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Meniscus sizing using three-dimensional models of the ipsilateral tibia plateau based on CT scans – an experimental study of a new sizing approach

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Abstract

Purpose: Selection of a meniscus allograft with a similar three-dimensional (3D) size is essential for good clinical results in meniscus allograft surgery. Direct meniscus sizing by MRI scan is not possible in total meniscectomy and indirect sizing by conventional radiography is often inaccurate. The purpose of this study was to develop a new indirect sizing method, based on the 3D shape of the ipsilateral tibia plateau, which is independent of the meniscus condition.

Methods: MRI and CT scans of fifty healthy knee joints were used to create 3D surface models of both menisci (MRI) and tibia plateau (CT). 3D bone models of the proximal 10 mm of the entire and half tibia plateau (with / without intercondylar area) were created in a standardized fashion. For each meniscus, the best fitting “allograft” couple out of all other 49 menisci were assessed by the surface distance of the 3D meniscus (best available allograft), of the 3D tibia plateau (3D-CT) and by the radiographic method of Pollard (2D-RX).

Results: 3D-CT sizing was significantly better by using only the half tibia plateau without the intercondylar area ($p < 0.001$). But neither sizing by 3D-CT, nor by 2D-RX could select the best available allograft. Compared to 2D-RX, 3D-CT sizing was significantly better for the medial, but not for the lateral meniscus.

Conclusions: Automatized, indirect meniscus sizing using the 3D bone models of the tibia plateau is feasible and more precise than the previously described 2D-RX method. However, further technical improvement is needed to select always the best available allograft.

Keywords: Knee, Meniscus sizing, Meniscus medial, Meniscus lateral, Three-dimensionally segmentation, Magnetic resonance, MRI scans, Inter-observer variation

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Background

Partial or total meniscectomy is often a valuable treatment option to improve the symptoms of patients with meniscal tears. However, the biomechanical properties of the meniscus are thereby lost and early osteoarthritis or residual pain might occur [16].

Meniscus allograft transplantation has become a powerful tool in the treatment of postmeniscectomy syndrome in young patients with proven clinical and functional efficacy [21].

Overall, best biomechanical and clinical results could be achieved by the selection of an allograft with a similar three-dimensional (3D) meniscus shape [4, 10, 12, 19, 20, 25]. Nevertheless so far, the 3D shape of the meniscus was completely ignored and meniscus sizing performed only by meniscal width and length in conventional radiography [17, 26], MRI [7, 11, 15, 22] or – rarely – by CT [5, 9, 14]. Although good average sizing values are reported in literature, inaccuracy of sizing is still a relevant problem and has to be improved. The ignored 3D shape of the meniscus might lead to an inaccurate meniscus size selection, regrettably corresponding with clinical experience and confirmed by recently published data [1, 6, 9, 13, 14, 17, 22, 23].

So far, MRI sizing by width and length of the contralateral healthy meniscus is considered to be the gold standard [13, 18]. But recently, a 3D meniscus sizing method was

proposed by using the contralateral meniscus as a template, based on the closest mean surface distance [1, 2]. Herewith, the superiority of 3D sizing compared to sizing only by meniscal width and length has already been shown. However, this sizing method is strongly dependent on a healthy contralateral meniscus and time-consuming manual MRI segmentation of the menisci.

The aim of this study was, therefore, to develop a new indirect meniscus sizing method, that should be independent of the meniscus condition, fully automatized with validated technologies and should improve the accuracy of the entire 3D meniscus shape selection. We expected a more accurate sizing using the entire 3D information of the tibia plateau, compared to sizing only by meniscal width and length.

Methods

The methodological part is composed by three parts: Part 1 with focus on the basic material, imaging and measurement methods. Part 2 with description and implementation of the 3D CT sizing method. And part 3 with analysis and validation of the sizing methods. Ethical approval was granted by Kantonale Ethikkommission of Zurich, Switzerland (BASEC-Nr. 2018–00856), and informed consent was obtained from all individual participants included in the study. A written consent for publication of their clinical details and/or clinical images

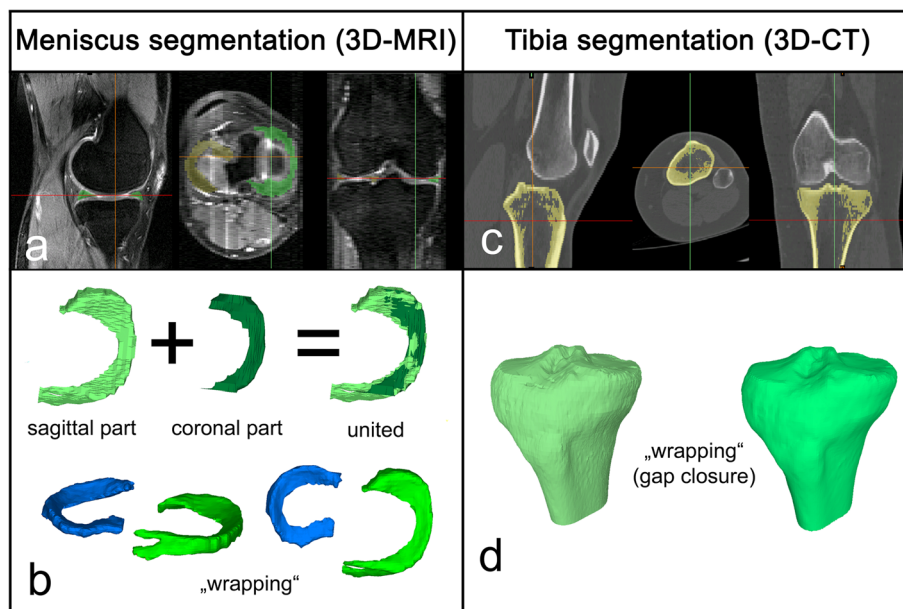


Fig. 1 3D surface models: **a.** Step 1 (Meniscus): Segmentation was performed in sagittal and coronal slides by manually annotation of all meniscus tissue. **b.** Step 2 (Meniscus): Three-dimensional sagittal and coronal meniscus parts were merged. If there was a shift due to patients movement during acquisition of the different reconstructions, manual realignment has to be performed first. Wrapping of the meniscus surface models was done by using the functionality of the 3-matic software. **c.** Step 1 (Tibia): Segmentation was performed in axial, coronal and sagittal reconstructions by semi-automatic annotation of all tibia bone. **d.** Step 2 (Tibia): Wrapping of the tibia surface models was done by using the functionality of the 3-matic software

was obtained from each patient. The datasets used and analyzed during the current study are available from the corresponding author on reasonable request. There are no conflicts of interest.

