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Morphological Analysis of Normal Meniscus on Magnetic Resonance Imaging (MRI)-Based Three-Dimensional Reconstruction Models in Healthy Chinese Adults

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Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: The purpose of this cross-sectional observational study was to determine the morphological meniscus characteristics in a normal Chinese population and assess possible relationships between demographic data and meniscal morphological parameters.

Material/Methods: We examined 116 menisci (58 lateral and 58 medial) from 29 healthy Chinese volunteers (10 men, 19 women, mean age 26 years [range, 20–33 years]) with MRI and three-dimensional reconstruction using Mimics software. The width, thickness, anteroposterior distance (APD), lateral-medial distance (LMD), and covering angle (CA) were measured on reconstructed models. Univariate analysis was used to evaluate the differences of morphological parameters between the medial and lateral menisci, between sides, and between males and females. Pearson correlation analysis was used to evaluate the correlation between meniscal morphological parameters and body height, weight, and body mass index (BMI).

Results: Univariate analysis demonstrated that the width, thickness, APD, LMD, and CA were significantly different between lateral and medial menisci. The LMD and APD of menisci in men were significantly larger than in women. There was no significant difference in meniscal thickness and CA between males and females. The lateral meniscus dimensions were slightly larger in the right knee. According to Pearson correlation analysis, the APDs of both lateral and medial menisci were strongly correlated with height and weight (lateral: r=0.596, r=0.500; medial: r=0.684, r=0.680).

Conclusions: The morphologies of medial and lateral menisci were different and were not significantly correlation with each other. The meniscal width and diameter were correlated with demographic data, but the thickness and CA did not significantly differ by sex, height, or BMI.

MeSH Keywords: **Imaging, Three-Dimensional • Magnetic Resonance Imaging • Menisci, Tibial**

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Background

The meniscus is an important protective structure of the human knee joint. Meniscal tear is one of the most common knee joint sports injuries and causes serious adverse consequences to the knees of athletes [1]. At present, the treatment of meniscus injury is mainly focused on surgical suture repair or meniscectomy [2]. Arthroscopic meniscus suture repair can usually be performed for injuries situated at the red-red zone, while white-white zone injuries and complex meniscal tears require meniscectomy, and large meniscal resection can cause quadriceps atrophy, osteoarthritis (OA), and even knee deformity. In cases of symptomatic segmental or total meniscectomy, meniscal allograft transplantation (MAT) becomes the last choice in an attempt to restore knee contact forces and reduce meniscal-related symptoms. However, the sources of MAT are relatively scarce and it is estimated that there are only 0.24 procedures performed per year per 100 000 patients. Successful meniscal transplantation is highly dependent on accurate size matching of the allograft to the native meniscus.

In recent decades, the construction of artificial menisci for MAT has been a research hotspot in sports medicine. Lee et al. [3] and Zhang et al. [4] reported that anatomic meniscal grafts in animals using three-dimensional (3D) printing technology achieve good structural matching, and the procedures can effectively prevent progressions of knee osteoarthritis.

Few studies have assessed the morphology of the human meniscus, and many anatomical dimensions of the normal meniscus are still unknown. The present study performed comprehensive morphological evaluations of the meniscus in normal Chinese adults by using 3D-reconstructed magnetic resonance image (MRI) meniscal models. It was hypothesized that meniscal anatomical parameters were significantly correlated with demographics in healthy Chinese adults. The goal of this study was to provide accurate morphological parameters for the design of an artificial meniscus and to provide anatomical principles to guide allograft selection in meniscal MAT.

