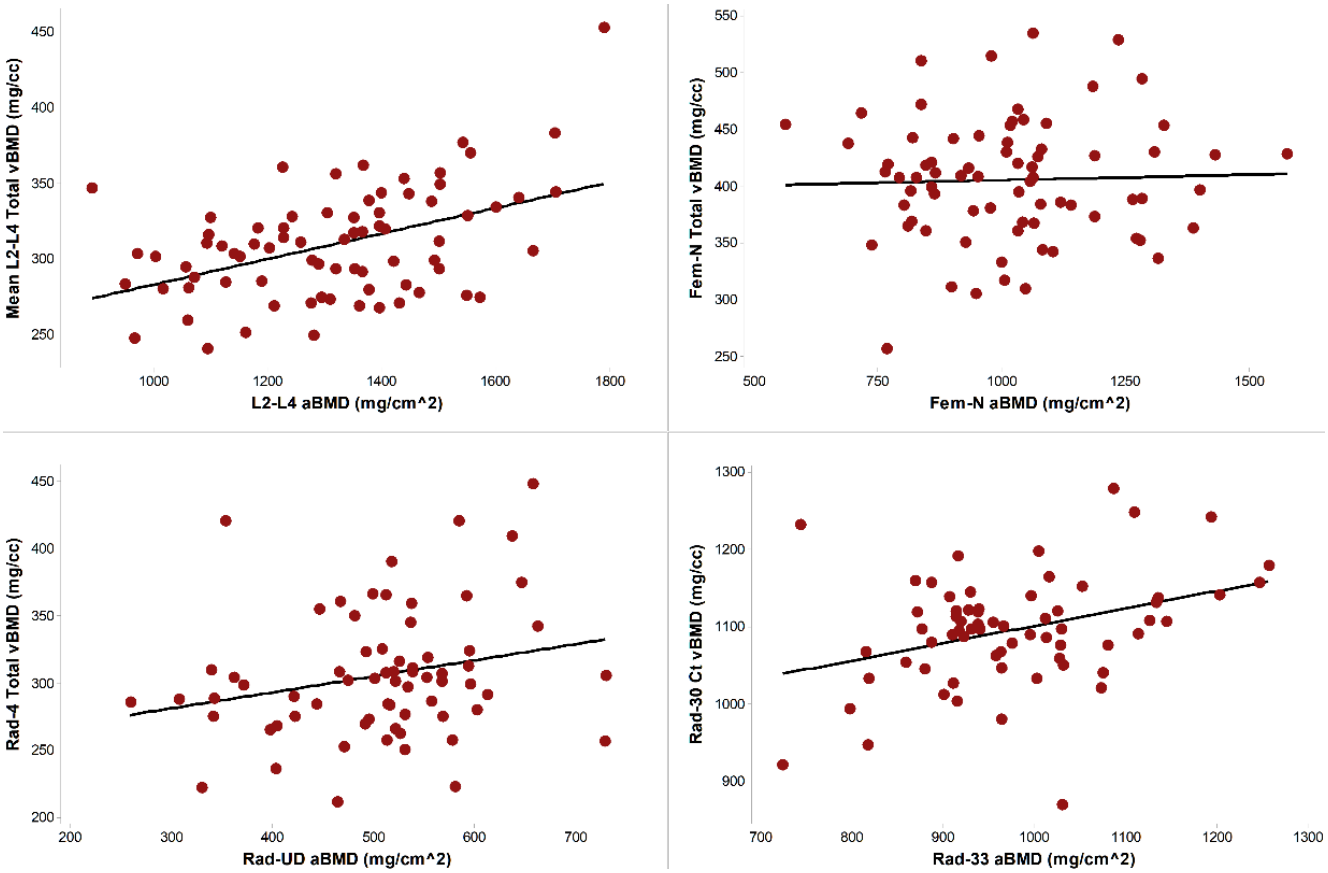

Fig. 7. Scatterplots of DXA aBMD (x-axis) and QCT vBMD (y-axis) demonstrating weak relationships between comparable skeletal sites

