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Original research

Predicting Implant Size in Total Hip Arthroplasty

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Background: Efficient resource management is becoming more important as the demand for total hip arthroplasty (THA) increases. The purpose of this study is to evaluate the ability of linear regression and Bayesian statistics in predicting implant size for THA using patient demographic variables.

Material and methods: A retrospective, single-institution joint-replacement registry review was performed on patients who underwent primary THA from 2005 to 2019. Demographic information was obtained along with primary THA implant data. A total of 11,730 acetabular and 8536 femoral components were included. A multivariable regression model was created on a training cohort of 80% of the sample and applied to the validation cohort (remaining 20%). Bayesian posterior probability methods were applied to the training cohort and then tested in the validation cohort to determine the 1%, 5%, and 10% error tolerance thresholds.

Results: The most predictive regression model included height, weight, and sex (cup: $R^2 = 0.57$, all $P < .001$; stem mediolateral size [M/L]: $R^2 = 0.32$, all $P < .001$). Removing weight had a minimal effect and resulted in a more parsimonious model (cup: $R^2 = 0.56$, all $P < .001$; stem M/L: $R^2 = 0.32$, all $P < .001$). Applying the posterior probability estimate to the validation cohort in the Bayesian model using height, weight, and sex demonstrated high accuracy in predicting the range of required implant sizes (95.3% cup and 90.4% stem M/L size).

Conclusion: Implant size in THA is correlated with demographic variables to accurately predict implant size using Bayesian modeling. Predictive models such as linear regression and Bayesian modeling can be used to improve operating room efficiency, supply chain inventory management, and decrease costs associated with THA.

Introduction

With the demand for total hip arthroplasty (THA) expected to continue to grow by approximately 174% by 2030, the ability to manage resources efficiently is becoming more important [1,2]. The ability to predict implant sizes allows for stocking optimization and improved operating room efficiency by potentially reducing resources required for THA, surgical time, and associated costs [1,3]. Currently, preoperative planning for THA implant size is an essential way to minimize surgical time and complications and aid in the optimization of implant availability [3-5]. Preoperative planning using either acetate or digital templating has proven successful in predicting implant size within one size [4]. Additionally, 3D imaging with the development of patient-specific instrumentation and template-directed instrumentation has been studied to reduce implant inventory in THA and total knee arthroplasty (TKA) [6,7]. Pourmoghaddam et al. sought to improve the accuracy of preoperative digital templating by implementing a predictive model that utilized patient-specific demographics using a multiple regression model [5]. They examined preoperative radiographs for 468 individuals who underwent THA from 2 different implant manufacturers and reported 89% accuracy in predicting femoral component size and 93% accuracy for acetabular component size within ±one size [5].

Currently, there does not exist a reliable way to determine the required implant sizes based on simple patient demographics alone for THA. Recently a study demonstrated an association between patient demographics and implant sizes in TKA [8]. Blevins et al. performed a single-institution, retrospective registry review from

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Table 1
Baseline demographics and implant details for the whole study cohort (training and testing).

Variable	Acetabular total (n = 11,730)	Femoral total (n = 8536)
Mean age, y (SD)	65.0 (11.8)	64.3 (11.5)
Mean height, cm (SD)	168.7 (10.4)	169.1 (10.4)
Mean weight, kg (SD)	81.1 (19.9)	81.5 (20.1)
Mean BMI, kg/m^2 (SD)	28.3 (5.8)	28.4 (5.9)
Mean cup OD, mm (SD)	52.7 (3.6)	-
Mean stem ML dimension, mm (SD)	-	31.1 (2.7)
Mean stem AP dimension, mm (SD)	-	16.7 (3.2)
Sex, n (%)		
Male	5232 (44.6)	3888 (45.5)
Female	6498 (55.4)	4648 (54.5)
Side, n (%)		
Left	5215 (44.5)	3757 (44.0)
Right	6515 (55.5)	4779 (56.0)
Primary diagnosis, n (%)		
OA	11000 (91.2)	7836 (91.8)
Non-OA	1037 (8.8)	700 (8.2)

OA, osteoarthritis; SD, standard deviation.