Material and Methods

Study subjects

This cross-sectional observational study was approved by the Institutional Review Board Ethics Committee of China-Japan Union Hospital (IRB No. 2016-nsfc028). All subjects provided signed informed consent prior to undergoing the MRI examination. All eligible volunteers were required to undergo MRI of the selected knee for review in the clinical imaging system using a Phillips 3.0-T MRI scanner. Volunteers were placed in the supine position with the knee fully extended. MRI scans were performed in coronal, sagittal, and horizontal position of the knee joint by 3-D dual-echo steady-state (3D-DESS), with a layer thickness of 0.5 mm. From January 2018 to January 2019, 40 (out of 98) volunteers were recruited from the community through use of research flyers. Eleven participants were later found to meet the exclusion criteria after taking MRI scans, and were therefore excluded from the present study. The inclusion criteria were: no knee joint pain or instability, skeletally mature, and healthy. The exclusion criteria were: congenital meniscus dysplasia, meniscus-related lesions, and preexisting cruciate ligament injuries. Finally, 29 subjects (10 men, 19 women, mean age 26 years [range, 20–33 years]) with 116 menisci (58 lateral and 58 medial) were included in the study (Figure 1).

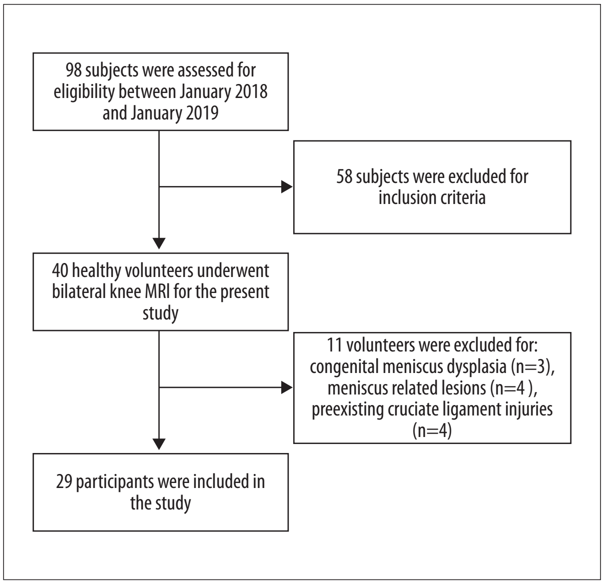

Figure 1. Flowchart of subject selection.

3D Reconstruction

The scan data from included subjects were extracted, deposited to a personal computer in Digital Imaging and Communications in Medicine (DICOM) format, and imported to Mimics 17.0 software (Materialise, Belgium) for 3D reconstruction. The luminance was set as 50~200, and the meniscus images of each section were inspected by the researchers layer by layer through the steps of threshold analysis, region growth, and mask editing. After 3D calculation, the 3D meniscus models were further trimmed by limited smoothing, and then were ready for subsequent measurements. We selected 3 discrete points of the tibial plateau to best fit the tibial plateau plane (Figure 2).

Data acquisition and measurements

The 3D models of the meniscus and tibial plateau plane were imported into 3-matic software, and the meniscal models were 2D-projected onto the tibial plateau planes. Then, best-fit

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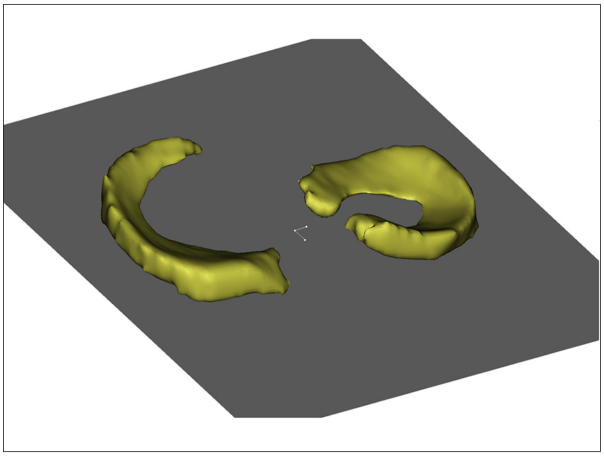

Figure 2. Meniscal models and tibial plateau plane were reconstructed in 3D.

