Meniscal Allograft Size Can Be Predicted by Height, Weight, and Gender

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Purpose: Our purpose was to determine if height, weight, and gender can be used to accurately predict proper meniscal allograft dimensions. **Methods:** Data were obtained from the Joint Restoration Foundation (AlloSource, Centennial, CO) regarding meniscal size and patient characteristics from meniscal donors. Donor height, weight, sex, age, and anatomic meniscal dimensions were recorded for 930 donor menisci in 664 patients. Multivariate regressions were completed using gender, height, and weight as independent variables and lateral meniscus length, lateral meniscus width, medial meniscus length, and medial meniscus width as dependent variables. The regression formulas were then reapplied to the data in order to produce estimated meniscus dimensions based on donor height, weight, and gender. A 90:10 split of the data was used to validate the regression models. Predicted meniscal size was then compared to actual meniscal size and the results compared to current measurement techniques. **Results:** Regression formulas showed the ability to predict meniscal size based on gender, height, and weight with standard deviations (SDs) equal to or less than current radiographic techniques (SD, 6.4% to 8.2%). Average differences between predicted size and actual size ranged from 5.2% to 6.5% for length and 5.2% to 6.0% for width. Patient height was found to be a much more powerful predictor of meniscal size than patient weight. Data from the 90:10 split of data validated the model on an independent sample. These validated outputs were then compared to contemporary techniques and found to have lower SDs and average error rates in the majority of cases. **Conclusions:** We have proposed a validated regression model that uses height, weight, and gender variables to accurately predict required allograft meniscal size. We compared it against previously published data for radiographic and magnetic resonance imaging sizing techniques and found it to produce results that were, overall, slightly more accurate. **Clinical Relevance:** This model provides a novel method for sizing meniscal allografts. **Key Words:** Allograft—Meniscus—Size—Transplant.

Meniscectomy has the potential to have devastating long-term consequences in young patients. Many procedures have been developed to address the changes caused by a meniscectomy, including tendon autograft meniscal replacement, meniscal engineering, and meniscal transplantation.[1,2] Of these, meniscal transplantation has received the most attention and clinical applicability in recent years. It is an evolving technology that has shown clinical and physiologic efficacy in various studies.[3-8] There have also been numerous techniques and modifications proposed for the transplantation procedure.[9] This continuous refinement has been fueled by ongoing research and the contributions of expert opinion.

Preoperative sizing of the allograft is one aspect of meniscal transplantation that is continually debated.[10,11] The importance of correct sizing has been considered by many authors and highlighted in recent biomechanical studies completed by Dienst et al.[12] and Al-

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halki et al.[13] Currently, there are two predominant methods for sizing the allograft: radiographic analysis, as proposed by Pollard et al.,[15] and magnetic resonance imaging interpretation as proposed by Haut et al.[16] In Pollard et al.'s method,[15] there is a correction made for magnification, and the width is then calculated on the anteroposterior radiograph of the knee by measuring from the tibial metaphyseal margin to the peak of the tibial eminence. The length is measured on the lateral radiograph and a 70% adjustment is made for the lateral meniscus and an 80% adjustment is made for the medial meniscus. Haut et al.[16] used MRI parameters of the meniscus in order to predict the required allograft size, and most recently Prodromos et al.[17] confirmed the accuracy of MRI in this application. However, the majority of contemporary studies have used radiographic measurements for sizing. Both methods have shown utility; however, they also have substantial standard deviations (SDs) of measurement and relatively large average error rates.

The need for accurate meniscal allograft size estimation and the purported error associated with contemporary sizing methods led us to investigate other feasible techniques for accurately determining the size of the required meniscal allograft. Furthermore, it has recently been suggested that patient height and weight may provide data that can be used to calculate accurate size estimates of meniscal allografts.[18] In the current study, 930 menisci have been analyzed in the context of the donor's height, weight, and gender. It is our hypothesis that this demographic data can be used to develop a reproducible formula that can be applied to future meniscal allograft sizing.

METHODS

Donor height, weight, sex, age, and gross anatomic meniscal dimensions were obtained from the Joint Restoration Foundation (AlloSource, Centennial, CO) for 930 menisci in 664 patients. The menisci were collected and processed using the following protocol: basic dissection of knee en bloc tissue was used to open the capsule; the menisci were evaluated for tears, hard spots, and weak insertion points; measurements of the length and width of each meniscus were taken before the menisci were released from the surrounding tissue of the proximal tibia; and the menisci were released from the tibia.

The grafts were cleansed and rinsed before being sent though a purge/soak process to facilitate the removal of blood and lipids form the bone block and cleaning of the tissue. The grafts were cultured and the dimensions were measured with calipers before being placed into the final packaging. According to American Association of Tissue Bank standards, the grafts were stored at or below −40°C until implantation.

