JSES International 8 (2024) 1102–1109

Contents lists available at ScienceDirect

JSES International

journal homepage: www.jsesinternational.org

Radiologic anatomic study of the humeral medullary canal

Jason N. Chen, BA[a], Caleb Gottlich, MD[b], Livia Frost, BS[a], Kyla A. Petrie, MD[a], Duke Appiah, PhD[c], Justin Harder, BS[b], Evan J. Hernandez, BS[b], Tammam Hanna, MD[b], Brendan MacKay, MD[b,*]

[a]School of Medicine, Texas Tech University Health Sciences Center, Lubbock, TX, USA
[b]Department of Orthopaedic Surgery, Texas Tech University Health Sciences Center, Lubbock, TX, USA
[c]Department of Public Health, Texas Tech University Health Sciences Center, Lubbock, TX, USA

A R T I C L E I N F O

Keywords:
Humeral canal
Anatomy
Supracondylar fossa
Humerus
Humeral shaft
Fractures

Level of evidence: Anatomy Study; Imaging

Hypothesis/Background: Patient-specific implants have become an increasingly researched area to improve surgical outcomes. Patient-specific implants have been suggested to provide advantages for better implant alignment and thus improve surgical outcomes. One such area for application is in the use of intramedullary nails for humeral fracture stabilization. However, the anatomy of the canal is not well defined, especially in a larger scale demographic study.
Methods: In this observational cross-sectional study, axial computed tomography scans of 150 humeri were used to measure the cortical thickness and canal width in both coronal and sagittal orientations. Measurements were made at 7 evenly spaced levels along the humerus from the surgical neck to the point immediately superior to the supracondylar ridge. X-rays were used to measure the valgus, recurvatum, and procurvatum angles, along with their associated locations. Demographic data recorded included age, gender, body mass index (BMI), race, and ethnicity.
Results: The mean coronal canal widths decreased inferiorly from the surgical neck to midshaft before increasing to the supracondylar fossa. Mean sagittal widths decreased along the complete course of the canal. The ratio of coronal to sagittal canal widths decreased from 1.09 at level 1 to 0.83 at level 5 before increasing to 1.30 at level 7. Females had significantly smaller canal widths and cortex thicknesses in both the sagittal and coronal planes throughout the course of the canal. There were no significant differences in canal widths among ethnicities. Age was positively correlated with the canal width in the coronal and sagittal orientations but was negatively correlated with cortical thickness in all 7 levels. BMI was not significantly correlated with canal width.
Conclusion/Discussion: The data included in this study may be used to determine standard widths and measurements of the humerus. However, there are notable patterns or differences in the shape of the medullary canal of the humerus between subgroups. This study is the first to conduct a larger scale demographic investigation comparing the humeral canal characteristics among sex, ethnicity, age, and BMI. These data may serve as a platform to further investigate the course of the medullary canal.

Fractures of the humeral shaft account for about 3% of all adult fractures[5], and 60% of all humeral fractures occur in the middle-third of the humerus. The treatment algorithm for such fractures is variable depending on the type and severity of the fracture. These algorithms have historically included nonoperative techniques such as compressive functional bracing using a Sarmiento brace.[16,23] However, open fractures, neurovascular injury, pathological fractures, intra-articular extension, bilateral humeral fractures, and failure of conservative treatment are indications that surgical intervention should be discussed.[29] The 2 most widely used surgical techniques include plate osteosynthesis and intramedullary nailing.[37]

Open reduction internal fixation techniques using compression plating were created to achieve fixation of long bones when conservative bracing was unsuccessful.[32] Plate osteosynthesis became the gold standard of humeral fracture fixation, and while it yields

This manuscript was exempt from formal review by the Institutional Review Board (IRB #: L22-001).
All work was performed at the Texas Tech University Health Sciences Center.
*Corresponding author: Brendan MacKay, MD, Department of Orthopaedic Surgery, Texas Tech University Health Sciences Center, 808 Joliet Avenue, Suite 310, Lubbock, TX 79415, USA.
E-mail address: Brendan.j.mackay@ttuhsc.edu (B. MacKay).

https://doi.org/10.1016/j.jseint.2024.05.004

high union rates,[3,9,33,35] compression plating requires direct visualization and operation at the fracture site. This increases the risks of infection, radial nerve injury, blood loss, and periosteal blood supply disruption.[6,13,18,33] As a result, surgical treatment and stabilization of humeral diaphyseal fractures have evolved over the years to include other potential techniques such as nailing.[33]

Stabilization of the humerus may be achieved internally through the medullary canal using an intramedullary nail (IMN). Nailing has been used by Clement and Zhao et al who have displayed data that indicate equivalency or improved outcome over nonoperative and plating techniques.[7,37] IMNs may decrease the risks that come from plating while also having theoretical benefits of smaller incisions, a less invasive procedure, fewer complications, shorter union times, preservation of biology, and allowing for early motion and stability.[8-10] Despite the potential benefits of using an IMN, surgeons have reported variable results with the procedure due to situational limitations. Intramedullary nailing has undergone several iterations of improvement; however, current designs and procedures still have complications including under-reaming of the cortex, nonunion/malunion, nail loosening, and osteonecrosis.[4,8,17,20,26,27,34,35]