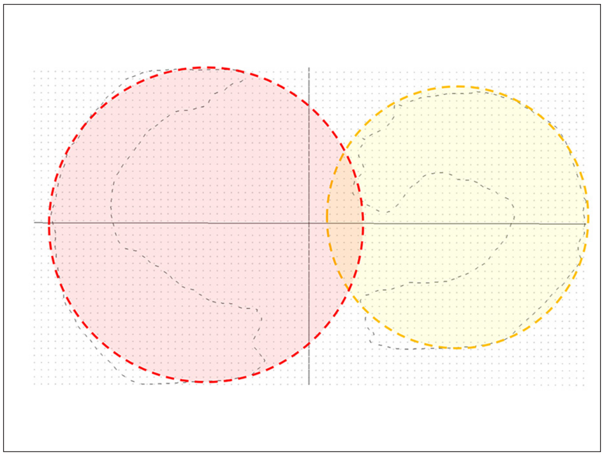

Figure 3. 2D projected menisci and the corresponding best-git circles are demonstrated.

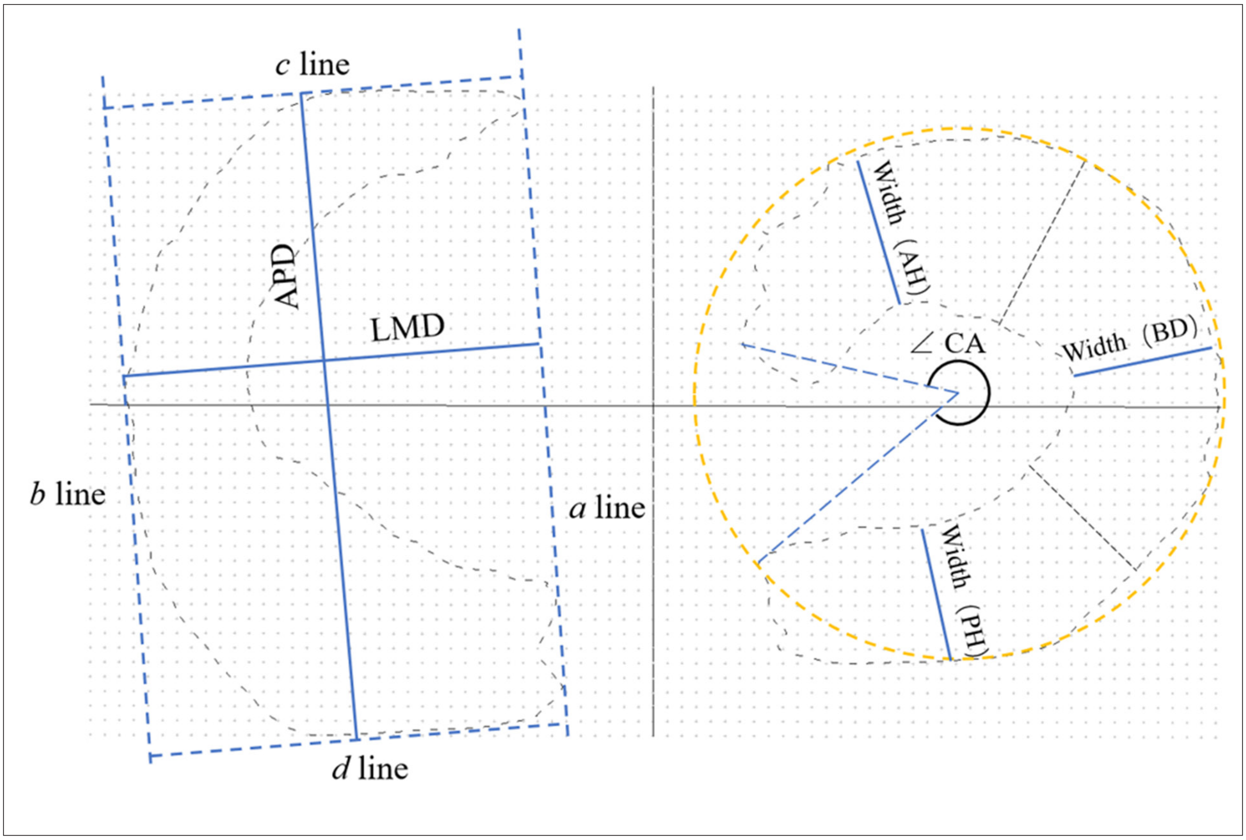

Figure 4. The measurements of meniscal anteroposterior diameter (APD), lateral-medial diameter (LMD), covering angle (CA), and meniscal width in AH, BD, and PH sections were performed on a 2D projection of the subject.