IV. DISCUSSION

Assessing bone quality and skeletal health is essential to understanding the complex nature of human injury and the accurate identification of at-risk populations. Results from this study's scoping review demonstrated that the methods and application of bone quality assessment in injury biomechanics literature is inconsistent. Specifically, only 40.2% of experimental whole-body PMHS testing from 2000 to 2021 reported the use of DXA or

CT/QCT to assess bone quality, resulting in 59.8% of studies assessing skeletal injury without accounting for bone quality. However, of those that were classified as "*none"* for their imaging modality (n=61), 16 studies conducted QCT scans for PMHS screening (Table A.IV) but did not utilize any opportunistic assessment of BMD that may be relevant to reported injury outcomes. Only one of the seven studies that conducted QCT scans to assess BMD/bone quality reported any specifics regarding scanner technical factors (e.g. kilovoltage peak (kVp) and resolution) that have been shown to influence measured tissue density and BMD [22–24]. Additionally, none of the studies that used QCT reported their methods of BMD calculation despite evidence demonstrating that different methods of quantification influence resulting BMD values [25][26]. Due to the potential impact of inconsistencies in BMD quantification, it is essential to report acquisition parameters and methodological details to increase the efficacy of bone quality assessment and to accurately identify at-risk individuals and inform injury prediction.

As expected, DXA was the primary imaging modality of BMD/bone quality assessment utilized in the studies identified in the scoping review, which reflects clinical practice guidelines defined by the World Health Organization and the American College of Radiology [1][2][27]. However, errors inherent to DXA's methodology can influence conclusions of overall bone quality [7][8][10][17]. Thus, assumptions of global bone quality and assessing a singular skeletal site can compound these sources of error. The scoping review found that almost 70% of injurious PMHS research assessed BMD/bone quality measures from skeletal sites that were not identified or not associated with the region of interest for injuries. Further investigation was therefore essential to determine the presence/magnitude of intra-skeletal variability of BMD and the appropriateness of using non-site-specific assessments. The current study found that aBMD differed between anatomical sites and using aBMD from one site to predict another explained only relatively small amounts of variation that are likely not of any biological or biomechanical utility. Markedly, when Fem-N aBMD was compared to the 33% radius (Rad-33), the two sites were similar in magnitude yet did not demonstrate a predictable relationship to each other. These findings indicate that mineralization could be related to the differential structural adaptations of the weight-bearing femoral neck and the non-weight-bearing radial diaphysis to their local mechanical loading environments. Evidence of femoral neck BMD adapting to mechanical loading has been previously investigated [28]. Similar evidence provides supporting data in the tibia where BMD was inversely related with cross-sectional morphometric measures such as cortical section modulus [14]. These results are in support of previous research [29] and demonstrate that bone quality should be considered site-specific. Thus, global assumptions of bone quality should be made with caution including during PMHS selection as non-site-specific assessment may be misrepresentative and alter inclusion/exclusion status for a particular study.

In those cases where BMD was utilized as a targeted inclusion criterion for PMHS to ensure comparability between subjects within the testing series, more than half of the studies used a global value for categorization of bone quality. Furthermore, by homogenizing a PMHS sample using this approach, aBMD is not expected to contribute to predictions of injury outcomes, but instead is an effort in normalization of the sample. Given the extreme variations in vBMD and lack of relationships in aBMD between sites throughout the body demonstrated in this study, this approach may be inappropriate or at least unnecessary. The scoping review found that in 7/9 of the studies that used DXA, aBMD and injury outcomes had no relationship likely due to the designation of a narrow range of aBMD values during PMHS selection. A notable exception is one study [30] that used lumbar aBMD to select an osteoporotic sample which resulted in higher numbers of observed rib fractures than comparable PMHS studies with less extreme inclusion criteria. Overall, these results are consistent with previous evidence reporting that DXA is largely unable to explain injury outcomes from PMHS testing [31], component testing [32], or real-world injury risk [33][34]. Yet, all four of the studies that discussed results of BMD/bone quality assessment from QCT found vBMD to be associated with reported injury outcomes. These findings are congruent with previous research that demonstrates the increased sensitivity of QCT to identify fracture risk compared to DXA [35–37] in a clinical population. Thus, the combination of variation in bone quality across the body and lack of relationships between aBMD and vBMD at comparable sites observed in this study indicates that assumptions of initial normalization of the PMHS sample using global aBMD may be unsuccessful.