2005 and 2016 and found that height, weight, and sex were associated with implant size with a relatively high accuracy of 94% using Bayesian modeling accepting a 5% tolerance of inaccuracy [8]. As described in their study, “Bayesian statistics is a statistical theory based on the Bayesian interpretation of probability where probability expresses a degree of belief in the event.” [8]. This method of implant size prediction becomes more valuable for those in centers without the ability to calibrate radiographs to allow for preoperative templating. Additionally, using patient demographics for size prediction would be valuable for surgeons who determine implant size on the day of surgery, by not only determining the minimum sizes that would be needed to be available but also by providing an expected size for a specific demographic scenario to give the surgeon extra caution when implant sizes appear to be outside an expected prediction. Also, such size predictions may prove invaluable to companies who supply orthopedic implants by allowing a streamlined use of inventory control and reduced shipping expenditures. The purpose of this study is to utilize and compare linear regression and Bayesian statistics to determine if specific patient demographics are associated with implant size in THA. We hypothesized that specific patient demographics will be associated with implant size in THA and that Bayesian statistics, in addition to multivariate regression analysis, will provide improved predictive modeling of implant sizes.

Material and methods

A retrospective review of a single-institution joint replacement registry was performed on all patients who underwent primary THA between January 2005 and 2019. Patients included were older than 18 years who underwent unilateral primary THA with complete implant data capture. Patient demographic information including age, sex, weight, height, and body mass index (BMI) was obtained for all patients included (Table 1). Bilateral surgery, revision surgery, and those with incomplete implant data were excluded. Primary THA implant data were categorized by manufacturers, and the 8 most frequently used acetabular components and 7 most frequently used femoral components were included in the analysis. The acetabular component size was determined from the corresponding manufacturer size, which was the exact number collected from the registry. The femoral component size was collected from the registry corresponding to the manufacturer’s described size. Femoral component sizes for each manufacturer were then individually measured to determine the widest, proximal mediolateral (ML) and anteroposterior (AP) width. Measurements were determined from manufacturer specifications, and measurements were made using an institutional picture archiving and communication system templating software program (Sectra IDS7, Sweden) appropriately calibrated and confirmed with the acetate template of the individual implant. Measurements were reported in millimeters (mm) to allow for comparison across different implant manufacturers. The widest, proximal ML and AP dimensions were chosen as these dimensions are typically the region where size is determined for primary THA in order to achieve metaphyseal, press-fit fixation.

In total, 11,730 primary acetabular components from the 8 most frequently used designs at our institution were included, and 8536 primary femoral components from the 7 most frequently used

Table 2
Example probability of recommending implant size based on 3 demographic variables based on the Bayesian model.

Scenarios			Cup OD (mm)						
Sex	Weight (kg)	Height (cm)	<42	42-46	46-50	50-54	54-58	58-62	62-66
Male	80-90	<150	0.0%	0.8%	13.7%	72.3%	10.3%	3.0%	0.0%
Male	80-90	150-155	0.0%	0.4%	13.4%	70.6%	13.1%	2.5%	0.0%
Male	80-90	155-160	0.0%	0.2%	9.2%	75.7%	13.6%	1.4%	0.0%
Male	80-90	160-165	0.0%	0.1%	5.4%	77.9%	15.2%	1.4%	0.0%
Male	80-90	165-170	0.0%	0.0%	2.4%	60.2%	35.7%	1.8%	0.0%
Male	80-90	170-175	0.0%	0.0%	0.7%	45.8%	50.0%	3.5%	0.0%
Male	80-90	175-180	0.0%	0.0%	0.2%	29.2%	61.9%	8.5%	0.2%
Male	80-90	180-185	0.0%	0.0%	0.0%	17.5%	68.8%	13.3%	0.4%
Male	80-90	185-190	0.0%	0.0%	0.0%	10.9%	68.7%	19.3%	1.1%
Male	80-90	>=190	0.0%	0.0%	0.0%	3.4%	63.3%	29.6%	3.7%

Blue color indicate probability of recommending implant size based on a given demographic scenario.