circles were used to outline the projected images to depict the sector covering the area of the medial and lateral meniscus (Figure 3). The covering angle (CA) of a meniscus was defined as the angle enclosed with lines connecting the center of the best-fit circle and the 2 most medial points of the anterior horn (AH) and posterior horn (PH) in a lateral meniscus (the 2 most lateral points in a medial meniscus). The lateral-medial distance (LMD) and anteroposterior distance (APD) of each meniscus was obtained on the same projection. For measuring the LMD, the line defined with the 2 most medial points in a lateral meniscus was set as the *a* line; another line parallel to the *a* line was drawn through the most lateral point of the meniscal body (BD) was defined as the *b* line; the distance between lines *a* and *b* is LMD. For measuring the APD,

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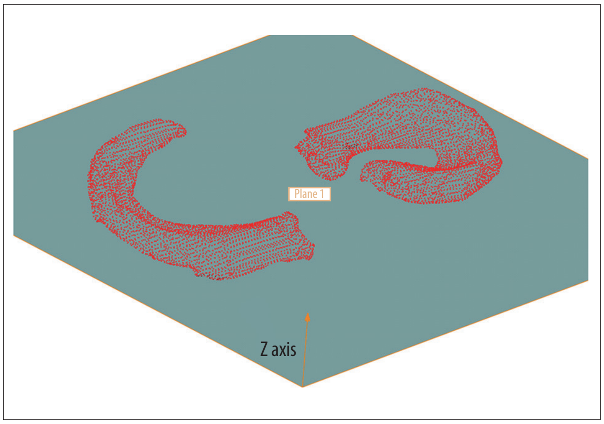

Figure 5. Meniscal model was converted to points cloud, and the value of Z axis of each point indicated local thickness.

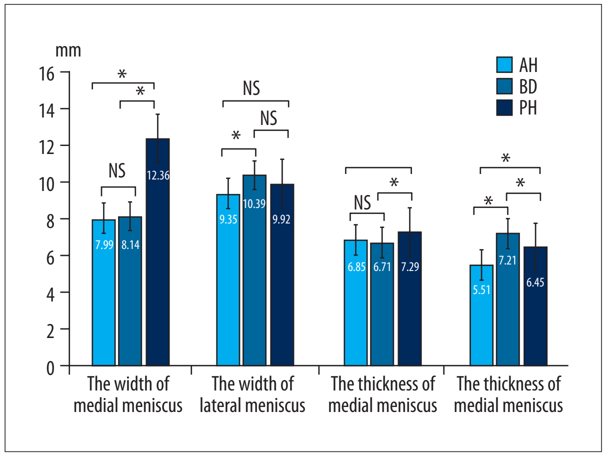

Figure 6. Comparison of the width and thickness of AH, BD, and PH of medial and lateral meniscus. * – statistically significant; NS – significant difference.

Table 1. Morphological measurements between medial and lateral meniscus.

	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Medial	7.99±1.47	8.14±1.62	12.36±1.72	6.85±1.10	6.71±0.92	7.20±1.09	33.18±3.47	45.41±3.55	265.55±8.42
Lateral	9.36±1.55	10.39±1.90	9.93±2.03	5.51±0.71	7.21±0.86	6.47±0.66	34.57±2.69	36.03±2.63	320.16±12.57
p	<0.001*	<0.001*	<0.001*	<0.001*	0.003*	<0.001*	0.018*	<0.001*	<0.001*

The values are expressed as the mean and the standard deviation. * $p<0.05$.

2 lines were drawn perpendicular to line *a* through the most anterior point and the most posterior point of the meniscus, respectively, named the *c* line and *d* line. APD was defined as the distance between lines *c* and *d*. For obtaining the widths of each meniscus, 3 sections were equally defined as meniscal anterior horn (AH), body (BD), and posterior horn (PH). The widths were measured at the middle of each section (Figure 4).