There has been increased interest and use of patient-specific and anatomic-specific implants in orthopedic surgery, including total knee arthroplasties, total hip arthroplasties, and corrective osteotomies. Benefits have been reported to include better alignment accuracy, shorter operating time, and decreased average deviation of implant position.[12] However, there has not been much research regarding anatomy-specific intramedullary nailing. This may in part be due to limited current data on the medullary canal in regards to measurements of the various diameters throughout the shaft and the curvature along its course. Current literature is lacking in sample size and comparison among demographics.[11,24,30] Other studies mainly focused on angulation but with nonuniform methodologies.[1] This raises the question as to how IMNs and osteosynthesis plates were designed given the paucity of literature. While aberrancies in 3-dimensional structure have been shown to impact fracture risk in lower extremity surgery, these have not yet been characterized in the upper extremity.[2,21,25] However, it can be inferred that aberrant 3-dimensional geometry could also lead to similar intraoperative risks in the humerus.

It has been suggested that some fracture fixation failures are attributed to an incompatibility between the implant and anatomic canal shape.[10] Therefore, as these techniques were not anatomically designed, if a consistent and reproducible ratio of medullary canal diameter between proximal and distal ends can be characterized, the variability of the patient population can be better defined leading to a better anatomical understanding of the humerus.

Methods

The literature on the humeral medullary canal was reviewed, with a recent study by Schwarz et al measuring the angles and canal width at 7 equally spaced levels.[30] Given that their protocol seemed to be complete, and the basis for which they developed the protocol was well based, we adopted the previously validated method by Schwarz et al. However, their study had a limited total sample size of 30 that restricted its ability to conduct demographic comparisons as it was underpowered.[30] We hoped to validate and expand further on their findings with a larger sample size including measurements of angles of 4 curvatures of the humerus. Our investigation is the first to expand on that study, using a sufficient sample size determined by power analysis to achieve statistical significance in comparing humeral characteristics as we determined this to be the most important data.

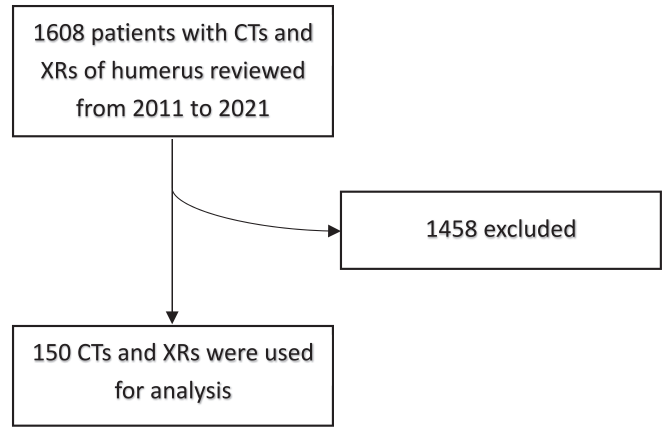

Figure 1 Flowchart showing patient selection process for study.

This study retroactively evaluated 150 humeri computed tomography (CT) scans and 150 humerus X-rays from any adult patients seen at the University Medical Center in Lubbock, Texas from 2011 to 2021. The sample size was determined based on a power analysis aimed at ensuring sufficient power to detect a specified effect size with an assumed standard deviation and alpha level of 0.05. Our biostatistician, D.A., verified the calculations, confirming that a sample size of 150 would achieve the necessary statistical power to reliably identify differences of clinical relevance in the humeral canal measurements. The Institutional Review Board of Texas Tech University Health Sciences Center in Lubbock approved this study. Patients with current or history of humeral fractures, prostheses, nailing, or tumors were excluded due to the potential of these conditions to change the measurements of the humerus from its original state. Other imaging was excluded due to poor resolution. If not falling under the previous exclusions, patients were chosen based on the clarity of their imaging regardless of their reason for needing imaging (Fig. 1).

Consistency in imaging was achieved through retrospective comparison to ensure that the orientation of the humerus on radiology was within acceptable limits. Only CT scans that had slices directly perpendicular to the long axis of the humerus were used for width measurements. All X-rays were true laterals or true anterior-posterior images for accurate and consistent angle measurements. All measurements were completed using the measurement tools within Cerner PowerChart. Axial CT scans were used to measure total humerus and medullary canal widths in the coronal and sagittal plane at 7 equally spaced levels along the humerus, from the surgical neck to the point immediately superior to the supracondylar ridge (Fig. 2). Total cortical thickness was calculated for both coronal and sagittal planes by subtracting the canal width from the total humerus width. The varus and valgus angles were measured using anterior-posterior X-rays using the Cobb angle tool within Powerchart as demonstrated in Figure 2, where the angle of intersection between 2 lines placed parallel to the canal was calculated. Lateral X-rays were used for measuring procurvatum and recurvatum angles. The apex location of each angle was marked and divided by the total humerus length to determine the proportional location of the angle apex in regards to the total humerus length. Demographic data recorded included age, gender, body mass index (BMI), race, and ethnicity. In the ethnicity category, humeri measurements from non-Hispanic Whites, Hispanics, and other (Blacks and Asians) are represented.