Part 1: Material/imaging/measurements

Material

We retrospectively analyzed fifty unilateral knee joints of fifty patients with patellofemoral disorders. Inclusion criteria were mature skeletal age (completely closed growth plate of femoral and tibial knee epiphyses in MRI), healthy meniscus (no tears, degeneration or extrusion), no tibio-femoral osteoarthritis (Kellgren & Lawrence grade 0), available magnetic resonance imaging (MRI; sagittal/coronal/axial plane; slice thickness of 3 mm), computer tomography (CT; axial; slice thickness of ≤ 2 mm) and conventional radiography (RX; antero-posterior (AP) / medio-lateral (LAT)).

Mean age of all fifty patients was 27.6 years (16–46 years). There were 18 left and 32 right knee joints of 35 female and 15 male patients.

Imaging

All radiographs (RX) were performed in a standard fashion, as already described in a previous paper [1]. Plain anteroposterior (AP) and lateral (LAT) view were acquired with a detector-to-tube distance of 1.15 m and using calibrators for the correction of magnification (Ysio, Siemens Healthcare, Erlangen, Germany).

All CT scans were performed on a 64-slice CT scanner (Philips Brilliance 64, Philips Healthcare, or Somatom Definition AS, Siemens Healthcare) using our standard protocol for knee joints. Technical specifications: tube voltage 120 kV, tube current 250 mAs, collimation 64×0.625 mm, and rotation time 0.5 s. Axial images were reconstructed with 1 mm slice thickness.

All MRI scans consisted of sagittal, coronal and axial sequences and were performed on a 3.0 T magnet (Skyra-fit, Siemens Healthcare, Erlangen, Germany) with a dedicated knee coil in supine position with stretched knee, as a part of the standard MRI protocol [2].

Measurements

3D surface models (meniscus, tibia plateau):

1) Meniscus: (3D-MRI)

Segmentation: Meniscus segmentation was done manually by two trained orthopaedic surgeons (S.B., L.J.) in sagittal and coronal slides (bi-planar) with the Materialise Interactive Medical Control System (MIMICS) 3D reconstruction software program 18.0 (Materialise, Leuven, Belgium), as described in a previous paper [2]. The 3D surface models of the final meniscal models were smoothed using the

wrapping functionality of the software with gap closing distance 0.0 and smallest detail 1.0 (Fig. 1a, b).

Mirroring: All 3D surface models of the left meniscus were mirrored to a right meniscus.

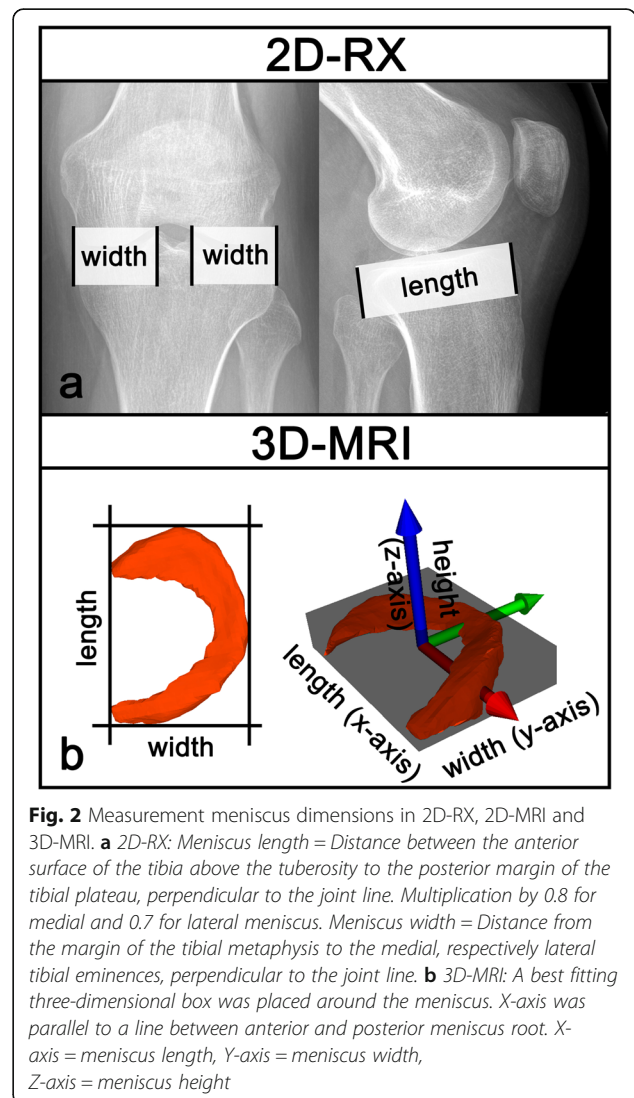
2) Tibia plateau: (3D-CT)

Segmentation: Tibia plateau segmentation was done semi-automated in axial, coronal and sagittal reconstructions with MIMICS. The segmentation was controlled and – if necessary due to the 2 mm slide thickness – slightly corrected by two trained orthopaedic surgeons (S.B., L.J.). The 3D surface models of the cortical layer were created and the same wrapping functionality was used as before (Fig. 1c, d).

Mirroring: All 3D surface models of the left tibia plateau were mirrored to a right tibia plateau.