Table 3
Multivariate regression analysis of demographic variables.

Variable	Coefficient	*P* value
Cup OD (mm)		R^2 = .57
Intercept	28.35	<.001
Male vs Female	2.66	<.001
Height (cm)	0.13	<.001
Weight (kg)	0.02	<.001
Stem ML (mm)		R^2 = .32
Intercept	16.23	<.001
Male vs Female	1.38	<.001
Height (cm)	0.08	<.001
Weight (kg)	0.01	<.001
Stem AP (mm)		R^2 = .09
Intercept	8.13	<.001
Male vs Female	0.92	<.001
Height (cm)	0.04	<.001
Weight (kg)	0.01	<.001

Outcome variables are given in bold.

Table 4
Accuracy of multivariate linear regression model on testing cohort.

Dimension	Total, n	Accuracy, %
Cup OD		
±2 mm	945	40.3
±4 mm	1724	73.5
±6 mm	2185	**93.2**
±8 mm	2310	**99.6**
Stem ML/AP		
±1 mm	495/294	28.9/17.2
±2 mm	953/734	55.6/42.8
±3 mm	1294/1077	75.5/62.9
±4 mm	1494/1365	87.2/79.9
±5 mm	1613/1522	**94.2/88.8**
±6 mm	1669/1601	**97.4/93.5**
±7 mm	1694/1672	**98.9/97.6**
±8 mm	1707/1699	**99.6/99.2**

Bold values highlight accuracy >90%.

designs at our institution were included in analysis (Table 1). The 8 acetabular components included R3 (Smith & Nephew, Memphis, TN), 4011 (34.2%); Trident Hemispherical (Stryker, Mahwah, NJ), 2200 (18.8%); Pinnacle 100 series Gription Shell (DePuy Synthes, Warsaw, IN), 1305 (11.1%); Trilogy (Zimmer Biomet, Warsaw, IN), 1061 (9.0%); Restoration ADM (Stryker, Mahwah, NJ), 904 (7.7%); Trident PSL (Stryker, Mahwah, NJ), 812 (6.9%); G7 (Zimmer Biomet, Warsaw, IN), 733 (6.2%); Trabecular Metal (Zimmer Biomet, Warsaw, IN), 704 (6.0%). The 7 femoral components included Synergy Porous Plus HA (Smith & Nephew, Memphis, TN), 3091 (36.2%); Tri-Lock BPS with Gription (DePuy Synthes, Warsaw, IN), 1278 (15.0%); Novation Splined HA (Exactech, Gainesville, FL), 1167 (13.6%); Anthology (Smith & Nephew, Memphis, TN), 1142 (13.4%); Secur-Fit Advanced (Stryker, Mahwah, NJ), 681 (8.0%), Secur-Fit Max (Stryker, Mahwah, NJ), 633 (7.4%); Trabecular Metal Primary (Zimmer Biomet, Warsaw, IN), 544 (6.4%).

Statistical analysis

The THA acetabular components and THA femoral components were randomly split into a training cohort (acetabular N = 9386, femoral N = 6823) and a testing cohort (acetabular N = 2344, femoral N = 1713). Multivariable regression was then performed on various models using a combination of patient sex, height, weight, and BMI on the training cohort. The model using sex, height, and weight yielded the highest R-square value; therefore, this model was then used on the testing cohort to determine the prediction accuracy.

A Bayesian model was also performed starting with prior distributions. Bayesian statistical methods use Bayes' theorem—P(B) = P(B A1) P(A1) + P(B A2) P(A2) + … + P(B An) P(An) = Σi P(B | Ai) P(Ai)—to compute and update probabilities after obtaining new data [9,10]. The unadjusted probability of recommending a specific cup outer diameter (OD), stem ML, or AP size was calculated in the training cohort for each demographic variable. The posterior probability of recommending a specific size was then determined by combining 3 demographic variables (sex, height, and weight) to create a patient scenario (Table 2). An example of the "posterior probability" formula can be found in the appendix of the article by Lyman et al. [10].

