Original Article

Assessment of the deformation model of the proximal tibia in the course of degenerative disease: analysis of the 3-dimensional mathematical model

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Background: The high tibial osteotomy (HTO) is an effective knee-saving procedure, which relieves arthritis symptoms and prolongs the life of the knee joint. This procedure requires detailed preoperative planning. Usually, the contralateral side is used as a template for this purpose. Some intra-operative complications made us thinking how exactly the degenerative disease alter the epiphysis if the tibia. Our study aimed to assess morphological differences between healthy knees and degenerative knees using a three-dimensional mathematical model.

Methods: Twenty-three computed tomography (CT) examinations were collected out of 237 individuals screened for inclusion/exclusion. The inclusion criteria were: age between 40 and 69 years, degenerative knees with visible varus deformation, and signs of radiological osteoarthritis (OA) in the knee joint (such as joint space narrowing, subchondral sclerosis, subchondral cyst formation, and osteophytes. The average age of the included patients was 56.2 years. Nine men's and 14 women's knee joints were used for the calculation and comparisons.

Results: Female varus knees showed much more significant variability in tibial plateau dimensions according to sides of the body than male ones. These differences were statistically significant (P=0.03). In comparison between the basal bone and bones with OA, variability in 3D dimensions was statistically significant only for lateral condyles in males' right knees (P=0.025). Compared to the degenerative knees to the most average, healthy knees, there were significant differences in the measured surface area of males' right knees for both condyles: for the medial P=0.0046, for lateral P=0.005. Male varus knees had a statistically more considerable (P=0.028) surface area for all measured condyles. Angles of inclination differ significantly between knees with OA and healthy knees in the male population for the medial condyle plateau in the left knees. The female population for the lateral condyle in left knees and the medial condyle in right knees.

Conclusions: The proximal tibial plateau deformation showed high variability in the two-dimensional and three-dimensional analysis in the designed mathematical models. This finding must be considered during preoperative planning.

Keywords: Tibia; three-dimensional model (3D model); anatomical variations

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Introduction

Osteoarthritis (OA) of the knee is often a cause of considerable deformation of the proximal tibia and previous studies have shown that this joint is more commonly affected by degenerative changes that any other in the human motor system (1).

There are a few treatment methods we can offer to patients depending on the age or the stage of disease.

When Jackson published the first reports of high tibial osteotomy (HTO) in 1958 (2), it became an established treatment for young, active patients with symptomatic arthritis of the knee, significantly improves their quality of life (1). An important aim of HTO is to prevent or delay the need for total knee replacement. As a result of the operation the lower limb force line axis is transferred to the lateral compartment, what reduces the load of the medial compartment and delays the progress of OA. However, this procedure requires detailed preoperative planning with an assessment of axial deformity of the lower extremity and congruency of the knee joint. HTO is predominantly scheduled for patients with unicompartmental medial OA, and varus knees.

One of the HTO's intraoperative complications is lateral hinge or intra-articular fracture (3), which are concerning for surgeons because it can be critical in correction loss and delayed or nonunion and consequently results in poor patient satisfaction. This made us thinking of possible overloads within the bone structure.

We decided to examine the way chronic degenerative diseases modify the geometry of the articular surfaces of the knee joint.

There has been a long-standing interest in the geometric bilateral symmetry of the bones forming the knee joint (4-6). This interest is partly due to the symmetry postulation that is frequently made in clinical assessments and research studies.

Most often, the contralateral unaffected side is used as a model to plan corrective osteotomy (7,8). This way of preoperative planning assumes that there is no significant differences between the left and right extremities. Moreover, these templates assume that there are insignificant differences between males' and females' proximal tibia morphology.

We divided our study into two parts.

In first stage of the research was to design a mathematical model for 3-dimensional (3D) reconstruction of average proximal tibia, in healthy knees, separately for males and females, as well as for right and left limbs. Results were published in the article: "Assessment of morphological differences of the proximal tibia in healthy knees: analysis of the 3-dimensional mathematical model" (9). In second part of our study, described in this paper, dimensional base was created for varus tibia in patients with OA. Both parts were carried out with the same methods to reliably compare the results. We present the following article in accordance with the MDAR checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-21-1210/rc).

Methods

The methodology of imaging and data processing was identical as described in our previous paper about 3D model of healthy knees (10). In this part of the study the analysis was focused on comparing varus tibia due to OA to the 3D model created in our previous publication (9). After this comparison all the differences between healthy bone dimensions and dimensions in varus tibias with OA were possible to analyze.