Meniscus dimensions (width, length, height):

1) Conventional radiography: (2D-RX) (Fig. 2a)



Meniscal width and length was measured based on the method proposed by Pollard [17]. Meniscus width was measured in the AP view as the distance from the margin of the tibial metaphysis to the medial, respectively lateral tibial eminences, perpendicular to the joint line. Meniscus length was measured in the lateral view as the distance between the anterior surface of the tibia above the tuberosity to the posterior margin of the tibial plateau, perpendicular to the joint line. All distances were measured twice by two different readers (S.B., L.J.) and the average value of both were used for further calculations.

- 2) Three-dimensional MRI: (3D-MRI) (Fig. 2b) Width, length and height was measured as described in a previous paper [2]. An oriented bounding box (OBB) was calculated from all model points. The OBB is the minimal-volume rectangular box fully enclosing the meniscal model. The box was now rotated around the z-axis (Fig. 2b, blue axis) until the box was oriented parallel to the anterior and posterior meniscus root (Fig. 2b, red axis). The box was now adjusted in width, length and height until the meniscus was fully enclosing by the box. Length (x-axis), width (y-axis) and height (z-axis) of the meniscus can now be defined by the lengths of the box.

Part 2: 3D-CT sizing

3D-CT sizing is an indirect sizing method, based on 3D surface bone models of parts of the tibia plateau. The sizing method is based on the assumption that an equal tibia plateau contains an equal shaped meniscus, similar to an imprint of a trace. Thereby, not the most similar meniscus is ordered from the tissue bank, but the most similar tibia plateau – with indirectly contained most similar meniscus (Fig. 3).

Creation of the different predefined 3D models of the tibia plateau

All 3D bone models of the tibia plateaus were imported into the in-house developed planning software CASPA (Computer Assisted Surgery Planning Application, Balgrist CARD AG). An average right tibia template of 3.5 cm length with preconfigured cutting planes served as a target alignment model for automatized adjustment and standardized creation of the different tibia plateaus. Following cutting planes were first defined with regard to the tibia plateau template: A first axial cutting plane (Fig. 4; red cutting plane) was set 1 cm distal and parallel to the medial and lateral tibia plateau. A second sagittal cutting plane (Fig. 4; blue and yellow cutting plane) was set perpendicular to the first and parallel to the

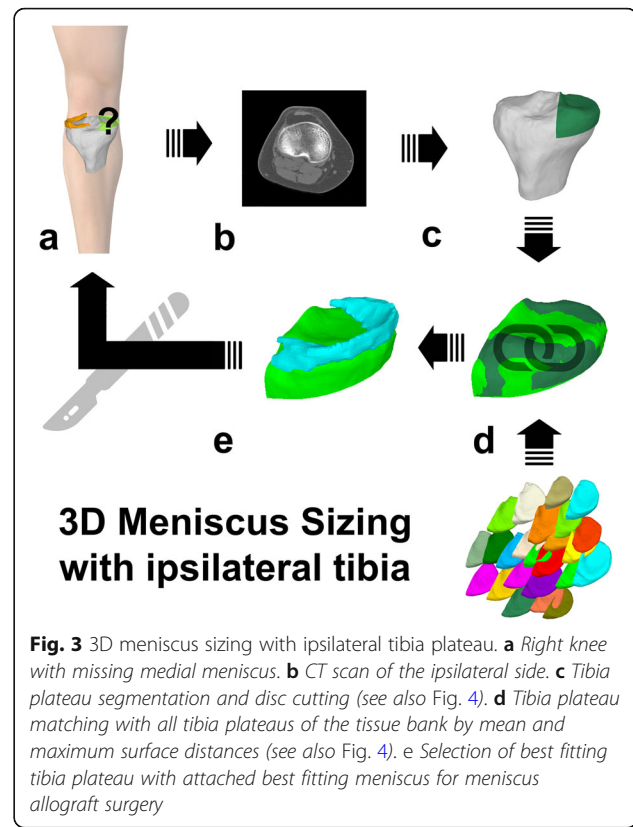


Fig. 3 3D meniscus sizing with ipsilateral tibia plateau. **a** Right knee with missing medial meniscus. **b** CT scan of the ipsilateral side. **c** Tibia plateau segmentation and disc cutting (see also Fig. 4). **d** Tibia plateau matching with all tibia plateaus of the tissue bank by mean and maximum surface distances (see also Fig. 4). **e** Selection of best fitting tibia plateau with attached best fitting meniscus for meniscus allograft surgery