The model was then applied to the testing cohort to determine the prediction accuracy of the model at 1%, 5%, and 10% tolerance of error. For example, as shown in Table 2, for a male patient weighing 80 kg to <90 kg with a height of 155 cm to <160 cm, the probabilities of recommending a cup implant size of <42 mm is 0%, 42 mm to <46 mm is 0.2%, 46 mm to <50 mm is 9.2%, 50 mm to <54 mm is 75.7%, 54 mm to <58 mm is 13.6%, 58 mm to <62 mm is 1.4%, and ≥62 mm is 0%. With a 5% tolerance of error checking in the testing cohort, 2 patients fall in this scenario with an implant size of 50 mm to <58 mm, and no patient fell outside the predicted implant size range. Overall, 104 (4.4%) patients were outside the predicted acetabular implant size range, 164 (9.6%) for the femoral stem ML implant size range, and 113 (6.6%) for the femoral stem AP implant size range, accepting 5% tolerance of error.

Results

Multivariate linear regression analysis demonstrated sex, height, and weight as significant predictors of implant size although precision was variable with the predicted cup OD R^2 = 0.57, femoral stem ML R^2 = 0.32, and femoral stem AP R^2 = 0.09 (Table 3). Accuracy for predicting the cup OD to be ±4 mm was 73.5%, which increased to 93.2% for ±6 mm (Table 4). Accuracy for predicting femoral stem ML size was 94.2% at ±5 mm and 93.5% for for stem AP size ±6 mm.

When the Bayesian modeling described above (Table 2) was used on the testing data set, for predicting implant size with a tolerance of 5%, the accuracy of the model improved to 95.3%, 90.4%, and 93.4% for the cup OD, stem ML, and stem AP sizes, respectively. For an error tolerance of 1%, the accuracy was 98.7%, 97.8%, and 99.6%, while for an error tolerance of 10%, the accuracy was 90.9%, 82.7%, and 78.9% for cup OD, stem ML, and stem AP, respectively.

Discussion

The ability to predict THA implant size has numerous benefits including optimized supply efficiency, reduced cost, and improved patient care. Our analysis demonstrated patient demographic variables can be used to predict implant size using multivariate linear regression and Bayesian models. Sex, height, and weight all demonstrated a significant relationship with implant size ($P < .001$, Table 3). Our regression model based on these variables predicted cup OD ±4 mm with 73.5% accuracy when applied to the testing cohorts. Likewise, stem ML size ±5 mm with 94.2% accuracy and stem AP size ± 93.5% accuracy. Multiple models were initially analyzed combining the collected variables of sex, height, weight, and BMI; however, the combination of sex, height, and weight provided the higher R^2 values of 0.57, 0.32, and 0.09 for cup OD, stem ML, and stem AP, respectively. Although significant, these values range from adequate precision with cup OD to relatively poor precision with stem AP prediction.

Pourmoghaddam et al. also found patient demographic variables to be relevant to implant size [5]. They performed a multivariate regression, which included BMI, weight, age, sex, and height, in addition to preoperative templated acetabular and femoral sizes using 2 manufacturers. Interestingly, they found the significant predictors to be templated acetabular and femoral size, height, and BMI with an adjusted $R^2 = 0.795$ for the acetabular component and adjusted $R^2 = 0.727$ for the femoral component. Sex and weight were not significant in their model. The difference in their analysis against ours appears to be the methodology of using a backward stepwise algorithm to remove predictors without significant contribution and the inclusion of preoperative templated sizes, which would significantly improve the precision of their size prediction. Templating alone is an accurate way to prepare for THA size prediction [7,11], and they concluded that patient demographics improve templating alone. Our study demonstrates in the absence of templated sizes, demographics alone can be useful in predicting THA sizes. Although there may be outliers with the prediction based on patient demographics, a better understanding of expected implant sizes for a specific patient assists the surgeon through the expected cautionary approach to patients that fall outside the predicted values, such as dysplasia or syndromic cases [12].