Though this study demonstrated variation in aBMD, the two-dimensional imaging nature of DXA does not allow for detailed assessments of variability in BMD throughout the skeleton or distinct skeletal types (trabecular or cortical) that are likely key components of injury risk. QCT was used to further investigate discrepancies in skeletal mineralization across the body. Trabecular (Tb) bone vBMD varied throughout the skeleton, especially between

sites with different habitual loading environments (e.g., distal radius and calcaneus). Similar to these results, [12] demonstrated variation in Tb vBMD between lumbar spine, distal tibia, distal radius, and calcaneus sites. In contrast to findings from this study, [12] reported values of Fem-N Tb vBMD that were lower than other anatomical sites. As the density of bone marrow adipose tissue is substantially lower than skeletal tissue, this discrepancy is likely a result of measuring vBMD from trabecular bone without methods to exclude bone marrow adipose tissue, which artificially lowers BMD [17][18]. In general, results from the current study found that Tb vBMD from one site was able to predict another but only explained small amounts of variation between sites of different bones. These findings are indicative that assumptions of homogenous Tb bone quality likely have little utility to predict or explain injury results particularly across anatomical sites.

When including Cortical vBMD with Trabecular vBMD to create Total vBMD, larger differences were found across most sites. Compared to Tb regressions, an overall decrease in R^2 values was observed when using Total vBMD from one site to predict another (e.g., femoral neck Total vBMD). These results align with previous research in the femoral neck, where cortical (Ct) bone adapts to its loading environment differently than Tb bone [37][39] and suggests that measures that include cortical BMD (i.e., Total BMD) may better represent localized bone strength. Additionally, these findings are consistent with research [39][40] that indicates the critical role of cortical bone in responding to mechanical loading and resisting fracture compared to trabecular bone alone. Examining the contribution of Ct bone to Total vBMD in the Fem-N and the calcaneus indicated a larger average increase of vBMD compared to other sites that is likely attributable to differences in cortical bone (Fig.A.1). The drastic increase in density from calcaneal Tb to Total vBMD may be representative of previous findings which demonstrated increased equivalent stress in the calcaneus compared to the distal tibia using finite element (FE) models [41]. Additionally, [41] presented lower stresses in the distal tibia compared to the distal tibial diaphysis, which may explain results from this study that found a minimal increase from Tb to Total vBMD in the distal tibia. Results from an FE study, [42] reported variable micro-strain throughout the femoral neck due to its unique off-axis loading suggesting that the notable increase in femoral neck Total vBMD may also be influenced by this loading. Overall, the results from this study demonstrate intra-skeletal variability that differs by skeletal element *and* the importance of considering the relative contributions of both cortical and trabecular bone.

In addition to differences across anatomical regions, cortical vBMD significantly varied within skeletal elements. Specifically, the inferior cortex of the femoral neck demonstrated significantly higher vBMD compared to the superior cortex, similar to previous findings [43], and is likely attributed to the functional adaptation of the cortices *within* the femoral neck. Further, previous research [44] has demonstrated that femoral neck fractures were associated with failure of the superior cortex, indicating that individually assessing BMD/bone quality in the femoral neck cortices may aid in the explanation of injury outcomes from PMHS testing specific to this region. Similar differences were found within the tibia where vBMD increased from the proximal (66%) to distal (38%) diaphysis consistent with findings from [14]. Although tibia morphometrics were not quantified in this study, [14] also found that vBMD was inversely related to section modulus, and results from [45] further indicate that mineralization in the distal tibia (22.5 mm from the end plate) is influenced by mechanical loading. These data suggest an important link between the adaptation of geometric properties and mineralization of bone, which, considered together, may enhance the utility of BMD/bone quality assessments for injury risk prediction in experimental testing.