The donors for the menisci had died of various conditions and circumstances that were not made known to us. Once their menisci were harvested, patient demographic information was obtained. Heights, weights, and gender were recorded from the medical record or, if the medical record did not contain this information, from the patient's drivers license.

The information for 930 menisci was entered into an Excel database (Microsoft, Redmond, WA), including meniscal length (anteroposterior), meniscal width (mediolateral), meniscal side, meniscal compartment, donor height, donor weight, donor age, and donor gender. These data were analyzed with Excel to calculate significance values ($P < .05$) and perform multivariate regression analysis for the different sets of data.

Statistical Analysis

Multivariate regression analyses were used to examine the association between the individual outcomes, which included lateral meniscus length, lateral meniscus width, medial meniscus length, and medial meniscus width and the predictors (height and weight). These associations are examined separately in male and female subgroups.

The data were randomly split into a sample set and a validation set in a 90:10 ratio. The multivariate regression models were fit on the sample set and the fitted models were then used to predict the outcome variables (lateral meniscus length, lateral meniscus width, medial meniscus length, and medial meniscus width) on the validation set. The residuals—that is, the difference between actual and predicted values—were then computed only on the validation set. The mean absolute differences and SDs were then calculated on these validation residuals. The process of randomly splitting the data in a 90:10 sample and validation sets was then repeated 50 times, and the average mean absolute differences and SDs of the ratios over these repetitions were obtained.

The results of these analyses based on height and weight were then compared with the published results from Pollard et al.[15] and Shaffer et al.[19] using the criteria established in those articles. Therefore, SD percentages were calculated and compared to Pollard et al.'s results.

TABLE 1. *Regression Results*

	Constant	Height (in)		Weight (kg)		Overall Sig
Subgroup	Coefficient	Coefficient	*P*	Coefficient	*P*	*P*
Lateral length						
Female	9.93	0.31	.000	0.02	.08	.000
Male	8.95	0.37	.000	0.006	.46	.000
Lateral width						
Female	15.64	0.15	.005†	0.04	.001†	.000
Male	7.89	0.34	.000	0.01	.20	.000
Medial length						
Female	15.92	0.31	.000	0.05	.002†	.000
Male	16.67	0.35	.000	0.03	.005†	.000
Medial width						
Female	17.07	0.16	.005†	0.02	.02	.000
Male	16.84	0.19	.000	0.03	.000	.000

NOTE. Regression equation (meniscal dimension) = [constant coefficient] + [(height coefficient) × (height)] + [(weight coefficient) × (weight)].
†Height can be converted to centimeters by dividing the height coefficient by 2.54.
Abbreviations: Sig, significance.

Mean absolute differences and SD values were also calculated and compared with Shaffer et al.[19]

RESULTS

The data included 930 menisci in 664 patients, consisting of 297 male lateral menisci, 137 female lateral menisci, 322 male medial menisci, and 174 female medial menisci. Donor female height ranged from 52 in to 75 in (mean, 65.7 in); female weight ranged from 41 kg to 136 kg (mean, 68.5 kg); male height from 56 in to 78 in (mean, 70.7 in); and male weight 48 kg to 159 kg (mean, 84.1 kg). The results of the multivariate regressions are reported in Table 1. The overall significance of each of these regressions is very strongly significant (overall Sig $P < .001$ in each case). The effect of height is strongly significant in 2 cases ($P < .01$) and very strongly significant in the remaining cases ($P < .001$). The effect of weight is significant to strongly significant in 5 out of the 8 cases. Out of the remaining 3 cases, the effect of weight is marginally significant for predicting lateral length in the female subgroups and is not significant for predicting lateral lengths and lateral widths in males. The R^2 values for the regression equations are as follows: female lateral length, 0.22; female lateral width, 0.17; female medial length, 0.17; female medial width, 0.11; male lateral length, 0.22; male lateral width, 0.21; male medial length, 0.18; and male medial width, 0.16.

TABLE 2. *Statistical Comparison*

	SD Percent		Mean Absolute Differences (mm)		SD Absolute Differences (mm)	
Subgroup	Pollard[15]	90:10 Valid	Shaffer[19]	90:10 Valid	Shaffer[19]	90:10 Valid
Lateral length						
Female	8.0	7.1	2.65 rad	1.75	2.12 rad	1.44
Male		6.6	2.13 MRI	1.86	1.96 MRI	1.46
Medial length						
Female	7.4	8.2	2.85 rad	2.59	2.06 rad	2.27
Male		6.7	3.37 MRI	2.29	2.76 MRI	1.96
Lateral width						
Female	8.4	7.0	2.15 rad	1.57	1.35 rad	1.19
Male		6.9	1.35 MRI	1.79	1.4 MRI	1.47
Medial width						
Female	7.9	7.2	1.74 rad	1.68	1.51 rad	1.35
Male		6.4	2.13 MRI	1.69	1.44 MRI	1.32

Abbreviations: MRI, magnetic resonance imaging; Rad, radiographic; SD, standard deviation.