Using this defined set of variables, a Bayesian model was created to predict the required range of implant sizes. When applying the various possibilities of sex, height, and weight into the model on the testing data set, the accuracy of the model for predicting implant size was high while accepting various tolerances of inaccuracy of 1%, 5%, or 10%. For example, from the posterior probability of implant sizes based on the 3 variables scenario, when applied to a testing scenario using the same 3 variables, the model demonstrated the ability to predict the appropriate implant size with an accuracy of 95.3%, 90.4%, and 93.4% for the cup OD, stem ML, and stem AP sizes, respectively, accepting that 5% of the time, the model would not predict the implant size. This analysis is unique to THA implant prediction in the existing literature. Blevins et al. [8] used the same technique for TKA size predictions. They performed a retrospective review of an institutional registry for all primary TKAs performed from 2005 to 2016 and collected patient demographics to predict implant size with multivariate linear regression and Bayesian statistics creating a model using a training cohort ($n = 4022$) and validating the model with a testing cohort ($n = 4078$). Their Bayesian model also showed high accuracy in predicting the range of required implant sizes with 94.4% accuracy for the femur and 96.6% accuracy for the tibia with 5% error tolerance. With the addition of our current study, these findings add value that the recommended implant sizing range determined by the Bayesian model appears to be highly accurate for THA and TKA when applied to a testing cohort, which is of high importance if a surgeon, implant company, hospital, or ambulatory surgery center is making the decision to have a limited number of implants available.

There are several limitations to this study. This is a retrospective study including multiple implant manufacturers. Regarding the acetabular components, there can be slight differences in the true size of the implant depending on the OD composition and design rationale for the specific implant. Although there are subtle differences, in order to simplify the analysis for future use, the reported size was analyzed since the determination to accept a specific cup size intraoperatively is largely due to the reaming process, which should theoretically be similar across manufacturers. Standardizing femoral components across all stem types is more difficult as various techniques are required. This study included multiple types of stems including shorter, tapered-wedge designs, and longer, metaphyseal filling designs. Regardless of the stem type, the goal during primary THA at this institution is metaphyseal fixation, and therefore, the stems were measured and reported as true ML and AP dimensions in the widest, most proximal region of the stem in 1-mm increments. There are differences in the change of proximal dimensions between sizes among the various manufacturers, which could result in differences in the final implanted stem between different implants. For example, for a specific patient with a relatively wide AP distance compared with the ML distance, the final implant for a more fit and fill designed stem may be smaller in the AP dimension because fixation is achieved in the ML dimension. This variation may have resulted in the lower R^2 values reported in our study; however, when attempting to answer our primary question of whether demographic variables can predict implant size across all THA implants, these small differences would be relevant. Regardless of the differences, the goal of primary THA is to ensure press-fit fixation in the metaphyseal region along the cortical bone. This study also included multiple surgeons at this single institution, which could result in slight variations of final implant sizes if a particular surgeon tends to oversize or undersize an implant for various reasons such as the need for larger head sizes or prevention of overhang; however, it does allow our study to be generalized to multiple surgeons and implants. Lastly, as this study reported the relationship between demographic variables and implant size, comorbidities and bone quality were not recorded. Conditions such as osteoporosis or dysplasia or certain medications can result in reduced bone quality and, therefore, affect the final implant size.

Conclusions

Implant size in THA is correlated with demographic variables including height, weight, and sex. Bayesian modeling and linear regression can more accurately predict the required implant size based on these demographic variables. Overall, Bayesian models can be used to improve operating room efficiency, manufacturer supply chain optimization, and hospital and ambulatory surgery center inventory management, as well as decrease costs associated with THA.

Conflicts of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: S. Lyman is a paid consultant for Corin USA; is in the editorial or governing board of HSS journal; is a member of ISAKOS, JOSKAS, and JBJS. J. L. Blevins is a paid consultant for Globus, KCI, and Lima Corporate. G. H. Westrich receives royalties from Stryker and Exactech; is in the speakers' bureau or have paid presenations for and is a paid consultant for Stryker, Ethicon, and Exactech; receives research support as a principal investigator from Stryker and Exactech; and is a member of the Eastern Orthopedic Association. All other authors declare no relevant conflicts to disclose.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2022.02.018.

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