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ORIGINAL RESEARCH

Prediction of Proximal Humerus Morphometric Characteristics for Patient-Specific Humerus Prosthesis Design

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ABSTRACT

The human arm and shoulder joint depend on the humerus, which is the bone that bears the most weight in the upper limb. An individual's quality of life could be affected by a humeral fracture; the rigid geometry of current prosthetic systems complicates the process of obtaining anatomical restoration after arthroplasty. This study aimed to generate hypotheses about the morphometric properties of the proximal end of the humerus, derived from the morphometric characteristics of the distal end of the individual's humerus, to enable the construction of a personalized humeral prosthesis. There were 33 dry humerus bones used in the study; IBM SPSS Statistics was used for statistical analysis. This paper developed predictive linear regression models using 33 dry humeral bones in order to determine proximal humerus morphometric features. The approach showed developments in patient-specific humeral prosthetic design and offers a solution to problems related with current standardized prosthetic systems. The thorough approach, clinically relevant approach, and clear presentation of results of the study make it a major source for building patient-specific humeral prosthesis. The developed equations might improve surgical results and patient quality of life. Validating these equations in vivo using CT imaging and clinical data should be given priority in future studies.

Keywords: Anatomy. Morphometry. Prosthesis. Humerus. Fracture.

Kişiye Özgü Humerus Protezi Dizaynı için Humerus'un Proksimal Bölümünün Morfometrik Özelliklerinin Tahmin Edilmesi

ÖZET

İnsan kolu ve omuz eklemi, üst ekstremitedeki en fazla ağırlık taşıyan kemik olan humerus'a bağlıdır. Bir bireyin yaşam kalitesi, bir humerus kırığı tarafından etkilenebilir; mevcut protez sistemlerinin kalıp geometrisi, artroplasti sonrası anatomik restorasyon elde etme sürecini karmaşıklaştırır. Bu çalışmada, bireyin humerus'unun distal ucunun morfometrik özelliklerinden türetilen, humerus'un proksimal ucunun morfometrik özellikleri hakkında hipotezler oluşturmak amaçlandı ve böylece kişiselleştirilmiş bir humeral protez dizaynı geliştirme yönünde yeni formüller ortaya kondu. Çalışmada 33 kuru humerus kemiği kullanıldı; istatistiksel analiz için IBM SPSS Statistics v28.0 kullanıldı. Bu makale, proksimal humerus morfometrik özelliklerini belirlemek amacıyla 33 kuru humerus kemiği kullanarak öngörücü doğrusal regresyon modelleri geliştirmiştir. Yaklaşım, hasta spesifik humeral protez tasarımında gelişmeler gösterdi ve mevcut standartlaştırılmış protez sistemleriyle ilgili sorunlara bir çözüm sundu. Kapsamlı yaklaşım, klinik olarak ilgili yaklaşım ve çalışmanın sonuçlarının net sunumu, hasta spesifik humeral protezlerin oluşturulmasında önemli bir kaynak haline getiriyor. Geliştirilen denklemler, cerrahi sonuçları ve hasta yaşam kalitesini artırabilir. Bu denklemlerin in vivo olarak CT görüntüleme ve klinik veriler kullanılarak doğrulanması, sonraki çalışmalarda ön planda olmalıdır.

Anahtar Kelimeler: Anatomi. Morfometri. Protez. Humerus. Kırık.

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The humerus is the largest bone of the upper extremity and defines the human brachium. The humeral and cubital joints are two important joints that are used in daily lives. Proximally, the shoulder joint is formed by the humeral head articulating with the glenoid cavity, and distally, it articulates with the radius and ulna through the cubital joint. The most proximal part of the humerus is the caput humeri, and it forms a ball-and-socket joint with the shallow cavity called the glenoid cavity on the scapula. Because it combines the structure of two important joints, any pathology in this bone affects the individual's life quality[1-4]. About 5% of the fractures showing up to the emergency room are proximal humerus fractures. Patients with poor bone quality, those unsuitable for osteosynthesis, those in poor health, and those with low rehabilitation potential, as well as those with poor fracture dislocation and multiple anatomical neck fractures are advised hemiarthroplasty, a shoulder replacement whereby the humerus is replaced with a metal implant and the other part of the shoulder joint belonging to the scapula is left intact[4,5]. However, it was shown that restoring normal anatomy during arthroplasty could be challenging due to the relatively fixed geometry of current prosthetic systems[2]. Therefore, the dimensional data of the proximal end of the humerus are important for the optimal design of prosthetic components[3]. Recent designs for the replacement of the proximal end of the humerus with a prosthesis have emphasized the importance of accurately reconstructing the normal three-dimensional anatomy. For replacing the proximal part of the humerus with a prosthesis is to recreate normal anatomy, it is important to understand the normal humeral morphology in three dimensions[6]. The gold standard for determining the premorbid anatomy of a fractured bone is to mirror the contralateral side and use it as a template for reconstruction. However, this approach has its limitations; it requires a computed tomography (CT) scan of both arms, the contralateral humerus must be healthy, and there may be differences in the morphology of the dominant and non-dominant humerus[7].