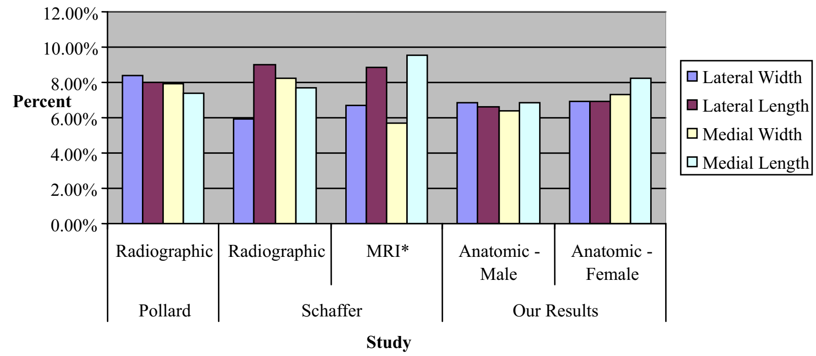

FIGURE 1. Comparison of standard deviations. The asterisk denotes the magnetic resonance imaging results of the ipsilateral knee.

Table 2 reports the SDs of the ratio of the residual to the actual values (SD percent) and compared to those reported by Pollard et al.[15] The "90:10 valid" column is based on the repeated random calculations in the validation set. The results were stratified into 2 gender subgroups. In all cases except the female medial length, the 10% cross-validated SD results are superior to Pollard et al.'s values (Fig 1).

The next set of comparisons in Table 2 is based on the mean and SDs of the absolute differences. These are compared with the radiographic and MRI values reported by Shaffer et al.[19] For both lateral length and medial width, the mean absolute differences and SDs for the 10% cross-validated analyses are superior to the values reported by Shaffer et al. (Fig 2). For medial length, the mean absolute differences are again superior, but the SDs for females are higher than the values reported by Shaffer et al. based on radiographs. However, the regression model produces a lower SD for male estimates. With regard to lateral width, the mean absolute difference based on MRI reported in Shaffer is smaller than our estimates for both males and females; however, radiographic measurements produce a larger average error than the regression model. The SD in radiographs and MRI for lateral width reported by Shaffer et al.[19] is smaller than those for the regression estimated males, yet the regression estimated females are lower than both groups studied in Shaffer et al.[19] Mean absolute differences for each meniscal dimension are included in Table 3. Of note, female average absolute percent differences and percent SDs are slightly larger than predicted male values.

DISCUSSION

Meniscal transplantation is a procedure that has been growing in popularity in recent years. The procedure was first tested in dogs and shown to have metabolic longevity and biomechanical value by Arnoczky et al.[20] in 1984. Further testing in the canine model by Canham and Stanish[21] and a published description of the procedure by Wirth[22] in Germany led to Milachowski et al.[23] performing meniscal transplantation in humans in 1989. However, there remains much debate surrounding the efficacy and the technical aspects of the procedure.[4,24-26]

It has been established that appropriate sizing of the meniscal graft is an important factor in restoring meniscal function. Dienst et al.[12] proposed a 10% limitation for the difference between a native and an allograft lateral meniscus based on biomechanical contact pressures. However, menisci were placed into groups based on their combined anteroposterior and

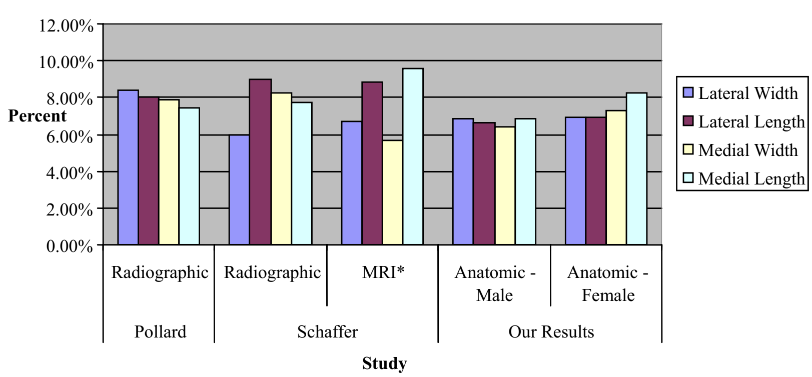

FIGURE 2. Comparison of average differences. The asterisk denotes the magnetic resonance imaging results of the ipsilateral knee.