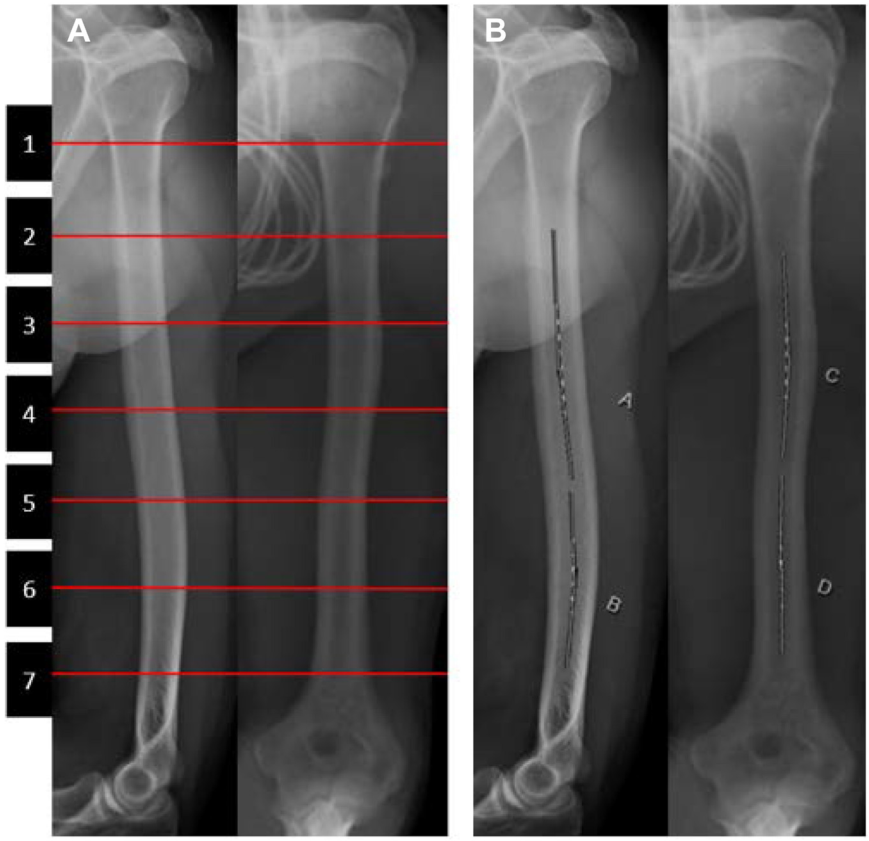

Figure 2 Lateral (*left*) and AP (*right*) of a representative humerus. (**A**) Width measurement locations are demonstrated by the markings 1-7. (**B**) Angle measurements, where *A*- procurvatum angle; *B*- recurvatum angle; *C*- varus angle; *D*- valgus angle.

Statistical analyses

Data were described using means and standard deviations. Pearson correlation coefficients were calculated to evaluate the relationship between age and BMI with cortical thickness measures. Average canal width and cortical thickness measures were compared among groups using *t*-tests and analysis of variance. Because these hypotheses were prespecified, adjustment of *P* values for multiple testing was not performed. In all analyses, statistical significance was determined with an alpha of less than 0.05 using the SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

The mean coronal canal widths decreased inferiorly from the surgical neck (20.9 mm at level 1) to approximately midshaft (10.9 mm at level 5) before increasing to the supracondylar fossa (12.5 mm at level 7, Table I). Mean sagittal canal widths decreased along the complete course of the canal, from 19.4 mm at the surgical neck to 9.7 mm at the supracondylar fossa (Table I). All coronal canal widths were statistically significantly different from each other except for levels 4 and 7, 4 and 6, and 5 and 6. All sagittal canal widths were significantly different from each other except for levels 3 and 4, as well as 5 and 6. The ratio of coronal to sagittal canal widths decreased from 1.1 at level 1 to 0.83 at level 5 before increasing to 1.3 at level 7 (Fig. 3). The mean cortical thickness in the coronal plane increased from 5.4 mm at level 1 to 9.0 mm at level 7, although levels 3 to 7 were similar in thickness (Table I). Sagittally, the cortex thickened from level 1 to 4 before thinning to level 7.

Males and females shared similar coronal canal width patterns, where the mean width decreased from the surgical neck to level 5 before increasing to the supracondylar fossa (Table II). Additionally, the mean canal widths in the sagittal orientation decreased throughout the complete course in both sexes. However, females had significantly smaller canal widths in both the sagittal and coronal planes throughout the course of the canal (Table II). The cortex of the humerus at all 7 levels, coronally and sagittally, was also significantly thinner among females than among males (Table III). There were no observed differences in canal widths among ethnicities. However, Hispanics had a significantly thinner cortex at level 7 in the coronal plane (Table III). Patients with osteopenia, osteoporosis, or osteoarthritis had a statistically significantly wider mean sagittal canal width at level 6 compared to their healthy counterparts (13.4 mm compared to 11.9 mm, $P = .019$). Patients with these conditions also had thinner coronal cortices in levels 3 to 6 and thinner sagittal cortices in levels 4 to 6 (all P values $< .05$).

The ages ranged from 19 to 92 years. Age was weakly positively correlated with canal width in the coronal orientation, where levels 5 to 7 reached significance (Table IV). Age was also positively correlated with canal width in the sagittal orientation, where levels 2 to 7 reached significance. Furthermore, increased age correlated with decreased cortical thickness in both the coronal and sagittal planes (Table V). All levels reached significance except for level 7 in the coronal plane and level 1 in the sagittal plane. No significant correlations were observed between BMI and canal widths. However, BMI was weakly positively correlated with coronal cortical thickness, reaching significance in levels 1 to 2 and levels 4 to 6 (Table V).