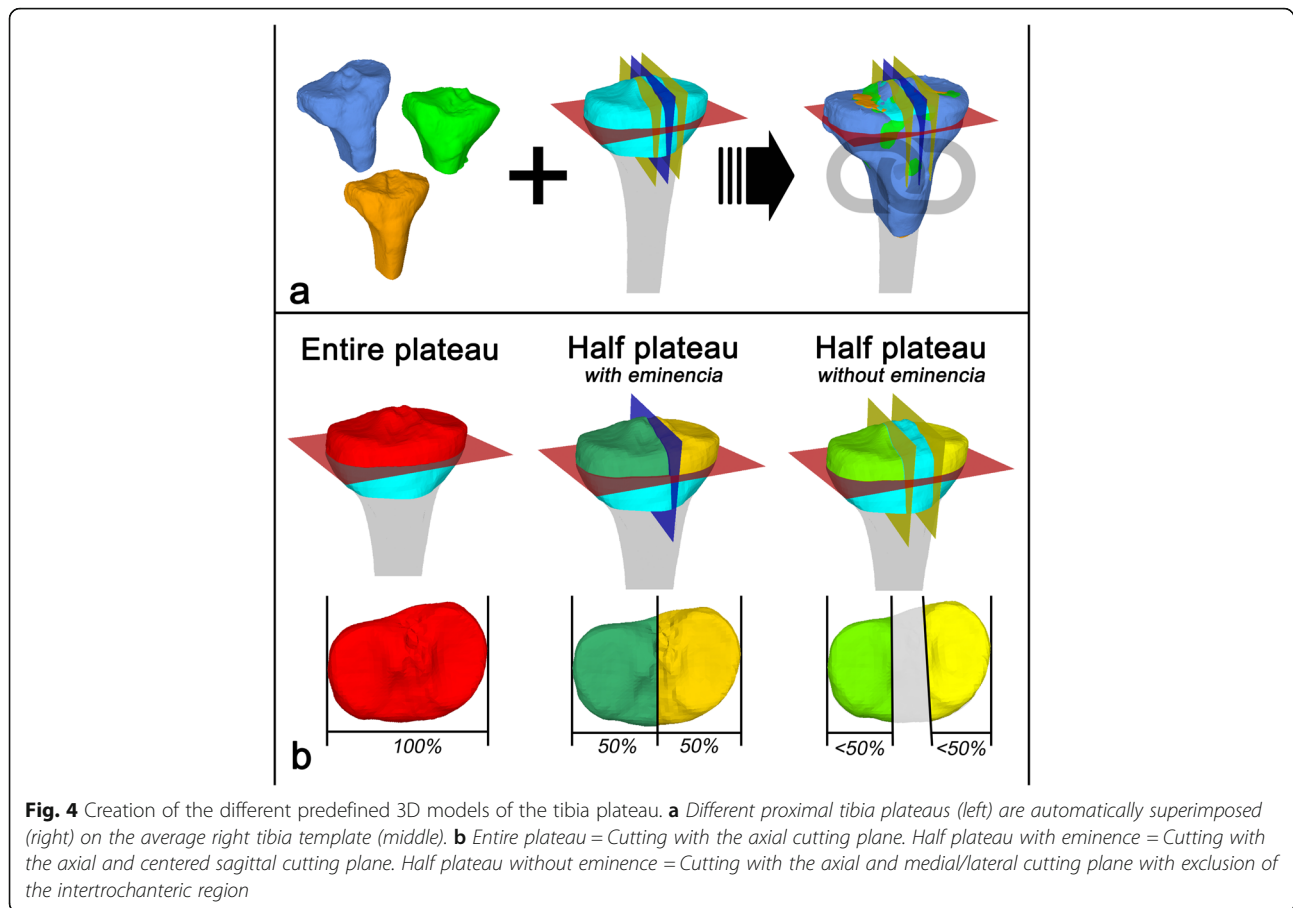
orientation of medial and lateral intercondylar tubercles and tibia plateau.

For tibia plateau sizing, we selected three different configurations:

- 1) Entire tibia plateau (100%): The proximal tibia was only cut with the first, axial cutting plane (Fig. 4; red cutting plane).
- 2) Half tibia plateau with intercondylar area (50%): The proximal tibia plateau was cut with the first and second cutting plane. Thereby, the second cutting plane was set centered to the medial and lateral plateau dimensions (Fig. 4; blue cutting plane).
- 3) Half tibia plateau without intercondylar area (< 50%): The proximal tibia plateau was cut with the first and second cutting plane. Now, the second two cutting planes were set once through the medial and once through the lateral intercondylar eminence (Fig. 4; medial and lateral yellow cutting planes).

3D-CT sizing by closest surface points distance

The similarity of two 3D models can be quantified by the closest surface points distance [2]. After automatically superimposing using the iterative closest point (ICP)



algorithm, mean (MeSD) and maximum distances of all surface points (MaSD) of one model to the closest points of the second model – and vice versa – can be calculated. For further calculations, only the highest values are used according to the Hausdorff distance [2]. This process can now be repeated between all 3D models. The best fitting pair can be found by the lowest mean and maximum surface distances.

Part 3: validation

Unlike previously sizing methods, that allowed directly comparison of measured width and length of the original and the calculated meniscus dimensions, the 3D-CT sizing method allows only indirect measurements. Therefore, we solved this problem by a simulation, as already used in a previous study about 3D-MRI meniscus allograft sizing [1].

In a first step, for each meniscus, the best fitting “allograft” was selected by all three methods (3D-MRI, 3D-CT, 2D-RX). Thereby, the other 49 menisci served as an imaginary “tissue bank”. All measurements were made separately for the medial and lateral meniscus.

- 1.) 3D-MRI meniscus sizing by surface distance (best possible allograft) (3D-MRI):

Direct meniscus sizing by the lowest mean surface distance was assessed to select the best possible 3D fitting meniscus in our “tissue bank” of 49 different menisci. Thereby, meniscus “1” was matched with meniscus “2”, “3”, ... to “50”. The best fitting couple (1 × 49 possibilities) was selected and used for further calculations. Then, meniscus “2” was matched with meniscus “1”, “3”, ... to “50”, and again, the best fitting couple was selected. This was repeated for all fifty menisci. Together, there were 2'450 (50 × 49) possibilities. All calculations could be done full automatized by an in house-developed application.

Mean/maximum surface distance and the differences of width/length/height between the best fifty couples were used for comparison of the different sizing methods.

- 2.) 3D-CT tibia sizing by surface distance (3D-CT):

Indirect meniscus sizing by the tibia plateau was done in two steps. First, the corresponding tibia plateau (tibia)

of the original meniscus served as template. Tibia “1” (of corresponding meniscus “1”) was matched with tibia “2”, “3”, ... to “50”. The best fitting couple (49 possibilities) was selected. Then, tibia “2” was matched with tibia “1”, “3”, ... to “50” and the best couple was selected. This was repeated for all fifty tibia plateaus (2’450 possibilities). Second, the selected best fitting tibias were replaced by the corresponding menisci.

Mean/maximum surface distance and the differences of width/length/height between the best fifty couples were used for comparison of the different sizing methods.

This procedure was done with the 1) entire tibia plateau, 2) half tibia plateau with intercondylar area and 3) half tibia plateau without intercondylar area.