The meniscal thicknesses were acquired under Geomagic Control environment (Geomagic, USA), and the 3D models of the menisci and tibial plateau planes were imported into the software. The XY plane of the global 3D coordinate system was aligned with each of the tibial plateau planes, and the value of the Z axis in each selected top edge point of the models equals the thickness of the meniscus (Figure 5).

Statistical analysis

All statistical analyses were performed using SPSS version 17.0 (SPSS, Inc., Chicago, IL), and P<0.05 was considered to be statistically significant. The mean and standard deviations were calculated for continuous data. To assess the statistical significance of differences among anatomical parameters, independent and paired *t* tests were used for univariate analyses. Pearson's correlation analysis was used to assess the potential association between demographic data and anatomical parameters.

To assess interobserver reliability, 2 experienced surgeons independently performed the 3D reconstructions and measurements. To assess intraobserver reliability, the 3D reconstructions and the measurements were performed twice by the same researcher 1 month apart. The intraclass correlation coefficient (ICC) was used to calculate interobserver and intraobserver effects.

Results

The mean CA, LMD, and APD were 320.16°, 34.57 mm, and 36.03 mm, respectively, for the lateral meniscus, compared with 265.55°, 33.18 mm, and 45.41 mm in the medial meniscus group. The paired *t* test revealed statistically significant differences in all anatomical parameters between the lateral meniscus and medial meniscus groups (Table 1). Statistically significant differences were found in the width at all 3 sections between the lateral and medial meniscus groups (P<0.001, Table 1). The meniscal widths of AH and BD sections in the

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Table 2. Morphological differences of medial meniscus between sides.

	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Left	8.15±1.71	8.09±1.61	12.21±1.63	6.90±1.06	6.82±0.83	7.17±1.08	33.65±4.02	46.31±4.04	265.57±9.03
Right	7.83±1.19	8.20±1.65	12.51±1.82	6.79±1.16	6.60±1.00	7.23±1.11	32.70±2.82	44.51±2.77	265.53±7.92
p	0.313	0.697	0.371	0.572	0.217	0.802	0.153	0.009*	0.985

The values are expressed as the mean and the standard deviation. * $p<0.05$.

Table 3. Morphological differences of lateral meniscus between sides.

	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Left	9.11±1.29	10.10±1.81	9.97±1.76	5.57±0.67	6.93±0.74	6.46± 0.57	33.88±2.62	35.52±2.57	321.23±11.36
Right	9.60±1.76	10.68±1.97	9.88±2.30	5.46±0.76	7.49±0.88	6.47± 0.75	35.25±2.63	36.55±2.63	319.09±13.78
p	0.148	0.031*	0.866	0.414	0.002*	0.979	0.007*	0.014*	0.367

The values are expressed as the mean and the standard deviation.* $p<0.05$.

Table 4. Morphological differences of medial meniscus between genders.

	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Female	7.63±1.20	7.66±1.35	11.92±1.49	6.63±0.92	6.58±0.78	7.09±1.00	32.22±3.48	43.83±2.55	265.83±9.23
Male	8.67±1.71	9.06±1.71	13.19±1.85	7.25±1.31	6.96±1.11	7.40±1.24	35.00±2.71	48.42±3.26	265.03±6.80
p	0.01*	0.001*	0.006*	0.071	0.128	0.308	0.003*	<0.001*	0.734

The values are expressed as the mean and the standard deviation. * $p<0.05$.

Table 5. Morphological differences of lateral meniscus between genders.