Table I
Mean canal width and cortical thickness measurements at each of the 7 levels in the coronal and sagittal orientations.

	Average canal width (mm)	Average total cortical thickness (mm)
Coronal level 1	20.87 ± 3.39	5.39 ± 1.48
Coronal level 2	15.35 ± 2.72	6.69 ± 1.49
Coronal level 3	13.72 ± 2.55	8.65 ± 1.97
Coronal level 4	11.73 ± 2.31	8.82 ± 2.04
Coronal level 5	10.85 ± 2.08	8.74 ± 2.00
Coronal level 6	11.14 ± 1.98	8.48 ± 1.98
Coronal level 7	12.46 ± 2.08	9.03 ± 2.58
Sagittal level 1	19.38 ± 3.68	5.85 ± 1.40
Sagittal level 2	15.81 ± 3.37	7.98 ± 1.97
Sagittal level 3	14.68 ± 3.21	8.91 ± 2.14
Sagittal level 4	14.02 ± 2.86	9.73 ± 2.10
Sagittal level 5	13.24 ± 2.34	9.45 ± 2.07
Sagittal level 6	12.05 ± 2.05	8.79 ± 1.81
Sagittal level 7	9.70 ± 1.81	8.62 ± 1.87

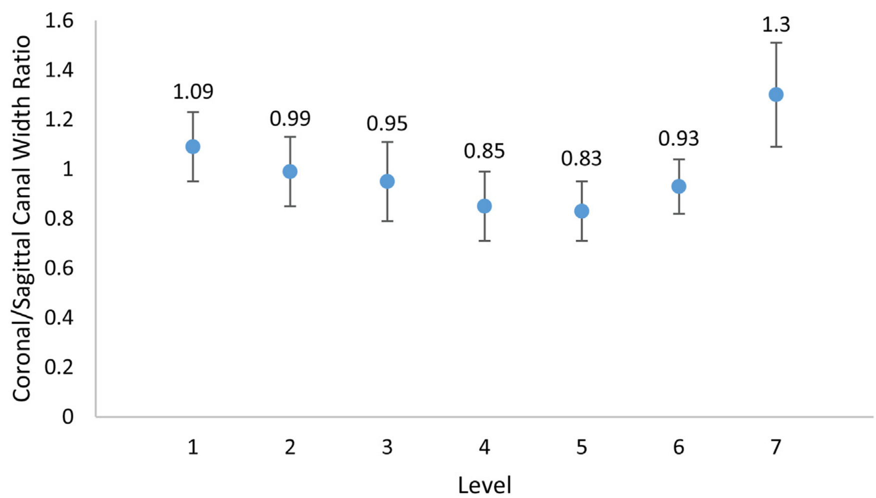

Figure 3 Mean coronal to sagittal canal width ratios at each of the 7 levels.

Table II
Gender and race differences in mean canal widths (mm) for coronal and sagittal orientations.

	Male	Female	*P* value	Non-Hispanic White	Hispanic	Other	*P* value
Coronal level 1	22.40	18.98	<.0001*	20.94	20.84	20.79	.980
Coronal level 2	16.57	13.85	<.0001*	15.60	15.13	15.35	.638
Coronal level 3	14.67	12.55	<.0001*	13.90	13.41	14.16	.399
Coronal level 4	12.72	10.51	<.0001*	11.77	11.47	12.42	.258
Coronal level 5	11.71	9.79	<.0001*	10.66	10.95	11.05	.663
Coronal level 6	11.91	10.18	<.0001*	10.82	11.19	11.86	.110
Coronal level 7	13.00	11.75	.0003*	12.34	12.46	12.76	.734
Sagittal level 1	21.26	17.06	<.0001*	19.02	19.49	20.05	.525
Sagittal level 2	17.36	13.90	<.0001*	15.59	15.66	16.88	.289
Sagittal level 3	15.85	13.25	<.0001*	14.66	14.30	15.92	.130
Sagittal level 4	14.67	13.23	.0025*	13.99	13.88	14.57	.625
Sagittal level 5	13.68	12.70	.0124*	13.21	13.16	13.56	.788
Sagittal level 6	12.63	11.34	.0001*	11.96	12.06	12.24	.859
Sagittal level 7	10.13	9.15	.0012*	9.51	9.83	9.82	.593

*Statistically significant at $\alpha < 0.05$.

Four angles were consistently observed. The mean varus, valgus, procurvatum, and recurvatum angles were 3.1 ± 1.8°, 3.3 ± 1.4°, 3.3 ± 1.7°, and 10.4 ± 2.4°, respectively (Table VI). The proportional location of the varus, valgus, procurvatum, and recurvatum angle apexes were 0.44 ± 0.04, 0.60 ± 0.04, 0.45 ± 0.04, and 0.71 ± 0.03 of the total humerus length, respectively (Table VI). There were no significant sex differences in the angles or their locations. The only significant ethnicity differences were in the location of the recurvatum apex, where Hispanics had a more superior apex compared to non-Hispanic Whites, and others (P = .042). Compared to patients with no bone conditions, patients with osteopenia, osteoporosis, or osteoarthritis had a significantly smaller mean recurvatum angle (8.9° vs. 10.5°, P = .009), with no additional differences.