This could also cause the approach to be suboptimal[7]. The aim of the study is to develop formulas that predict the morphometric characteristics of the proximal end of the humerus based on the morphometric features of the distal end of the individual's humerus to design a personalized humerus prosthesis.

Material and Method

This study commenced after receiving ethical approval from Institutional Ethical Board (Degree No. 2025/4-11).

The study was performed on 33 dry humeri of unknown age and sex and without distinction between right and left sides, in the Anatomy Laboratory of the authors' institution. Bones with anatomical variations, pathology, erosion and fractures that would affect the measurement and statistical results were not included in the study. As a result of the power analysis test performed to determine the number of humeri to be used in the study, using a two-sided test, 5% significance level test (α=0.05) and 80% power (β=0.2) for an effect size of 0.75, the required sample size was approximately 33 (n=33) humerus.

Morphometric measurements were performed by the same researcher using a manual caliper with sensitivity of 0.1 millimeter (mm) in the standard position in the morphometry laboratory. Three researchers observed the measurements to ensure standardization. Standardization. The researchers observed the researcher who made the main measurement and checked whether the measurement was between the correct landmarks, whether the measurement on the caliper was read correctly, and whether the measurement added to the data set was added correctly. Maximum length of the humerus (MLH), humeral shaft diameter (HSD) (Figure 1), eleven perimeters of the proximal part (Figure 2) and sixteen perimeters (Figure 3) of the distal part of the humerus were measured.

Figure 1.
Maximum length of the humerus (MLH), Humeral shaft diameter (HSD)

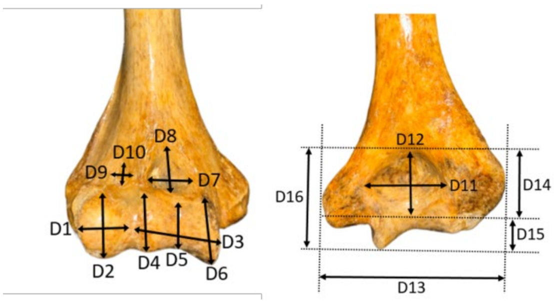

Figure 2.
Variables measured on the proximal part of the humerus. P1- Humeral head transverse diameter; P2- Humeral head vertical diameter; P3- Anatomical neck diameter; P4- Surgical neck diameter; P5- Intertubercular sulcus length; P6- Intertubercular sulcus width; P7- Intertubercular sulcus depth; P8- Humeral head height; P9- Angle between humeral head and humeral shaft; P-10 Vertical distance between the top of the greater tubercle and the top of the humeral head; P11- Distance between the lower border of the humeral head and the upper point of the greater tubercle