The independent examination of BMD using DXA or QCT provided insight into the extensive variability of mineralization throughout the human body. However, both methods of bone quality assessment (DXA/QCT) are differentially associated with their ability to predict injury and fracture risk. Therefore, it was prudent to cross-examine measures of BMD at comparable sites to determine if DXA was representative of the data collected from QCT. Results from this study identified weak relationships between BMD quantified from the same individuals at the same anatomical sites using DXA and QCT. The discrepancies between DXA and QCT are likely a result of the limited two-dimensional assessment of DXA where superimposed anatomy skews measures of BMD [6][46] and inaccurately depicts fracture risk compared to QCT [37]. Notably, the lack of relationship between aBMD and vBMD at the femoral neck and at the distal radius, common sites for clinical bone quality assessment, may provide different conclusions of fracture risk when using DXA versus QCT. These results suggest that bone quality measured through DXA is not only capturing different data than more discriminant QCT methods, but it is also unable to successfully predict injury as QCT provides increased sensitivity of bone quality.

This study has presented evidence that should be considered when assessing bone quality for experimental

testing in injury biomechanics, but there are limitations that should be discussed. First, this study conducted an introductory scoping review that was limited to selected sources and whole-body PMHS testing, which may not include all relevant studies. Future research should conduct a systematic review to further investigate these findings on a larger scale. By excluding component PMHS testing, the entirety of imaging assessments of bone quality that are conducted in the field of injury biomechanics are not included here. However, as the aims of this study were to inform methods of whole-body PMHS bone quality assessment and identify variability of BMD throughout the body, future investigations into experimental PMHS component testing should follow similar site/modality-specific recommendations. The sample in this study consisted only of male PMHS, which does not account for the influence of sex on the variability of BMD throughout the body which should be quantified in next steps. Though PMHS from a large age range were included, the effects of age on the variability in BMD within the body were not addressed in this research and should be studied in the future. Overall, these results demonstrated substantial evidence of variability in the methods and utilization of bone quality assessments, as well as variations in BMD throughout the body that should be considered. Without approaches that standardize methods of bone quality assessment, these factors may influence the utility of BMD to assess and explain injury, limit the comparability of data between studies, and potentially hinder efforts to relate injury risk identifiers to real-world populations.

V. CONCLUSIONS

The explanation and prediction of skeletal injury in experimental PMHS studies is potentially limited by the differential use of bone quality assessment, especially DXA. Results identified that non-site-specific assessments of BMD may further skew conclusions attempting to predict and explain skeletal injury. Despite the variability between previously published experimental PMHS studies, new data from this study demonstrated that a single skeletal element *does not* represent global bone quality and disregards the complexity of intra-skeletal and intra-element variation. Furthermore, BMD quantified using DXA provides dissimilar indications of bone quality compared to QCT. Specifically, DXA is unable to capture BMD without inherent methodological errors that skew resulting assessments of bone quality. The accurate assessment of skeletal health is therefore essential to the field of injury biomechanics and necessitates standardized approaches of site-specific bone quality assessment using QCT. Methods of assessment should then account for the variability in BMD to ensure comparability between studies and enhance explanations of injury patterns and severity in PMHS biomechanical testing.