	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Female	9.32±1.57	10.03±2.08	9.49±2.16	5.46±0.65	7.08±0.71	6.35±0.58	33.84±2.47	34.87±2.09	320.86±14.61
Male	9.43±1.54	11.07±1.29	10.77±1.45	5.61±0.82	7.46±1.06	6.70±0.76	35.96±2.61	38.23±2.11	318.83±7.37
p	0.795	0.019*	0.021*	0.398	0.161	0.058	0.003*	0.001*	0.484

The values are expressed as the mean and the standard deviation. * $p<0.05$.

lateral meniscus were significantly wider than those in the medial meniscus, but the width at PH section in the lateral meniscus was significantly narrower. For a medial and lateral meniscus, the widest locations were in PH and BD sections, and the narrowest location was AH in both sides. As depicted in Table 1, the thickness at AH and PH (6.85±1.10 mm and 7.20±1.09 mm) of the medial meniscus group were greater than in the lateral group (5.51±0.71 mm and 6.47±0.66 mm). Nevertheless, the thickness at BD section on the medial meniscus was significantly smaller (P=0.003, Table 1). The thickest locations were at PH and BD sections in the medial and lateral meniscus (Figure 6).

Between the left and right sides of the same subject, most of the morphological parameters of the medial meniscus were similar in both knees, but the APD in the right medial component was slightly smaller than the left (44.51±2.77 mm *vs.* 46.31±4.04 mm). In the lateral meniscus, the width and

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Table 6. Correlations of height, weight, meniscal measurements for lateral meniscus.

	Pearson Correlation (r)								
	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Height	–0.40	0.069	0.155	0.051	0.119	0.278	0.283	0.596	–0.217
p	0.765	0.606	0.247	0.705	0.373	0.035*	0.031*	<0.001*	0.102
Weight	–0.012	0.141	0.249	0.201	0.272	0.409	0.346	0.500	–0.121
p	0.926	0.290	0.060	0.131	0.039*	0.001*	0.008	<0.001*	0.364
BMI	0.008	0.141	0.253	0.252	0.298	0.406	0.312	0.368	–0.064
p	0.954	0.291	0.056	0.057	0.023*	0.002*	0.017*	0.005*	0.633

A strong correlative value is represented with r≥0.65, a fair correlative value is represented with r=0.50 to 0.64, and a weak correlative value is represented with r<0.50.

Table 7. Correlations of height, weight, meniscal measurements for medial meniscus.

	Pearson Correlation (r)								
	Width (mm)			Thickness (mm)			LMD (mm)	APD (mm)	CA (°)
	AH	BD	PH	AH	BD	PH			
Height	0.339	0.335	0.234	0.221	0.206	0.175	0.416	0.684	–0.078
p	0.009*	0.010*	0.077	0.096	0.121	0.188	0.001*	<0.001*	0.559
Weight	0.310	0.338	0.351	0.355	0.376	0.397	0.462	0.680	–0.021
p	0.018*	0.010*	0.007*	0.006*	0.004*	0.002*	<0.001*	<0.001*	0.873
BMI	0.245	0.273	0.366	0.37	0.411	0.451	0.411	0.574	0.011
p	0.064	0.038*	0.005*	0.004*	0.001*	<0.001*	0.001*	<0.001*	0.937

A strong correlative value is represented with r≥0.65, a fair correlative value is represented with r=0.50 to 0.64, and a weak correlative value is represented with r<0.50.

thickness at BD of the right knee were significantly greater than that of the left knee, but the difference was small (width: 10.68±1.97 mm *vs.* 10.10±1.81 mm; thickness: 7.49±0.88 mm *vs.* 6.93±0.74 mm); the APD and LMD measurements were also greater in the right (APD: 36.55±2.63 mm *vs.* 35.52±2.574mm; LMD: 35.25±2.63 mm *vs.* 33.88±2.62 mm) (Tables 2, 3).

When the measurements were stratified by sex, the CAs of bilateral menisci in women were close to those in men. For APD and LMD measurements, the results were significantly greater in men than in women. The meniscus was significantly wider in males than in females in all sections, but the widths of AH were similar. Finally, there was no difference in thickness between males and females (Tables 4, 5).

Between the meniscal anatomical parameters and body height and weight, as well as BMI, the APD of the lateral meniscus was positively correlated with height and weight (r=0.596, r=0.500), and this was also true for the medial meniscus group (r=0.684, r=0.680) (Tables 6, 7).