The only difference observed between left and right humeri was that the procurvatum apex was more inferiorly located in the left

Table III
Gender and race differences in mean cortical thicknesses (mm).

	Male	Female	*P* value	Non-Hispanic White	Hispanic	Other	*P* value
Coronal level 1	5.61	5.12	.0463*	5.43	5.39	5.29	.932
Coronal level 2	6.98	6.34	.0103*	6.84	6.60	6.59	.625
Coronal level 3	9.17	8.03	.0005*	8.86	8.39	8.93	.339
Coronal level 4	9.59	7.86	<.0001*	9.04	8.58	8.94	.441
Coronal level 5	9.55	7.74	<.0001*	9.03	8.31	9.26	.061
Coronal level 6	9.39	7.37	<.0001*	8.78	8.10	8.85	.116
Coronal level 7	10.06	7.72	<.0001*	9.50	8.41	9.69	.027*
Sagittal level 1	6.25	5.37	.0001*	5.89	5.84	5.80	.969
Sagittal level 2	8.68	7.11	<.0001*	7.91	7.93	8.29	.730
Sagittal level 3	9.66	7.99	<.0001*	8.87	8.89	9.05	.945
Sagittal level 4	10.46	8.83	<.0001*	9.78	9.63	9.92	.840
Sagittal level 5	10.31	8.40	<.0001*	9.59	9.32	9.44	.777
Sagittal level 6	9.51	7.91	<.0001*	8.99	8.48	9.15	.184
Sagittal level 7	9.48	7.54	<.0001*	8.78	8.33	9.06	.204

*Statistically significant at $\alpha < 0.05$.

Table IV
Canal widths at each of the 7 levels correlation with age and BMI.

	Age correlation	Age correlation *P* value	BMI correlation	BMI correlation *P* value
Coronal level 1	0.01485	.8603	−0.03604	.6702
Coronal level 2	0.14507	.0839	0.00964	.9093
Coronal level 3	0.11186	.1851	0.02874	.7351
Coronal level 4	0.12955	.1230	−0.04697	.5788
Coronal level 5	0.16712	.0460*	−0.07032	.4057
Coronal level 6	0.19206	.0216*	−0.04929	.5602
Coronal level 7	0.18183	.0292*	−0.01697	.8406
Sagittal level 1	0.11576	.1686	−0.04347	.6075
Sagittal level 2	0.23612	.0045*	−0.05215	.5376
Sagittal level 3	0.32478	<.0001*	−0.07335	.3873
Sagittal level 4	0.39110	<.0001*	−0.04021	.6347
Sagittal level 5	0.36696	<.0001*	−0.05229	.5380
Sagittal level 6	0.32150	<.0001*	−0.14381	.0889
Sagittal level 7	0.20090	.0161*	−0.16376	.0515

BMI, body mass index.
*Statistically significant at $\alpha < 0.05$.

Table V
Cortical thickness at each of the 7 levels correlation with age and BMI.

	Age correlation	Age correlation *P* value	BMI correlation	BMI correlation *P* value
Coronal level 1	−0.23738	.0043*	0.23813	.0043*
Coronal level 2	−0.28952	.0005*	0.21999	.0085*
Coronal level 3	−0.26733	.0013*	0.10265	.2258
Coronal level 4	−0.39905	<.0001*	0.29391	.0004*
Coronal level 5	−0.28406	.0006*	0.19864	.0178*
Coronal level 6	−0.27262	.0010*	0.20324	.0153*
Coronal level 7	−0.13481	.1060	0.10380	.2157
Sagittal level 1	−0.10043	.2327	0.07615	.3677
Sagittal level 2	−0.34618	<.0001*	0.16065	.0562
Sagittal level 3	−0.38919	<.0001*	0.12899	.1274
Sagittal level 4	−0.34702	<.0001*	0.11390	.1771
Sagittal level 5	−0.28816	.0005*	0.10480	.2162
Sagittal level 6	−0.26632	.0014*	0.16461	.0511
Sagittal level 7	−0.19744	.0177*	0.14607	.0817

BMI, body mass index.
*Statistically significant at $\alpha < 0.05$.

humerus compared to the right (0.46 ± 0.04 vs. 0.45 ± 0.04 of the total humerus length, $P = .03$).

Discussion

Similar to findings by Drew et al and Schwarz et al, overall mean sagittal canal widths narrowed the whole length of the canal, while coronal widths narrowed before widening at the distal segment.[11,30] Mean widths were also very comparable between studies, with less than 1 mm difference at each level. The mean coronal to sagittal canal width ratios at each level reflected the changes in sagittal and coronal width along the length of the canal. Ratios steadily decreased from the surgical neck to approximately two-thirds down the canal before the increase in coronal widths at levels 6 and 7 caused the ratio to also increase. Therefore, the majority of the canal is slightly wider sagittally, except for the distal end where it is wider coronally (Fig. 4).

Table VI
The average angle measurements in degrees for males, females, non-Hispanic (NH) Whites, Hispanics, other race, and total, along with the average locations of the angle apices along the length of the canal.