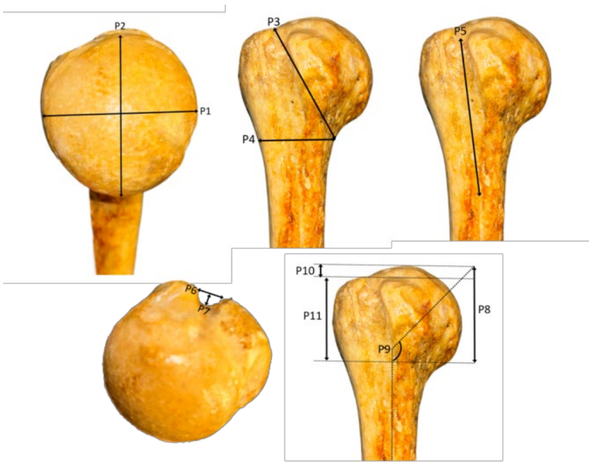

Figure 3.
Variables measured on the distal part of the humerus. D1- Capitulum humeri width; D2- Capitulum humeri height; D3- Trochlea humeri width; D4- Lateral height of humeral trochlea; D5- Medial height of humeral trochlea; D6- Median height of humeral trochlea; D7- Width of coronoid fossa; D8- Height of coronoid fossa; D9- Radial fossa width; D10- Radial fossa height; D11- Olecranon fossa width; D12- Olecranon fossa height; D13- Epicondylar width; D14- Distance between the upper and lower borders of the olecranon fossa; D15- Distance between the lower border of the olecranon fossa and the lower border of the trochlea humeri; D16- Distance between the distal end of the humerus and the upper border line of the olecranon fossa

Statistical data analyses were performed in IBM SPSS 29.0.2.0 (IBM Corp. Released 2023. IBM SPSS Statistics for Windows, Version 29.0.2.0 Armonk, NY: IBM Corp.). The descriptive statistical analysis was performed for Median (Med) ((Minimum (Min) – Maximum (Max)) and Mean ± Standard Deviation (SD) values of the data. We performed the stepwise multiple linear regression analysis to develop equations to estimate the dimensions of the proximal part of the humerus using the morphometric characteristics of the distal part of the humerus, which were correlated. Statistically, the significance level was accepted as $\alpha=0.05$.

Results

In the study, 33 dry humeri of unknown gender and age were used without any distinction between right and left. Statistical findings of the measurements taken from the bones are given in Median (Minimum-Maximum) and Mean ± Standard Deviation in Table I.

Table I. Descriptive statistics of measured variables on the humerus (mm)

Variables	Med (Min-Max)	Mean ± SD
MLH- Maximum length of the humerus	323.00 (280.00 – 354.00)	324.09 ± 17.02
P1- Humeral head transverse diameter	44.00 (37.00 – 49.00)	43.63 ± 2.56
P2- Humeral head vertical diameter	47.00 (39.00 – 52.00)	46.72 ± 3.13
P3- Anatomical neck diameter	47.00 (39.00 – 53.00)	46.84 ± 3.28
P4- Surgical neck diameter	31.00 (24.00 -36.00)	30.63 ± 3.43
P5- Intertubercular sulcus length	71.00 (50.00 – 115.00)	71.45 ± 11.84
P6- Intertubercular sulcus width	9.00 (7.00 – 10.00)	8.63 ± 1.08
P7- Intertubercular sulcus depth	5.00 (3.00 -7.00)	4.83 ± 0.69
P8- Humeral head height	38.00 (32.00 -45.00)	38.24 ± 3.24
P9- Angle between humeral head and humeral shaft	125.00 (112.00 - 136.00)	124.69 ± 5.36
P-10 Vertical distance between the top of the greater tubercle and the top of the humeral head	6.00 (3.00 -7.00)	5.48 ± 1.17
P11- Distance between the lower border of the humeral head and the upper point of the greater tubercle	32.00 (24.00 -39.00)	31.96 ± 3.54
HSD- Humeral shaft diameter	21.00 (17.00 -26.00)	21.27 ± 1.95
D1- Capitulum humeri width	17.00 (11.00 -21.00)	17.27 ± 1.79
D2- Capitulum humeri height	21.00 (17.00 – 25.00)	20.84 ± 1.84
D3- Trochlea humeri width	27.00 (24.00 – 33.00)	27.27 ± 2.06
D4- Lateral height of humeral trochlea	19.00 (15.00 – 22.00)	19.12 ± 1.89
D5- Medial height of humeral trochlea	25.00 (20.00 – 30.00)	24.93 ± 2.30
D6- Median height of humeral trochlea	17.00 (14.00 -21.00)	16.96 ± 1.89
D7- Width of coronoid fossa	14.00 (11.00 – 18.00)	14.15 ± 1.97
D8- Height of coronoid fossa	11.00 (7.00 -16.00)	10.87 ± 1.69
D9- Radial fossa width	11.00 (8.00 – 13.00)	10.45 ± 1.17
D10- Radial fossa height	9.00 (6.00 – 11.00)	8.60 ± 1.14
D11- Olecranon fossa width	25.00 (19.00 – 29.00)	24.96 ± 2.43
D12- Olecranon fossa height	17.00 (14.00 -21.00)	17.78 ± 1.74
D13- Epicondylar width	63.00 (53.00 – 72.00)	62.60 ± 4.32
D14- Distance between the upper and lower borders of the olecranon fossa	19.00 (16.00 -22.00)	19.57 ± 1.87
D15- Distance between the lower border of the olecranon fossa and the lower border of the trochlea humeri	18.00 (13.00 -21.00)	17.39 ± 2.01
D16- Distance between the distal end of the humerus and the upper border line of the olecranon fossa	37.00 (31.00 – 40.00)	36.30 ± 2.55)