- 3.) 2D-RX tibia sizing by width/length according to Pollard [17] (2D-RX):

Width and length were measured as described above in conventional radiography of all fifty knee. The best fitting meniscus pair for meniscus “1” was selected out of the three-dimensional measured width/length of the other 49 menisci. Thereby, width and length were equally weighted and selected by the lowest error sum of squares: $(Width_{Sized} - Width_{Allograft})^2 + (Length_{Sized} - Length_{Allograft})^2$ (2’450 possibilities).

Mean/maximum surface distance and the differences of width/length/height between the best fifty couples were used for comparison of the different sizing methods.

Finally, the best fifty selected menisci of each method were compared according to the MeSD, MaSD and the differences of width/length/height. Further, outliers were analyzed as a mismatch between the “original” and “selected meniscus” of > 5 mm in width, > 5 mm in length, > 4 mm in height or > 5 mm MaSD [1].

Statistics

Average performance of the different CT-based matching techniques was compared using repeated measures ANOVA with Greenhouse-Geisser correction where applicable. The CT technique with the best average performance measured by mean surface distance between the original meniscus and the chosen allograft was further compared against the other applied modalities. Here average performance (i.e. accuracy) in all included proximity measures as well as consistency (i.e. precision) of the different methods was assessed. The former was conducted analogously to the method described above and the latter was determined using Levene’s test for equality of variance. The assessed methods were then compared in pairwise manner using paired t-tests to analyze consistency and F-testing to analyze accuracy. Significance levels were Bonferroni-corrected.

Results

Meniscus sizes

The medial meniscus was on average 31.9 mm (range 24.8–38.2 mm, SD 3.14) wide, 46.4 mm (range 37.4–55.0 mm, SD 46.4) long and 8.9 mm (range 6.1–13.5 mm, SD 1.51) high. The lateral meniscus was on average 32 mm (range 24.8–39.8 mm, SD 3.52) wide, 35.3 mm (range 29.4–42.4 mm, SD 3.01) long and 9.7 mm (range 7.8–13.2 mm, SD 1.37) high.

3D CT sizing

The half tibia plateau without the intercondylar eminence yielded the most reliable sizing. Significant differences could be found in mean surface distance ($F(2) = 13.075, p < 0.001$) and maximum surface distance ($F(1.780) = 8.491, p = 0.001$) of the medial meniscus and in mean surface distance ($F(1.789) = 14.375, p < 0.001$) and maximum surface distance ($F(2) = 7.606, p = 0.001$) of the lateral meniscus. All results can be seen in Table 1.

Table 1 3D-CT Sizing by entire and half tibia plateau

(mm)	Entire plateau		Half plateau with eminence		Half plateau without eminence	
	MM	LM	MM	LM	MM	LM
Mean Surface Distance						
Mean	1.32	1.39	1.23	1.29	0.96	1.02
Min-Max	0.71–2.57	0.73–2.84	0.74–2.48	0.74–2.32	0.67–1.44	0.71–1.46
Std	0.447	0.495	0.452	0.399	0.180	0.216
Maximum Surface Distance						
Mean	5.51	5.58	5.11	5.29	4.36	4.61
Min-Max	2.35–10.1	3.13–8.58	2.97–9.9	3.07–8.79	2.09–8.2	2.87–7.96
Std	1.86	1.61	1.89	1.60	1.22	1.08

MM Medial Meniscus, LM Lateral Meniscus

Validation

Allograft selection by the 3D surface of the target meniscus (3D MRI) served as the gold standard (= best possible meniscus allograft out of the imaginary tissue bank of 49 different menisci). With this quantity of only 49 different allografts, it was possible to select a relatively similar allograft with a MeSD less than 1.12 and MaSD less than 5.33 mm. And there were no meniscus mismatch (outliers) > 5 mm in width/length and > 4 mm in height.

Neither the 3D-CT nor 2D-RX sizing method could detect in each case the best fitting allograft (3D-MRI). (see Tables 2 and 3, Figs. 5 and 6).

Meniscus sizing by 3D-CT was significantly better than 2D-RX considering the average values (p = at least 0.002). There were no significant differences for the lateral meniscus. Outliers could be reduced by 56% for medial and 9% for lateral meniscus, compared to the 2D-RX method.

All results are listed in Tables 2 and 3 and Figs. 5 and 6.

Table 2 Sizing results of medial meniscus

MEDIAL MENISCUS					
	3D MRI (most similar menisci in tissue bank)	3D CT		2D RX	
Mean Surface Distance (MeSD)					
Mean (mm)	0.787	0.962		1.14	
Min-Max (mm)	0.59-1.12	0.67-1.44		0.74-1.93	
Std	0.114	0.180		0.283	
p-value 3D MRI	-	<0.001	<0.001	<0.001	<0.001
p-value 3D CT	-	-	-	<0.001	0.002
Maximum Surface Distance (MaSD)					
Mean (mm)	2.95	4.36		4.94	
Min-Max (mm)	2.09-5.33	2.09-8.20		3.05-7.87	
Std	0.587	1.22		1.16	
p-value 3D MRI	-	<0.001	<0.001	<0.001	<0.001
p-value 3D CT	-	-	-	0.002	0.725
Width Difference					
Mean (mm)	1.28	2.40		2.77	
Min-Max (mm)	4.4	6.4		7.8	
Std	1.22	1.89		2.00	
p-value 3D MRI	-	<0.001	0.003	<0.001	<0.001
p-value 3D CT	-	-	-	<0.001	<0.001
Length Difference					
Mean (mm)	1.19	2.02		4.11	
Min-Max (mm)	4.2	6.4		10.5	
Std	1.11	1.60		2.48	
p-value 3D MRI	-	0.003	0.012	<0.001	<0.001
p-value 3D CT	-	-	-	<0.001	<0.001
Height Difference					
Mean (mm)	1.33	1.40		1.63	
Min-Max (mm)	4.3	3.8		6.0	
Std	1.10	1.18		1.21	
p-value 3D MRI	-	0.735	0.625	<0.001	0.001
p-value 3D CT	-	-	-	<0.001	0.005
Outliers					
W/L/H	0	12		27	
MaSD	1	14		19	