Measure	Male	Female	NH White	Hispanic	Other	Total
Varus angle	3.31	2.96	2.94	3.29	3.45	3.1
Varus apex location	0.44	0.44	0.44	0.44	0.43	0.4
Valgus angle	3.33	3.25	3.17	3.34	3.73	3.3
Valgus apex location	0.6	0.6	0.6	0.6	0.59	0.6
Procurvatum angle	3.43	3.26	3.21	3.43	3.78	3.3
Procurvatum apex location	0.46	0.45	0.45	0.45	0.45	0.5
Recurvatum angle	10.67	10.04	10.54	9.95	11.56	10.3
Recurvatum apex location	0.71	0.71	0.72*	0.7*	0.73*	0.7

NH, non-Hispanic.
*Statistically significant at $\alpha < 0.05$.

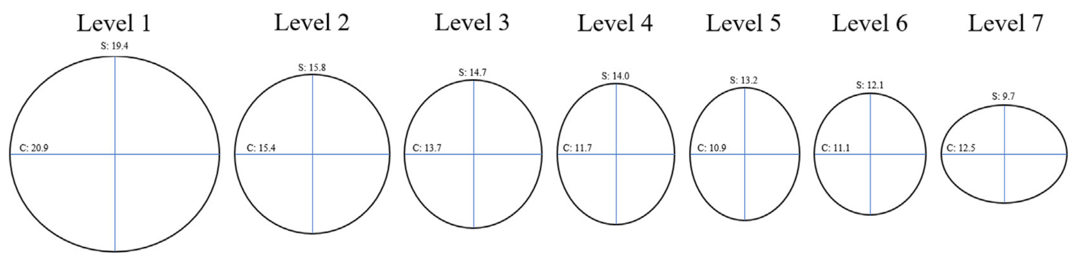

Figure 4 Scaled axial cross-sectional representations of the canal at each of the 7 levels. —— lines labeled C are in the coronal orientation and | lines labeled S are in the sagittal orientation. The lengths are scaled in relation to each other.

Overall angles measured in this study were also similar to Schwarz et al's findings. These consistent findings display promise as it denotes potential consistency in the data. Our investigation was the first to examine the location of the angles as well as the varus angle, which was seen in the majority of the study population. The varus and procurvatum apexes were at a similar location, approximately just proximal to the midshaft. The valgus angle apex was located just distal to the midshaft, while the recurvatum was even more distal, at approximately three-fourths of the total humerus length. This is also comparable with Akpinar et al, who measured recurvatum angles found to be at the distal one-third part with an average of 9° angulation.[1] These bends along the canal should be noted when inserting IMNs to avoid cortical perforation and iatrogenic fractures.[28]

There are currently no substantive studies performed comparing the intraoperative fracture rate between males and females during humerus intramedullary nailing procedures. However, the gender differences observed in this study may help explain the increased risk that females have for intraoperative fractures in the humeral shaft during upper extremity operations like shoulder arthroplasties and humeral head replacements.[31,36] Compared to their male counterparts, females had significantly smaller canal widths and thinner cortices along the entire canal, with no differences in the angles or their locations (Tables II and III). Although it has been shown that females have thinner cortices than males, this study is the first to report significant gender differences in the canal width over its entire course.[30] Females contribute to the majority of both proximal and shaft fractures of the humerus,[15] emphasizing the importance to address the high prevalence of intraoperative fractures in this large demographic. Due to the narrower canal and thinner cortex in females, customized IMNs based on gender and specific patients' measurements would likely reduce the discrepancy of intraoperative fractures between males and females.

Hispanics were the only race/ethnicity group with a significant difference in the cortex width compared to non-Hispanic Whites, and other races. Hispanics were found to have a significantly thinner cortex at level 7 in the coronal plane (Table III). Also, in regards to the location of the recurvatum apex, Hispanics were the only ethnicity with a significant difference, with a more superior apex compared to all other ethnicities. In previous studies, the anatomical differences between ethnic groups have been limited to Arab, Asian, African American, and Caucasian populations with small sample sizes.[19,24] This study provides insight into the anatomical morphology of the Hispanic population. The differences between measurements in this study may also explain the lower fracture rate found in Hispanic populations despite having similar bone density to Caucasian populations.[14] While the study population mirrors the population of West Texas, the external validity of this study may not reflect on a wider population outside of the Southwestern United States. Inconsistencies in rates of intraoperative fracture due to IMN procedures between different races and ethnicities are important to address to achieve better surgical outcomes.

Older patients tended to have wider canals in both orientations (Table IV) and smaller cortical thickness in most levels (Table V). This is in contrast to previous findings of no significant correlations between age and medullary canal width.[30] The findings in this study align with the knowledge that the aging process contributes osteopenia, which leads to canal widening and cortex thinning.[22] In contrast to the previous study, the larger sample size of this study may have captured the effects of demineralization as part of natural aging. Due to the high prevalence of humeral fractures in older patients, age is an additional factor that should be considered when IMN operations are performed.[15]

Limitations

While our study was conducted based on the absolute number of humeri required for statistical analysis, in an effort to extract all the potential from the data, post hoc subgroup analysis was performed. However, we acknowledge that the study is not powered statistically to make subgroup analyses and would benefit from a larger study to define whether these findings are consistent and bear out among other populations. The questions we identify based on these results may benefit by being further addressed with a larger study in which the right power required for each individual subgroup is identified. Limitations in regionality of the study having only 3 ethnic groups (Non-Hispanic White, Hispanic, and Other) represented were also noted. Additionally, we are aware that there may be slight inconsistencies in imaging, such as the tilt of the humerus when the image was taken in both CT scans and X-rays; however, we compensated for this by excluding images that were not true anterior-posterior and laterals based on rotation of the upper extremity. In addition, this study used a cross-sectional design that limits the ability to determine causality regarding the relationship between age and bone thickness.