The stepwise multiple linear regression equations were developed to estimate the dimensions of the proximal part of the humerus from the morphometric measurements taken from the distal part of the humerus using the values correlated between the proximal part and the distal part of the humerus, the adjusted R squared and the standard error of the estimate values was given in Table II.

Table II. The Stepwise multiple linear regression equations estimating the dimensions of the proximal part of the humerus from morphometric characteristics of the distal part (mm)

Equations	Model Significance: Test statistics	Model Significance: P value	Adjusted R^2	Standard Error of the Estimation
MLH- Maximum length of the humerus (mm)=70.128 + (1.987 x HSD) + (2.021 x D1) – (2.004 x D2) + (1.576 x D3) + (2.964 x D5) + (2.540 x D7) + (1.810 x D16)	F(7;25)=7.755	<0.001	0.596	10.817
P1- Humeral head transverse diameter (mm)= 8.405 + (0.256 x HSD) + (0.309 x D1) + (0.347 x D3) + (0.313 x D5) – (0.310 x D10) + (0.503 x D14)	F(6;26)=8.430	<0.001	0.582	1.655
P2- Humeral head vertical diameter=1.507 + (0.354 x HSD) + (0.508 x D1) + (0.581 x D3) + (0.368 x D5) – (0.308 x D6) + (0.693 x D7) + (0.294 x D16) – 0.344 x D2) – (0.402 x D9)	F(8;24)=8.655	<0.001	0.667	1.810
P3- Anatomical neck diameter= -9.119 + (0.617 x HSD) + (0.489 x D1) + (0.510 x D3) – (0.522 x D9) – (0.456 x D12) + (0.212 x D13) + (0.562 x D14) + (0.269 x D16)	F(8;24)=7.757	<0.001	0.628	2.006
P4- Surgical neck diameter=-16.0908 + (0.829 x HSD) – (0.433 x D2) + (0.317 x D3) – (0.422 x D4) + (0.752 x D12) + (178 x D13) + (0.796 x D15)	F(7;25)=8.724	<0.001	0.628	2.095
P5- Intertubercular sulcus length=43.336 + (1.575 x HSD) + (1.858 x D6) + (2.292 x D7) – (5.027 x D9) + (5.374 x D10) – (1.528 x D11) – (1.271 x D14)	F(7;25)=3.069	<0.001	0.312	9.824
P6- Intertubercular sulcus width= -1.422 + (0.105 x HSD) + (0.143 x D3) – (0.252 x D7) + (2.16 x D11) + (0.118 x D12)	F(5;27)=7.520	<0.001	0.505	0.763
P7- Intertubercular sulcus depth= 4.960 – (0.092 x HSD) + (0.075 x D2) – (0.094 x D8) – (0.156 x D10) + (0.148 x D12)	F(5;27)=2.556	0.051	0.196	0.621
P8- Humeral head height=17.852 + (0.436 x HSD) + (0.580 x D3) – (0.658 x D4) – (1.026 x D5) + (1.051 x D6) – (0.442 x D7) + (0.450 x D14) + (0.754 x D15)	F(8;24)=2.448	0.043	0.266	2.735
P9- Angle between humeral head and humeral shaft= 137.892 + (0.881 x D1) + (1.136 x D3) – (0.937 x D6) – (1.170 x D8) – (2.124 x D10) – (0.287 x D13) – (1.327 x D15) + (0.786 x D16)	F(8;24)=1.787	0.129	0.181	4.856
P10- Vertical distance between the top of the greater tubercle and the top of the humeral head= 1.237 + (0.192 x HSD) 0.176 x D1) – (0.205 x D3) + (0.217 x D5) – (0.235 x D6) + (0.311 x D7) – (0.224 x D10) + (0.151 x D14) – (0.236 x D15)	F(9;23)=1.885	0.129	0.199	1.052
P11- Distance between the lower border of the humeral head and the upper point of the greater tubercle= 3.212 + (0.651 x HSD) + (0.631 x D2) + (0.653 x D3) – (1.472 x D4) – (1.037 x D5) + (1.461 x D6) – (0.538 x D8) + (0.545 x D11) – (0.497 x D12) + (0.818 x D15)	F(10;22)=4.204	0.002	0.500	2.502

The equation with an adjusted R^2 value of 0.667 has the highest prediction percentage among the developed equations and the standard error of the estimation of the equation was 1.810.