Mean = Mean values in mm. Min-Max = Minimum and Maximum value. SD = Standard Deviation. P-value = Displayed are the p-values of pairwise comparison of all applied methods. The left cell displays the p-value for the comparison of mean performance whereas the right cell displays p-values for differences in variance of the methods. Significance level after Bonferroni-correlation: $\alpha = 0.0083$. Outliers: W = Width difference > 5 mm and L = Length difference > 5 mm and H = Height difference > 4 mm / MaSD = Maximal surface distance > 5 mm

Table 3 Sizing results of lateral meniscus

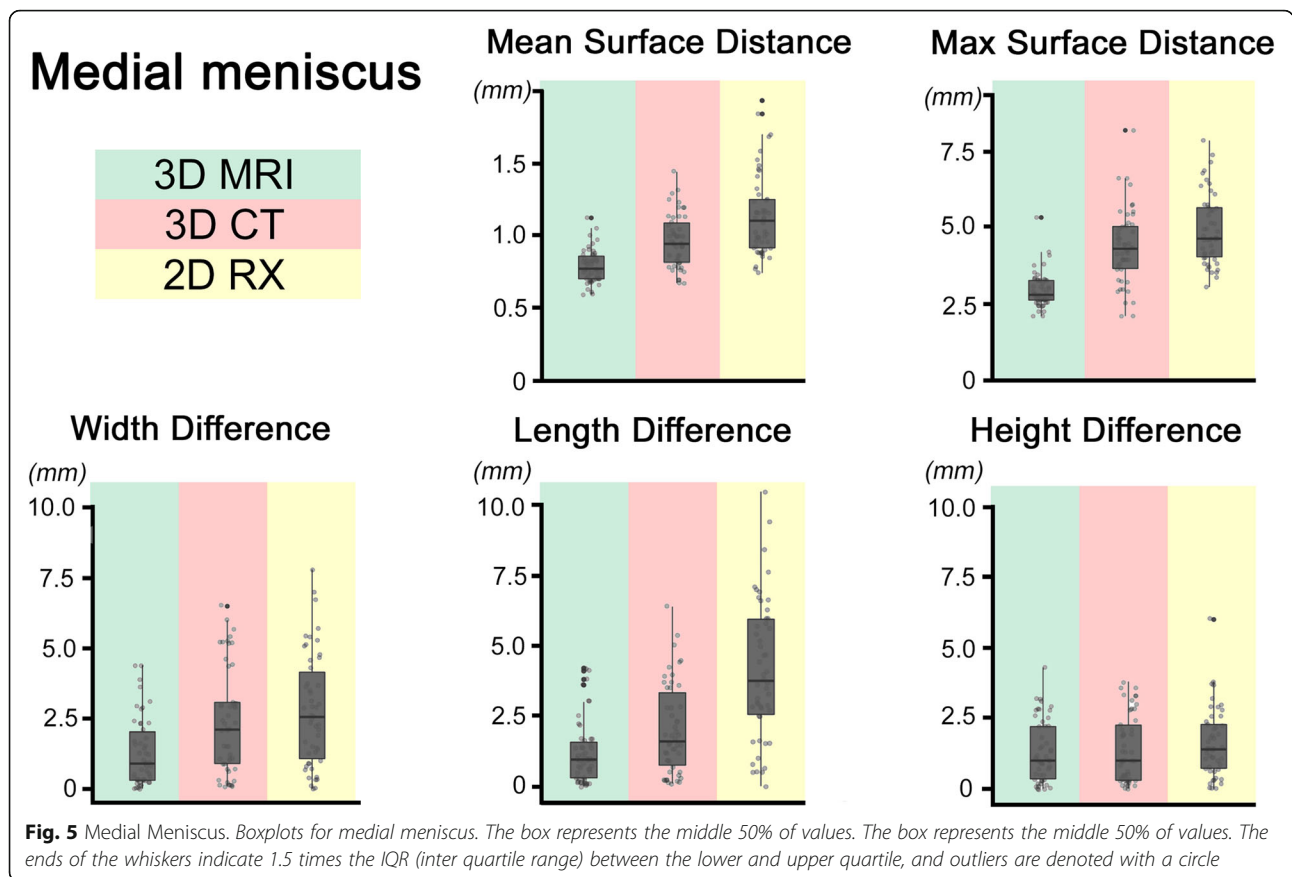
LATERAL MENISCUS					
	3D MRI (most similar menisci in tissue bank)	3D CT		2D RX	
Mean Surface Distance (MeSD)					
Mean (mm)	0.83	1.02		1.09	
Min-Max (mm)	0.61-1.35	0.71-1.46		0.71-1.86	
Std	0.154	0.216		0.274	
p-value 3D MRI	-	<0.001	0.008	<0.001	<0.001
p-value 3D CT	-	-	-	0.082	0.155
Maximum Surface Distance (MaSD)					
Mean (mm)	2.91	4.61		4.73	
Min-Max (mm)	2.28-5.00	2.87-7.96		2.28-7.36	
Std	0.563	1.08		1.36	
p-value 3D MRI	-	<0.001	<0.001	<0.001	<0.001
p-value 3D CT	-	-	-	0.576	0.110
Width Difference					
Mean (mm)	1.34	2.61		2.49	
Min-Max (mm)	3.60	6.8		7.50	
Std	0.927	1.59		1.97	
p-value 3D MRI	-	<0.001	<0.001	<0.001	<0.001
p-value 3D CT	-	-	-	0.719	0.137
Length Difference					
Mean (mm)	1.75	2.51		2.56	
Min-Max (mm)	5.40	7.6		10.00	
Std	1.32	1.93		1.97	
p-value 3D MRI	-	0.015	0.008	0.012	0.003
p-value 3D CT	-	-	-	0.903	0.777
Height Difference					
Mean (mm)	1.30	1.47		1.26	
Min-Max (mm)	4.20	4.10		3.70	
Std	1.05	1.18		0.893	
p-value 3D MRI	-	0.413	0.417	0.791	0.251
p-value 3D CT	-	-	-	0.276	0.051
Outliers*					
W/L/H	2	10		11	
MaSD	1	13		18	