VI. ACKNOWLEDGEMENTS

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VIII. APPENDIX

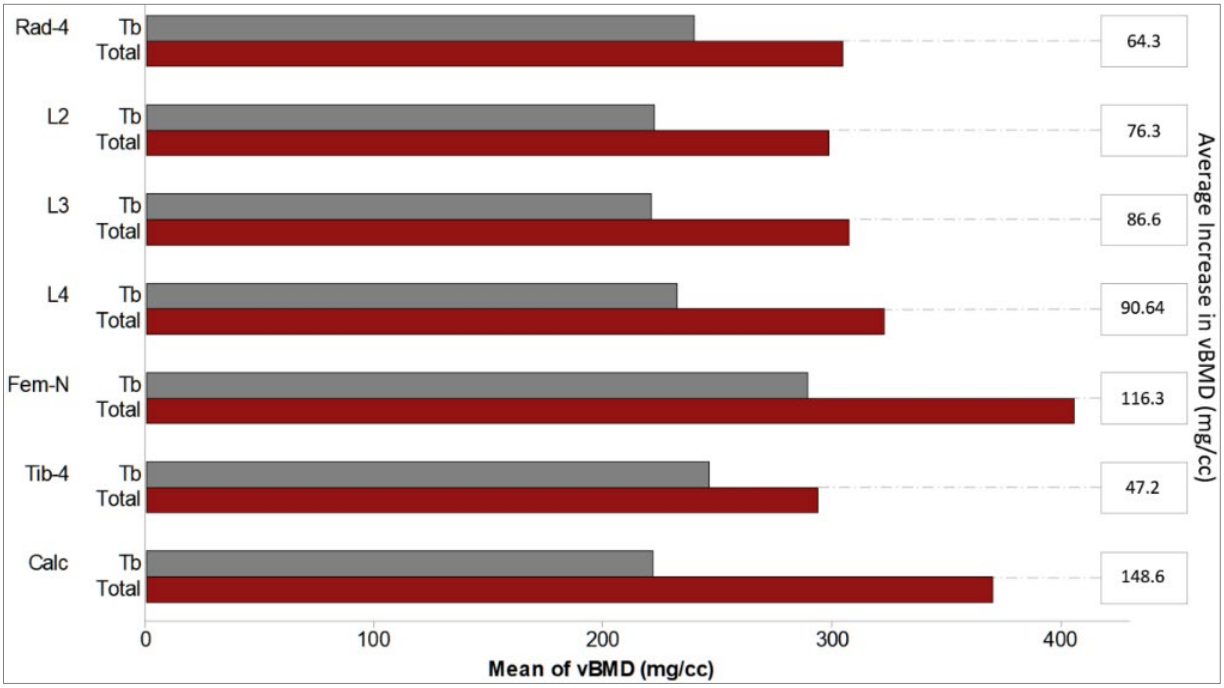

Fig.A.1. Bar chart of the relative contribution of vBMD in Tb and Total sites

TABLE A.I
DESCRIPTIVE STATISTICS OF aBMD*

Skeletal Site	Mean ± Standard Deviation	Minimum	Maximum
L2-L4	1315.9 ± 198.2	891.0	1790.0
Fem-N	1015.0 ± 195.9	563.0	1577.0
Rad-UD	506.8 ± 96.8	259.0	730.0
Rad-33	978.0 ± 113.0	723.0	1257

*aBMD(mg/cm^2)

TABLE A.II
DESCRIPTIVE STATISTICS OF TRABECULAR AND TOTAL vBMD*

Skeletal Site	Mean ± Standard Deviation	Minimum	Maximum
Rad-4 Tb	240.5 ± 43.1	159.8	383.6
Rad-4 Total	304.8 ± 47.4	211.9	448.1
L2 Tb	222.7 ± 36.3	165.0	329.9
L2 Total	299.0 ± 41.6	223.5	467.4
L3 Tb	221.2 ± 31.4	158.8	296.7
L3 Total	307.7 ± 37.5	243.9	419.7
L4 Tb	232.2 ± 31.8	174.0	341.6
L4 Total	322.8 ± 40.1	255.0	471.0
Fem-N Tb	289.5 ± 44.0	192.2	409.4
Fem-N Total	405.8 ± 53.2	256.6	534.5
Tib-4 Tb	246.6 ± 39.8	172.0	373.0
Tib-4 Total	293.8 ± 45.6	198.6	419.7
Calc Tb	222.2 ± 31.5	165.3	307.8
Calc Total	370.8 ± 50.6	275.4	527.7
L2-L4 Total	309.8 ± 36.2	240.8	452.7