Future directions

Further research directions include studies that are more representative of the ethnic makeup of the population of the United States as a whole, such as seen in the national census. Other factors affecting bone composition and shape could be explored and linked to surgical complications during IMN procedures. We attempted to define the issues of bone morphology that most highly correlate with the reasons we have problems with intramedullary nailing. As these data have not been addressed previously, we believe that these findings are significant enough to affect outcomes through an IMN design change or a completely new design that would allow our study to bear out into the future. Further clinical research studies would be needed to determine if the customized IMNs result in fewer complications and intraoperative fractures and lead to improved outcomes.

Conclusion

This study's findings indicate significant demographic variations in the anatomy of the humeral medullary canal, necessitating the development of demographic-specific IMNs. By addressing these anatomical differences, we can potentially reduce the incidence of complications and intraoperative fractures, thereby enhancing the efficacy of orthopedic treatments. Our research emphasizes the critical need for personalized orthopedic solutions to improve patient outcomes.

Disclaimers:

Funding: No funding was disclosed by the authors.
Conflicts of interest: Each author certifies that there are no funding or commercial associations (consultancies, stock ownership, equity interest, etc.) that might pose a conflict of interest in connection with the submitted article related to the author or any immediate family members. A U.S. Provisional Patent Application (63/444,816) was filed on February 10, 2023 and is currently pending.

References

1. Akpinar F, Aydinlioglu A, Tosun N, Dogan A, Tuncay I, Unal O. A morphometric study on the humerus for intramedullary fixation. Tohoku J Exp Med 2003;199:35-42. https://doi.org/10.1620/tjem.199.35.
2. Arnone JC, Crist BD, Ward CV, El-Gizawy AS, Pashuck T, Della Rocca GJ. Variability of human femoral geometry and its implications on nail design. Injury 2021;52:109-16. https://doi.org/10.1016/j.injury.2020.09.028.
3. Bell MJ, Beauchamp CG, Kellam JK, McMurtry RY. The results of plating humeral shaft fractures in patients with multiple injuries. The Sunnybrook experience. J Bone Joint Surg Br 1985;67:293-6.
4. Bhandari M, Devereaux PJ, McKee MD, Schemitsch EH. Compression plating versus intramedullary nailing of humeral shaft fractures–a meta-analysis. Acta Orthop 2006;77:279-84. https://doi.org/10.1080/17453670610046037.
5. Bounds EJ, Frane N, Kok SJ. Humeral shaft fractures. Treasure Island (FL): StatPearls; 2022.
6. Changulani M, Jain UK, Keswani T. Comparison of the use of the humerus intramedullary nail and dynamic compression plate for the management of diaphyseal fractures of the humerus. A randomised controlled study. Int Orthop 2007;31:391-5. https://doi.org/10.1007/s00264-006-0200-1.
7. Clement ND. Management of humeral shaft fractures; non-operative versus operative. Arch Trauma Res 2015;4:e28013. https://doi.org/10.5812/atr.28013v2.
8. Cox MA, Dolan M, Synnott K, McElwain JP. Closed interlocking nailing of humeral shaft fractures with the Russell-Taylor nail. J Orthop Trauma 2000;14:349-53.
9. Dabezies EJ, Banta CJ 2nd, Murphy CP, d'Ambrosia RD. Plate fixation of the humeral shaft for acute fractures, with and without radial nerve injuries. J Orthop Trauma 1992;6:10-3.
10. Dilisio MF, Nowinski RJ, Hatzidakis AM, Fehringer EV. Intramedullary nailing of the proximal humerus: evolution, technique, and results. J Shoulder Elbow Surg 2016;25:e130-8. https://doi.org/10.1016/j.jse.2015.11.016.
11. Drew AJ, Tashjian RZ, Henninger HB, Bachus KN. Sex and laterality differences in medullary humerus morphology. Anat Rec (Hoboken) 2019;302:1709-17. https://doi.org/10.1002/ar.24138.
12. Haglin JM, Eltorai AE, Gil JA, Marcaccio SE, Botero-Hincapie J, Daniels AH. Patient-specific orthopaedic implants. Orthop Surg 2016;8:417-24. https://doi.org/10.1111/os.12282.
13. Heim D, Herkert F, Hess P, Regazzoni P. Surgical treatment of humeral shaft fractures–the Basel experience. J Trauma 1993;35:226-32.
14. Jorgetti V, dos Reis LM, Ott SM. Ethnic differences in bone and mineral metabolism in healthy people and patients with CKD. Kidney Int 2014;85:1283-9. https://doi.org/10.1038/ki.2013.443.
15. Kim SH, Szabo RM, Marder RA. Epidemiology of humerus fractures in the United States: nationwide emergency department sample, 2008. Arthritis Care Res (Hoboken) 2012;64:407-14. https://doi.org/10.1002/acr.21563.
16. Koch PP, Gross DF, Gerber C. The results of functional (Sarmiento) bracing of humeral shaft fractures. J Shoulder Elbow Surg 2002;11:143-50. https://doi.org/10.1067/mse.2002.121634.
17. Kurup H, Hossain M, Andrew JG. Dynamic compression plating versus locked intramedullary nailing for humeral shaft fractures in adults. Cochrane Database Syst Rev 2011;6:CD005959. https://doi.org/10.1002/14651858.CD005959.pub2.
18. Lin J. Treatment of humeral shaft fractures with humeral locked nail and comparison with plate fixation. J Trauma 1998;44:859-64.
19. Mahfouz M, Abdel Fatah EE, Bowers LS, Scuderi G. Three-dimensional morphology of the knee reveals ethnic differences. Clin Orthop Relat Res 2012;470:172-85. https://doi.org/10.1007/s11999-011-2089-2.
20. McCormack RG, Brien D, Buckley RE, McKee MD, Powell J, Schemitsch EH. Fixation of fractures of the shaft of the humerus by dynamic compression plate or intramedullary nail. A prospective, randomised trial. J Bone Joint Surg Br 2000;82:336-9.
21. Miettinen SS, Makinen TJ, Kostensalo I, Makela K, Huhtala H, Kettunen JS, et al. Risk factors for intraoperative calcar fracture in cementless total hip arthroplasty. Acta Orthop 2016;87:113-9. https://doi.org/10.3109/17453674.2015.1112712.
22. Novotny SA, Warren GL, Hamrick MW. Aging and the muscle-bone relationship. Physiology (Bethesda) 2015;30:8-16. https://doi.org/10.1152/physiol.00033.2014.
23. Pencle FJ, Varacallo M. Proximal humerus fracture. Treasure Island (FL): StatPearls; 2021.
24. Pospula W, Abu Al Noor T, Roshdy T, Al Rowaih A. Radioanatomical measurements of the medullary cavity of the humerus in Kuwait: ethnic differences and clinical implications for fracture fixation. Med Princ Pract 2004;13:206-10. https://doi.org/10.1159/000078317.
25. Purudappa PP, Ramanan SP, Tripathy SK, Varatharaj S, Mounasamy V, Sambandam SN. Intra-operative fractures in primary total knee arthroplasty - a systematic review. Knee Surg Relat Res 2020;32:40. https://doi.org/10.1186/s43019-020-00054-3.
26. Putti AB, Uppin RB, Putti BB. Locked intramedullary nailing versus dynamic compression plating for humeral shaft fractures. J Orthop Surg 2009;17:139-41. https://doi.org/10.1177/230949900901700202.
27. Raghavendra S, Bhalodiya HP. Internal fixation of fractures of the shaft of the humerus by dynamic compression plate or intramedullary nail: a prospective study. Indian J Orthop 2007;41:214-8. https://doi.org/10.4103/0019-5413.33685.
28. Rommens PM, Kuechle R, Bord T, Lewens T, Engelmann R, Blum J. Humeral nailing revisited. Injury 2008;39:1319-28. https://doi.org/10.1016/j.injury.2008.01.014.
29. Sargeant HW, Farrow L, Barker S, Kumar K. Operative versus non-operative treatment of humeral shaft fractures: a systematic review. Shoulder Elbow 2020;12:229-42. https://doi.org/10.1177/1758573218825477.