TABLE 3. *Average Percent Absolute Difference*

	Gender	Difference
Lateral length	F	5.6
	M	5.2
Medial length	F	6.5
	M	5.4
Lateral width	F	5.6
	M	5.4
Medial width	F	6.0
	M	5.2

mediolateral mean dimensions, making explicit dimensional parameters difficult to elucidate. Alhalki et al.[13] also showed an increased variability in contact pressures with an allograft compared to an autograft meniscus. This variability was attributed to the deviation in allograft meniscal size from the original dimensions. Therefore, a mismatch in sizing of the allograft has the potential to increase contact pressures and compromise the long-term results of the transplant. To complicate the issue, Kohn[27] has proposed that it is physiologically unacceptable to alter the size of the allograft meniscus because of the changes that result in the collagen scaffold and the mechanical properties.[14,28] Therefore, accurate and reproducible sizing methods are essential to the overall success of the meniscal transplant. Along those lines, a novel and reproducible method was established for sizing the required allograft.

Currently, the most prevalent methods for sizing meniscal allografts include MRI and radiographic imaging as proposed by Pollard et al.[15] and Haut et al.[16] Each of these techniques has significant deficiencies. MRI is expensive and impossible to use in an ipsilateral knee that has had a complete meniscectomy. MRI of the contralateral knee is also difficult and assumes that bilateral menisci are exact mirror images of each other. Furthermore, both techniques produce estimates with questionable accuracy and interobserver reliability (Table 2; Figs 1 and 2). In the original study by Pollard et al.,[15] menisci were marked with a radiopaque substance and then radiographically imaged. From these radiographs, the researchers were able to describe relationships between menisci and bony landmarks on the tibia. This was astutely completed; however, their sample size was small and the SDs reported in their predictions were sizeable (Table 2). These findings were later confirmed in a study by Shaffer et al.,[19] in which the size estimates based on radiographic and MRI images were compared to the actual gross anatomic size of the meniscus; again, significant variabilities were noted (Table 2).[19]

These studies illustrate the variability and inaccuracies inherent in the current methods used for sizing menisci in allograft transplantation.[10] The cause of variability experienced by the sizing methods based on radiographic parameters is likely multifactorial, including imaging interpretation, patient positioning, and magnification corrections; however, McDermott et al.[29] showed that there is almost certainly a large component of anatomic variability in the relationship between bony tibial landmarks and meniscus dimensions. In their study, bone landmarks were measured grossly and then compared to the meniscal dimensions.[30] Regression analysis was used to predict meniscal size based on these bone landmark relationships and then compared to actual meniscal values measured with a caliper. Their cumulative mean error was 7.2% (SD, 9.5%). This study illustrated that even if perfect interpretation, positioning, and magnification correction are applied, there will continue to be an inherent variability of each estimated meniscal size because of anatomic differences. These anatomic differences have been reported previously and are perhaps the greatest in the attachment of the anterior horn of the medial menisci in relation to the tibial spine.

It is well published in the anthropology literature that tibial size can be used to predict height in various populations.[31-34] In light of the error associated with contemporary sizing methods, these anthropologic principles led us to analyze meniscal dimensions in the context of gender, height, and weight through regression models from a database of 930 menisci. Stone et al.[18] have previously suggested a relationship between height, weight, and gender with regard to meniscal size on MRI. However, no discreet method for clinically applying this information was provided. Therefore, regression formulas (Table 1) were applied to the meniscal dataset in order to obtain predicted length and width measurements for each meniscus. These results were then compared to the actual gross meniscal dimensions. The regression models were validated by using a repeated 90:10 split of the data. Interestingly, the regression formulas produced accurate measurements with SDs equal to or less than published data that used radiographic or MRI criteria (Table 2).

There are potential limitations to our study. First and most importantly, donor height and weight were recorded from outside sources and do not represent exact measurements taken using strict criteria. Studies have shown that men tend to slightly overestimate height by 1.3% and women underestimate weight by 3%.[35,36] The large sample size does correct for some of this variation. Also, although it is unlikely that height would change over time, weight may clearly fluctuate, and there is no way to know if the recorded weight represents the actual weight of the donor at the time of harvest. However, as evidenced by the *P* values for the regression coefficients (Table 1), weight has a relatively small contribution to the predicted dimension compared to height. For example, a 50-lb weight difference in a 6-foot male only changes the predicted length for a medial meniscus by 1.5%. In order to address the limitations in this study, future studies have been planned that directly compare meniscal size, predicted size, and radiographic size.

CONCLUSIONS

We have proposed a validated regression model that uses height, weight, and gender variables to accurately predict required allograft meniscal size. We compared it against previously published data for radiographic and MRI sizing techniques and found it to produce results that were, overall, slightly more accurate.

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