The reliabilities of measurements of meniscal anatomical parameters were assessed by ICC. The intraobserver ICCs (range, 0.92 to 0.98) and the interobserver ICCs (range, 0.84 to 0.91) both had excellent reliability.

Discussion

Our results showed that the thickness and width of each section of the lateral and medial meniscus were significantly different, and the PH in the medial and BD section in the lateral meniscus were thicker and wider. The CA of the medial meniscus was smaller than that of the lateral meniscus, which

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is metaphorically referred to as "C" shape compared with the "O" shape of the lateral side. The medial meniscus showed a greater APD and a smaller LMD, like an ellipse, while the lateral side had similar APD and LMD. Between the bilateral knee joints of the same volunteers, there was little difference in the morphology of the medial meniscus; while in the lateral meniscus, the APD and LMD, as well as the width and thickness of BD section in the right knee, were slightly larger than those in the left side. When stratifying by sex, we found that regardless of the side, the width, LMD, and APD of menisci in males were significantly larger than in females. No difference was found in CA between males and females. Although the mean meniscal thickness in males was greater, the difference was not significant. In addition, we found that body height and weight were strongly correlated with APD in the medial side and moderately in the lateral side.

The normal meniscus morphology plays an important role in protection of the knee joint; it can relieve knee pressure, absorb shocks, and cushion during weight-bearing activities [5]. Morphological changes of the meniscus significantly contribute to the pathogenesis of knee OA [6,7]. In a longitudinal cohort study using population-based healthcare data from Sweden, Snoeker et al. [8] reportedthat meniscal tear increased the risk of future diagnosed knee OA. Through 3D finite-elemental analyses, Li et al. [9] demonstrated meniscal injury leads to biomechanical changes that can accelerate the progression of knee OA, and they found meniscectomy can relieve symptoms but increases the incidence of osteoarthritis. Because of the high incidence of discoid lateral meniscus [10–12], corresponding morphological research has been published [6,13,14], but little attention was paid to the medial side. In addition, most of the research concentrated on fetal or animal menisci, but information on *in vivo* meniscal anatomies, especially in normal Chinese adults, is still limited. In the present study, menisci from healthy adults were reconstructed and measured based on MRI, which is a novel method for the 3D morphological evaluations of the meniscus *in vivo*. To the best of our knowledge, this is the first study to use CA in meniscal anatomy investigations, and this easy-to-use measurement can be employed to evaluate the integrity of weight-bearing ability of the meniscus and to potentially predict the possibilities of OA development in the knee. Our results revealed that the CAs of medial and lateral menisci in healthy Chinese are 265.55° and 320.16°, respectively. Any variations in CA can contribute to degeneration, root tear, or lateral discoid change of the meniscus.

Samoto et al. [12] measured the width of normal lateral menisci on the coronal plane of MRI, and found the average width was 10.1 mm, which is similar to the value obtained in the present study (9.89 mm). Our results also suggest that the widths of lateral menisci measured on multiple locations were generally consistent. Knowing the width of the lateral meniscus in healthy adults can help surgeons maintain an appropriate width during partial meniscectomy in meniscal injury or discoid meniscus cases, and it also helps to determine the placement of a lateral meniscus graft during meniscal allograft transplantation. On the contrary, the width of the medial meniscus changes remarkably from AH to PH, and our results are consistent with Karola's review [15]. Meanwhile, we found the PH of the medial meniscus was significantly wider than AH and BD, which contributed to a larger area of contact during axial loading and flexion, and this could potentially explain the high incidence of medial meniscus posterior root tears and posterior horn tears [5,16–18]. Additionally, the meniscal width plays a similar role as CA in reflecting the meniscal coverage on articular cartilage of the knee joint. The narrower width of the anterior section and smaller CA in the medial meniscus also illustrate the susceptibility of knees to medial compartment OA [6]. Interestingly, when comparing the morphologies between the menisci of bilateral knees, we found the lateral meniscus of the right knee is significantly different from that of the left knee, but the differences were small. Prodromos et al. [19] reported that 97% of the APD and LMD measurements between sides were within 3 mm based on 500 pairs of cadaveric menisci, and they concluded that human menisci were bilaterally symmetric in size. Since the differences suggested in the present study were only about 1 mm (3% difference) in diameter, it is not considered to be clinical meaningful. Therefore, we agree with the conclusions drawn by Prodromos et al. In light of these findings, our study may help guide the design of artificial menisci to avoiding meniscal reinjury or knee OA after MAT.