30. Schwarz GM, Zak L, Hirtler L, Wozasek GE. Anatomical considerations of intramedullary humeral nailing and lengthening. J Clin Med 2020;9:806. https://doi.org/10.3390/jcm9030806.
31. Singh JA, Sperling J, Schleck C, Harmsen W, Cofield R. Periprosthetic fractures associated with primary total shoulder arthroplasty and primary humeral head replacement: a thirty-three-year study. J Bone Joint Surg Am 2012;94:1777-85. https://doi.org/10.2106/JBJS.J.01945.
32. Sonderegger J, Grob KR, Kuster MS. Dynamic plate osteosynthesis for fracture stabilization: how to do it. Orthop Rev (Pavia) 2010;2:e4. https://doi.org/10.4081/or.2010.e4.
33. Stannard JP, Harris HW, McGwin G Jr, Volgas DA, Alonso JE. Intramedullary nailing of humeral shaft fractures with a locking flexible nail. J Bone Joint Surg Am 2003;85:2103-10. https://doi.org/10.2106/00004623-200311000-00007.
34. Talmo CT, Bono JV. Preventing and managing intraoperative fractures and perforations in hip arthroplasty. Orthopedics 2005;28(9 Suppl):s1085-8. https://doi.org/10.3928/0147-7447-20050902-17.
35. Vander Griend R, Tomasin J, Ward EF. Open reduction and internal fixation of humeral shaft fractures. Results using AO plating techniques. J Bone Joint Surg Am 1986;68:430-3.
36. Wagner ER, Houdek MT, Elhassan BT, Sanchez-Sotelo J, Cofield RH, Sperling JW. What are risk factors for intraoperative humerus fractures during revision reverse shoulder arthroplasty and do they influence outcomes? Clin Orthop Relat Res 2015;473:3228-34. https://doi.org/10.1007/s11999-015-4448-x.
37. Zhao JG, Wang J, Wang C, Kan SL. Intramedullary nail versus plate fixation for humeral shaft fractures: a systematic review of overlapping meta-analyses. Medicine (Baltimore) 2015;94:e599. https://doi.org/10.1097/MD.0000000000000599.