*vBMD(mg/cm^3)

TABLE A.III
DESCRIPTIVE STATISTICS OF CORTICAL vBMD*

Skeletal Site	Mean ± Standard Deviation	Minimum	Maximum
Hum-50 Ct	1137.4 ± 92.5	870.4	1422.9
Rad-50 Ct	1109.9 ± 80.6	938.0	1400.7
Rad-30 Ct	1097.5 ± 71.3	896.3	1278.9
Fem-N Inf Ct	998.9 ± 71.2	871.8	1177.8
Fem-N Sup Ct	842.6 ± 69.2	682.3	1046.4
Fem-50 Ct	1209.6 ± 85.4	1052.7	1548.8
Tib-66 Ct	1152.2 ± 68.0	978.5	1314.9
Tib-50 Ct	1194.1 ± 64.2	1033.1	1410.8
Tib-38 Ct	1205.0 ± 54.4	1028.7	1345.2

*vBMD(mg/cm^3)

TABLE A.IV
SCOPING REVIEW SUMMARY

First Author Last Name	Year	DOI	Source Name	What is the reported imaging method used in the study? *DXA, CT, DXA & CT, None*	What was bone quality data (BMD and/or T/Z-scores) used to assess? *Selection criteria, Injury outcomes, Both, None*	Does reported bone quality data assess the same anatomical region of injury(ies)? *Yes, No, Both, Region Not Reported*	Are the injury results from PMHS testing supported by bone quality data? *Yes, No, Not Discussed*	Additional Notes
Acosta	2016	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	Used CT to screen PMHS
Albert	2018	10.4271/2018-22-0001	SAE: *Stapp Car Crash Journal*	DXA	None	No	-	Bone quality data use not specified
Bailey	2003	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Selection Criteria	Region Not Reported	No	
Bailey	2015	10.1115/1.4029981	*Journal of Biomechanical Engineering*	DXA	Both	No	No	
Barnes	2019		International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	Used CT to screen PMHS
Baudrit	2014	10.4271/2014-22-0004	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Bolte	2003	10.4271/2003-22-0003	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Chen	2018	10.1080/15389588.2018.1450979	*Traffic Injury Prevention*	None	-	-	-	
Compigne	2003	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Injury Outcomes	No	Not Discussed	
Cristino	2021	10.1007/s10439-021-02818-8	*Annals of Biomedical Engineering*	DXA	Selection Criteria	No	Not Discussed	CT 'Virtual' BMD was mentioned but not reported or discussed.
Danelson	2015	10.4271/2015-22-0017	SAE: *Stapp Car Crash Journal*	DXA & CT	Selection Criteria	Both	Not Discussed	DXA: lumbar CT: Tibia
Forman	2015	10.4271/2015-22-0016	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	No	Not Discussed	
Forman	2013	10.4271/2013-22-0014	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	No	Not Discussed	
Forman	2015	10.1016/j.jbiomech.2015.06.035	*Journal of Biomechanics*	DXA	Selection Criteria	No	Not Discussed	