Mean = Mean values in mm. Min-Max = Minimum and Maximum value. SD = Standard Deviation. P-value = Displayed are the p-values of pairwise comparison of all applied methods. The left cell displays the p-value for the comparison of mean performance whereas the right cell displays p-values for differences in variance of the methods. Significance level after Bonferroni-correlation: $\alpha = 0.0083$. Outliers: W = Width difference > 5 mm and L = Length difference > 5 mm and H = Height difference > 4 mm / MaSD = Maximal surface distance > 5 mm

Discussion

The most important finding of the present study is, that automatized, indirect meniscus sizing by the 3D tibia plateau is feasible and more precise than by the radiographic method of Pollard. To our knowledge, this is the first attempt to use the 3D surface of the tibia plateau for indirect meniscus allograft sizing. It is based on the hypothesis, that the menisci of two similar tibia plateaus are similar in the 3D size. Thereby, not the allograft itself has to be ordered. Rather, the surgeon receives an

equal tibia plateau with attached perfect fitting meniscus allograft. This method would be especially advantageous if meniscus fixation is performed by bone plugs [20] or combined osteochondral allograft with meniscal allograft transplantation [8]. An extension of this sizing method could be the possibility, to create a digital database of surface models of different tibia plateaus with corresponding meniscus models. 3D meniscus surface models, which could be needed as a template for biomimetic 3D printed scaffolds [24, 27] or 3D meniscus tissue

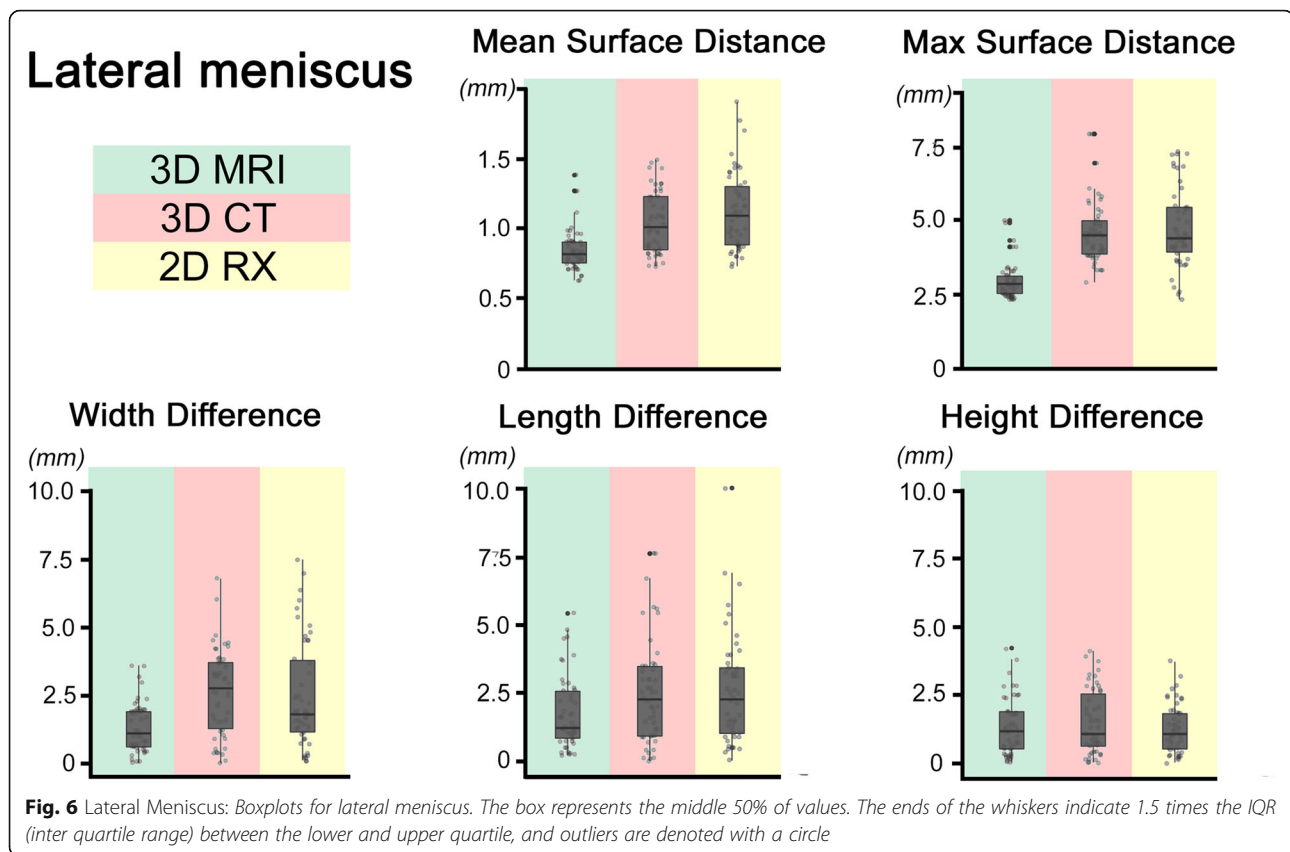


engineering [3] could now be selected indirectly over the tibia plateau with a CT scan of the ipsilateral tibia.