Discussion and Conclusion

From distal humerus measurements, this study efficiently built predictive linear regression equations to determine proximal humerus morphometric characteristics. This approach offers a reasonable solution to the problems connected with current standardized prosthetic systems and shows a clear development in the field of patient-specific humerus prosthetic design.

The main strength of this study was its practically appropriate and clinically relevant method. Using easily measured morphometric variables of distal humeri, the study provides a basis for estimating proximal anatomy. When contralateral imaging is unavailable or inaccurate, such as in bilateral fractures or when the other humerus exhibits disease, this method could be very helpful[8]. The established equations provide surgeons and prosthetic designers with a useful tool to personalize implants, hence potentially improving functional results and reducing issues.

The rigorous approach adopted in this study increases its validity. One researcher applying a specific measuring technique under validation by three observers decreases inter-observer variability and ensures data consistency[9]. Based on a clinically appropriate effect size, the estimation of sample size by means of power analysis shows a commitment to statistical accuracy. Moreover, a clear and understandable model for estimating proximal humerus dimensions is provided by linear regression analysis, appropriate for discriminating linear correlations among variables[8,10].

This study could help to create prediction equations. The equations shown in Table II offer a straightforward, quantitative method for evaluating proximal humerus form. Reflecting the variance in the dependent variable explained by the independent variables, the modified R-squared values show a strong predictive power of the produced models. The standard error of the estimate would help physicians to understand the likely range of variability by quantifying the accuracy of projections[11].

Especially relevant to prosthetic design was the focus on morphometric characteristics. Restoring suitable joint kinematics and stability depends on exact repair of the humeral head and other proximal features. This work presented equations that satisfy this demand by providing a means to estimate these fundamental dimensions using distal observations. This approach could increase the precision of implant choice and placement, therefore producing better patient results[12].

Using dry bone specimens offers a controlled environment for data collection, even though it limits the research to anatomical measurements. This approach would help to assess bone shape assess bone shape more precisely by eliminating the confusing factors linked to soft tissue and image artefacts. This controlled environment ensures the highest data accuracy acquired.

The clear and concise presentation of data, including descriptive statistics and regression analysis, would help physicians to understand and apply the results. Tables I and II provided a complete overview of the data, therefore allowing readers to quickly acquire and use the knowledge. The credibility of the study was enhanced and its application in clinical practice would be facilitated by the clarity in data presentation.

By means of measurements of the distal humerus, this work efficiently generated prediction equations for ascertaining the morphometric features of the proximal humerus. The virtues of this study were highlighted by the strict methodology, therapeutically relevant approach, and clear presentation of results. The developed equations offer a great tool for the design of patient-specific humeral prosthesis, thereby improving patient quality of life and maybe leading to improved surgical results. Future studies should focus on verifying these equations in vivo using CT imaging and clinical data and investigate the likely impact of these forecasts on prosthesis design and patient outcomes.

Orthopedic studies conducted on dry bones can indeed be beneficial for in vivo clinical trials, as they provide foundational insights into bone morphology and material properties that are crucial for developing and testing new orthopedic materials and treatments. These studies allow researchers to understand the structural and functional aspects of bones without the ethical and practical challenges associated with in vivo studies. This foundational knowledge can then be applied to in vivo settings to enhance the development and evaluation of orthopedic interventions. Dry bone studies, such as those using CT scans, provide detailed information on trabecular bone morphology, which is essential for understanding bone strength and adaptation. This information can be used to infer functional adaptations and compare them with in vivo data, as demonstrated by the Bone Ratio Predictor method, which links dry and fresh bone data[13]. Dry bones serve as a platform for testing new biomaterials, such as the 3D bioactive scaffolds designed for bone regeneration. These scaffolds are evaluated for their mechanical properties and biocompatibility before being tested in vivo, ensuring that only promising materials proceed to clinical trials[14].

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