TABLE A.IV
SCOPING REVIEW SUMMARY

First Author Last Name	Year	DOI	Source Name	What is the reported imaging method used in the study? *DXA, CT, DXA & CT, None*	What was bone quality data (BMD and/or T/Z-scores) used to assess? *Selection criteria, Injury outcomes, Both, None*	Does reported bone quality data assess the same anatomical region of injury(ies)? *Yes, No, Both, Region Not Reported*	Are the injury results from PMHS testing supported by bone quality data? *Yes, No, Not Discussed*	Additional Notes
Forman	2005	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Forman	2009	10.4271/2009-22-0002	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Forman	2006	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Hallman	2010	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Howes	2012	10.4271/2012-22-0001	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Howes	2015	10.4271/2015-22-0009	*SAE: Stapp Car Crash Journal*	None	-	-	-	
Humm	2018	10.1080/15389588.2018.1498973	*Traffic Injury Prevention*	CT	Selection Criteria	Both	Not Discussed	
Humm	2016	10.4271/2016-22-0006	SAE: *Stapp Car Crash Journal*	CT	Selection Criteria	Both	Not Discussed	
Jin	2019	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA & CT	Injury Outcomes	No	Yes	
Kang	2018	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Selection Criteria	No	Not Discussed	
Kang	2020	10.4271/2020-22-0005	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	Both	Not Discussed	
Kang	2017	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Both	No	Yes	
Kemper	2016	10.1080/15389588.2016.1203069	*Traffic Injury Prevention*	None	-	-	-	
Kemper	2008	10.4271/2008-22-0016	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Kent	2004	10.4271/2004-22-0022	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Kent	2011	10.4271/2011-22-0007	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Kent	2009	10.4271/2009-22-0013	SAE: *Stapp Car Crash Journal*	None	-	-	-	

TABLE A.IV
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Kent	2003	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Kerrigan	2008	10.4271/2008-22-0020	SAE: *Stapp Car Crash Journal*	DXA	Both	Both	No	
Kerrigan	2009	-	Enhanced Safety of Vehicles (ESV)	None	-	-	-	Used CT to screen PMHS
Kerrigan	2005	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	Used CT to screen PMHS
Kuppa	2003	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lebarbe	2013	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Lebarbe	2016	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lebarbe	2020	10.4271/2020-22-0006	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lebarbe	2005	10.4271/2005-22-0015	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lebarbe	2018	10.4271/2018-22-0008	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lebarbe	2017	10.4271/2017-22-0002	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Leport	2011	10.4271/2011-22-0009	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Leport	2007	10.4271/2007-22-0019	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Lopez-Valdes	2010	10.1080/15389580903575793	*Traffic Injury Prevention*	None	-	-	-	Used CT for post-test PMHS injury screening
Lopez-Valdes	2016	10.1080/15389588.2016.1189077	*Traffic Injury Prevention*	None	-	-	-	Used CT to screen PMHS
Lopez-Valdes	2014	10.1080/15389588.2013.817668	*Traffic Injury Prevention*	None	-	-	-	Used CT to screen PMHS
Lopez-Valdes	2018	10.1080/15389588.2018.1542139	*Traffic Injury Prevention*	None	-	-	-	Used CT to screen PMHS

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Luet	2012	10.4271/2012-22-0011	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Maltese	2002	10.4271/2002-22-0017	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Mattos	2016	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Michaelson	2008	10.4271/2008-22-0012	SAE: *Stapp Car Crash Journal*	None	-	-	-	Bone quality not described
Miller	2013	-	*SAE: Stapp Car Crash Journal*	None	-	-	-	
Ott	2020	10.1115/1.4046638	*Journal of Biomechanical Engineering*	DXA	Selection Criteria	Both	Not Discussed	
Ott	2021	10.1007/s10439-020-02656-0	*Annals of Biomedical Engineering*	DXA	Selection Criteria	Both	Not Discussed	
Paas	2012	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Perez-Rapela	2021	10.1007/s10439-020-02614-w	*Annals of Biomedical Engineering*	DXA	Selection Criteria	No	No	
Perez-Rapela	2019	10.4271/2019-22-0004	SAE: *Stapp Car Crash Journal*	DXA & CT	Injury Outcomes	No	Yes	Only 1 PMHS assessed with CT
Petit	2015	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Petit	2019	10.4271/2019-22-0005	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Pietsch	2016	10.4271/2016-22-0009	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	No	Not Discussed	
Pintar	2010	10.4271/2010-22-0008	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Ramachandra	2016	10.4271/2016-22-0004	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	Region Not Reported	Not Discussed	Skeletal injuries reported, but not study focus
Rhule	2011	10.4271/2011-22-0011	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	No	Not Discussed	
Rhule	2014	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Selection Criteria	No	Not Discussed	