With the currently used cutting planes, sizing with the entire plateau failed completely, while sizing without the intercondylar eminence could show the best results. As a conclusion, the medial and lateral tibia plateau do not correlate well and the better the anatomical separation of the plateau, the better would also be the sizing. While the meniscal base is defined well by the edge of the tibia plateau, the meniscus roots do not have a directly visible bony landmark. Nevertheless, the medial and lateral intercondylar tubercles with attached anterior and posterior cruciate ligaments are used as “indirect” landmarks to define the ends of the meniscus roots in bony based meniscal sizing methods [5, 9, 14, 17, 26]. Therefore, the intercondylar region between the medial and lateral intercondylar tubercles has been excluded on the average tibia plateau template. Herewith, the accuracy could be increased – compared to the method of Pollard [17]– for medial meniscus significantly, but not for lateral meniscus. Further, outliers could be reduced by 56% for medial and 9% for lateral meniscus. Nevertheless, there is still great potential for increasing the results of this study, because neither sizing by 3D-CT, nor by 2D-RX could select in each case the best possible allograft

(3D-MRI). Although the differences seem to be small (mean surface distance (MeSD) 0.18–0.35 mm, maximum surface distance (MaSD) 1.25–1.99 mm), a mean MaSD of 4.2–4.9 mm (compared to 2.91–2.95) indicates that the 3D shape could not be reproduced completely by both sizing methods [1]. According to meniscal width, length and height, the 3D-CT sizing method was better than the radiographic method, except for the meniscal height of the lateral meniscus. Although some tissue banks have much more different allografts than only 49, even then, they do not possess always the same 3D meniscus size and a more or less approximation of meniscal width and length of the measured dimensions could increase already existing inaccuracy, as shown in a previous study with an imaginary allograft tissue bank of 138 different menisci [1]. Nevertheless, a reliable sizing method would also detect the best possible 3D meniscus allograft, even in a tissue bank with less variety or rare meniscus shapes.

There is reason why we believe that a further improvement is possible. 3D-CT sizing depends crucially on the cutting planes of the proximal tibia. We deliberately chose an automatized method to exclude inter-rater and inter-reader inaccuracy by manual measurements. The basic idea was that similar tibia plateaus would be



matched similar good or similar bad to the average tibia plateau template. But, as mentioned above, the better the anatomical separation of the plateau, the better would be the sizing. Although the intercondylar region was excluded in a standardized fashion, an individual adaptation of the tibia plateau size was not performed. Thereby, a large tibia could probably have some remaining intercondylar region and otherwise smaller tibia some missing parts of the plateau. Further, the different orientation of the medial and lateral tibia plateau was matched by the entire plateau orientation. Thereby, the orientation of medial and lateral plateau would be approximated. But so far, an association of three-dimensional meniscal size and corresponding tibia plateau was never examined in detail. An inter-individual anatomical mismatch is therefore not excluded and could be responsible for part of the inaccuracy.

There are some limitations of this study.

1) Anatomical comparison: Measurements have not been compared with the anatomical meniscus dimensions. We chose 3D meniscus surface models as gold standard, which has not yet been proven. But MRI measurement seems to be the most exact imaging method for meniscus sizing, based on the literature [7, 9, 11, 13, 18].

- 2) Meniscus segmentation: Because of the retrospective design of the study, MRI had a slice thickness of up to 3 mm, which could falsify the 3D surface model. Therefore, we performed bi-planar segmentation on sagittal and coronal images, as described in a previous study with excellent inter-rater and inter-reader reliability for width and length (ICC_{inter} 0.913–0.973, ICC_{intra} 0.955–0.987, 2).
- 3) Meniscus shape deformation: The 3D shape of the medial and lateral meniscus changes during knee movement and could falsify our study results. All MRI scans were performed in supine position with full extended knee joint. Therefore, this limitation should be very low.
- 4) Imaginary “tissue bank”: We validated our method by an imaginary tissue bank of 49 different menisci. A larger tissue bank would have automatically a larger variety of the allografts. Therefore, the accuracy could be improved by an increasing number of different allografts. Nevertheless, there are also tissue banks with only 15–30 different menisci (on request) and a reliable sizing method should also be able to select a good fitting allograft out of a small databank.

- 5) Correlation of meniscus and tibia plateau size: So far, an inter-individual anatomical difference between the correlation of meniscus and tibia plateau size is not excluded and could be responsible for a part of sizing inaccuracy. Additional inaccuracy could be present in patients with beginning osteoarthritis and alterations of the tibia plateau (osteophytes). This has to be declared as a potential limitation of 3D-CT sizing.

Overall, 3D-CT sizing could be an interesting approach to revolutionize the currently used meniscus sizing methods, which could be especially useful for small companies with limited allografts to increase the accuracy of allograft selection. Although 3D-MRI meniscus sizing by the contralateral side seems to be – at the moment – more precise, 3D-CT sizing could be improved by machine learning and/or individual adjustment of the cutting planes. The advantages would be the independence of the meniscus condition, full automatized with already existing technologies, less cost intensive and faster compared to the 3D-MRI sizing method. But, as already mentioned in previous study [2], the tissue banks have to offer this option, which is associated with higher costs.

Conclusion

Automatized, indirect meniscus sizing by the 3D bone models of the tibia plateau is feasible and more precise than by the radiographic method of Pollard. This method might become the gold-standard after total meniscectomy if 2D-MRI sizing is not possible. However, further technical improvement is needed to select always the best available allograft.

Abbreviations

2D: Two-dimensional; 3D: Three-dimensional; AP: Antero-Posterior; CT: Computer Tomography; H: Height; i.e.: id est; that is to say; ICP: Iterative Closest Point; kV: Kilovolt; L: Length; LAT: Lateral; LM: Lateral Meniscus; mAs: Milliampere seconds; MaSD: Maximum Surface Distance; MeSD: Mean Surface Distance; MIMICS: Materialise Interactive Medical Control System; mm: Millimetre; MM: Medial Meniscus; MRI: Magnetic Resonance Imaging; OBB: Oriented Bounding Box; RX: Radiography; Std: Standard Deviation; T: Tesla; W: Width

Authors' contributions

SB, SFF, LV and LJ were involved in the idea and design of the study. All authors participated in the development of the protocol and final design. SB and LJ participate in the measurements and data analysis. RS participated in the radiological part. TG participated the statistic analysis. The author(s) read and approved the final manuscript.

Competing interests

None declared.

All authors were fully involved in the study and preparation of the manuscript. The manuscript and the material within will not be submitted for publication elsewhere.

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