Research on meniscus thickness is limited, and no specific consensus has been reached. Araki et al. [13] measured the morphological parameters of the normal lateral meniscus on MRI, and reported that the thickness at AH, BD, and PH were 3.9 mm, 6.3 mm, and 6.4 mm, respectively. Subsequently, the anatomical study of normal menisci in 174 healthy subjects conducted by Erbagci et al. [20] showed that the thickness at AH, BD, and PH of the lateral meniscus were 4.33 mm, 4.94 mm, and 5.36 mm, respectively. The thicknesses reported in the literature are smaller than those of the present study (5.51 mm, 7.21 mm, and 6.47 mm, respectively). Erbagci et al. [20] also reported the corresponding sections of the medial meniscus were 5.32 mm, 5.03 mm, and 5.53 mm, respectively, which were also smaller than the results of our study (6.85 mm, 6.71 mm, and 7.20 mm, respectively). The meniscus thickness gradually decreases from the attachment side to the free edge. In our work, the menisci were reconstructed in 3D, and the thicknesses of the meniscus was measured in 3D using the topmost point on the attachment edge of each section. This methodology allowed us to accurately acquire the measurements without any interference from image slicing or manually measuring on 2D MRI images. In addition, we found no

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significant difference in the thickness of any location between males and females, and the correlations between body height and the meniscal thickness were not significant or were only weakly significant. These findings suggest that the meniscal thickness is not be a key factor when considering the sizing in MAT or designing meniscal prostheses. Body weight and BMI were positively correlated with meniscus thicknesses in multiple locations (Tables 6, 7), but since the correlations were weak and the weight or BMI is more likely to change during development or during the lifespan, these factors are not important.

Regarding the diameters of menisci, we found that body height and weight were strongly correlated with meniscal APD, especially in the medial side. Previously, researchers studied anthropometric data to predict meniscal graft size [21–23]. Stone et al. [21] concluded that correlation coefficients between medial and lateral APD and height were r=0.5259 and r=0.5290, respectively, which is consistent with our study (r=0.684 in the medial; r=0.596 in the lateral side). Body weight and BMI presented similar positive correlations with meniscal APD, but both were weaker, suggesting the limited contributions of weight bearing in the changes of meniscal dimensions. Netto et al. [24] conducted a study based on knee MRI and found weight and height not only had strong correlations with APD (r >0.7), but also with LMD. However, the correlations between LMD and height/weight/BMI in our study were weak. Such differences might be attributed to the fact that our subjects were younger and less likely to have meniscal degeneration or extrusion.

Limitations

Some limitations should be considered when interpreting the results of this study. Firstly, differences in meniscus shape changes may be underestimated due to the non-weight-bearing condition during MRI acquisition [25]. Although it is sufficient to investigate the normal morphology of meniscus with the current methodology, mechanical loading treatments during MRI scanning are needed to mimic the working status of weight-bearing in the human meniscus. Secondly, the age range of the population recruited in this study was relatively narrow. However, the purpose of this study was to summarize the meniscal anatomy of healthy Chinese adults, and inclusion of more elderly people would have involved more degenerated knees. Finally, although the number of subjects included in this study was relatively small, we believe it was sufficient for studying the morphology of the meniscus in young healthy adults.

Conclusions

In conclusion, the present study described the meniscus morphology *in vivo* on MRI-based 3D reconstruction models. The meniscal width and diameter were correlated with the demographic data, but the thickness and covering angle were did not substantially differ by sex, height, or BMI. This information will be helpful for the evaluation and diagnosis of meniscal dysplasia or injuries, providing normal geometries for the construction of bionic menisci and increasing the reliability of meniscal sizing in MAT.

Conflict of interest

None.

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