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Richardson	2020	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Injury Outcomes	Region Not Reported	Not Discussed	
Richardson	2020	10.4271/2020-22-0004	*SAE: Stapp Car Crash Journal*	DXA	Both	No	No	
Richardson	2020	10.1080/15389588.2020.1837365	*Traffic Injury Prevention*	DXA	Selection Criteria	Both	Not Discussed	
Riley	2012	10.1080/15389588.2011.637251	*Traffic Injury Prevention*	None	-	-	-	
Roberts	2015	-	Enhanced Safety of Vehicles (ESV)	DXA	Selection Criteria	Region Not Reported	Not Discussed	
Rouhana	2006	10.4271/2006-22-0012	*SAE: Stapp Car Crash Journal*	None	-	-	-	
Rupp	2021	10.1007/s10439-021-02803-1	*Annals of Biomedical Engineering*	DXA	Selection Criteria	Both	Not Discussed	
Salzar	2013	10.1080/15389588.2012.692223	*Traffic Injury Prevention*	None	-	-	-	
Serre	2006	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Serre	2019	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	Evaluation of bone quality not described
Shaw	2017	10.1080/15389588.2016.1193599	*Traffic Injury Prevention*	DXA	Injury Outcomes	No	No	
Shaw	2014	10.1080/15389588.2013.792109	*Traffic Injury Prevention*	DXA	Injury Outcomes	No	No	
Shaw	2006	10.4271/2006-22-0007	SAE: *Stapp Car Crash Journal*	DXA	Selection Criteria	No	Not Discussed	
Shaw	2009	10.4271/2009-22-0001	SAE: *Stapp Car Crash Journal*	None	-	-	-	Used CT to screen PMHS
Sherman	2021	10.1007/s10439-021-02753-8	*Annals of Biomedical Engineering*	DXA	Both	Both	Not Discussed	
Shurtz	2018	10.4271/2018-01-0542	SAE Technical Reports	DXA	Selection Criteria	No	Not Discussed	

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Shurtz	2017	10.1007/s10439-017-1895-4	*Annals of Biomedical Engineering*	DXA	Selection Criteria	No	Not Discussed	
Snedeker	2006	10.1016/j.jbiomech.2005.09.008	*Journal of Biomechanics*	CT	Both	Yes	Yes	
Somasundaram	2021	10.1016/j.jmbbm.2020.104271	*Journal of Mechanical Behavior and Biomedical Materials*	DXA	Both	Yes	No	
Song	2017	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	Used CT to screen PMHS
Subit	2008	-	International Research Council on Biomechanics of Injury (IRCOBI)	DXA	Both	Both	No	
Sundararajan	2011	10.4271/2011-22-0008	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Trossielle	2009	10.4271/2009-22-0014	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Trossielle	2008	10.4271/2008-22-0009	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Trossielle	2019	10.4271/2019-22-0012	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Trossielle	2018	10.4271/2018-22-0003	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Untaroiu	2011	10.4271/2007-22-0018	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Uriot	2015	10.4271/2015-22-0008	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Vezin	2002	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Wiechel	2006	10.4271/2006-01-0674	SAE Technical Reports	DXA	Both	Region Not Reported	Yes	Imaging method not described but aBMD reported
Wood	2014	-	SAE: *Stapp Car Crash Journal*	CT	Injury Outcomes	No	Yes	
Yoganandan	2014	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	

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Yoganandan	2012	-	SAE: *Stapp Car Crash Journal*	None	-	-	-	
Yoganandan	2007	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Yoganandan	2008	-	International Research Council on Biomechanics of Injury (IRCOBI)	None	-	-	-	
Yoganandan	2015	10.1080/15389588.2015.1062887	*Traffic Injury Prevention*	None	-	-	-	
Zaseck	2019	-	SAE: *Stapp Car Crash Journal*	DXA	Both	Both	Not Discussed	

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