Data collection

Computed tomography (CT) scans of patients who had undergone CT scanning between 2015 to 2019 with idiopathic OA of the knee were collected from the university hospital database.

Our test group were patients in age between 40 and 70 years, with idiopathic OA and varus knees. We excluded patients with OA due to trauma. Because our study did not disclose any private patient data, individual consent for this retrospective analysis was waived. Each CT scan was evaluated by a trained medical doctor for signs of radiological OA in the knee joint (such as joint space narrowing, subchondral sclerosis, subchondral cyst formation and osteophytes). All inclusion criteria fulfilled CT examinations collected from 23 patients out of 237

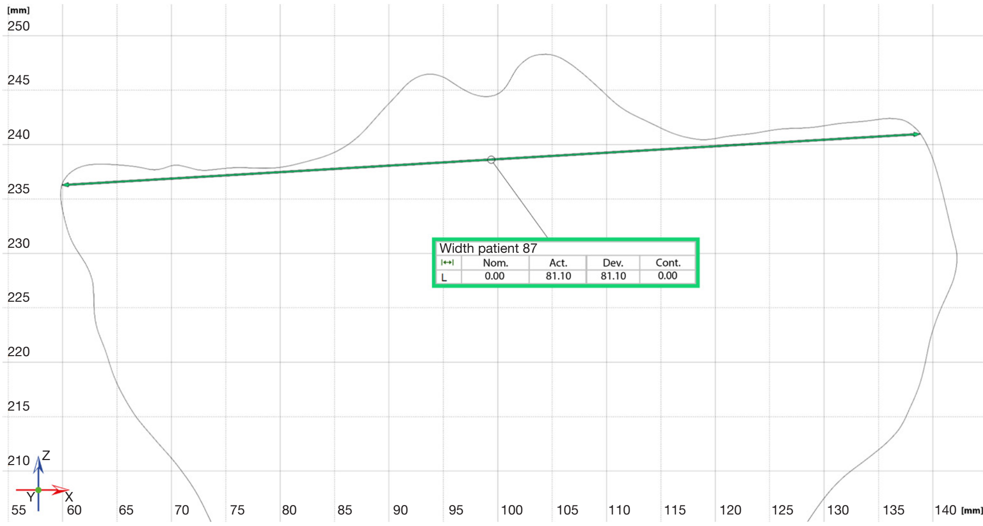

Figure 1 An example of a width measurement based on the left male bone.

individuals screened for inclusion/exclusion criteria.

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). An approval from the Local University Ethical Committee was obtained for the study design and data acquisition from CT scans. Because our study did not disclose any private patient data, individual consent for this retrospective analysis was waived. The average age of the included patients was 56.2 (range, 40–69) years. There were 9 men and 14 women in the test group. For the calculation and comparisons, separately right and left knee joints, were used.

Imaging

The CT scans were made using a Siemens SOMATOM Sensation 64 CT scanner. The acquisition parameters were the following: tube voltage 120 kVp, with automatic selection of exposure conditions-CARE DOSE, slice thickness 1 mm, a matrix size of 512×512 pixels, and a pixel size of 1.52344 mm, rotation time 1 s, Pitch 0,55. The first part of the work was transforming 2D CT images into 3D geometry by the image segmentation process. This action was intended to obtain a virtual 3D model named later as CAD body (CAD-computer-aided design). Later, the models were edited in 3D modeling software to obtain a closed model needed for numerical calculations. Then with GOM Inspect V8 SR1 (Braunschweig, Germany) and ANSYS 2019 R3 software (by ANSYS Inc. company, Canonsburg, PA, USA), 3D models were analyzed. Right and left tibial bones as well as the medial and lateral tibial condyle plateau were analyzed separately.

Bone width

First, the bone width was measured in the longest line in the cross-section view at the mid-plane at the coronal view (*Figure 1*). The width was calculated separately for each bone using GOM Inspect software.

2D dimensions' analysis

3D models of osteoarthritic bones were compared to the CAD body of most average bone (created in the first part of the study). Then cross-section plane was created in the measured center of base bone in the Y-axis view. Differences in the shape in Z-axis were measured by comparing examined bones to the base one at the line of the created cross-section. Models alignment was automatically calculated by the software, according to the middle line. For every measurement, the result was a set of points at equal distance (0.50 mm) in the X-axis (*Figure 2*). All measured points were in the same position according to gender and side of the body (right/left leg). A colorful map of deviations was created for better visualization distance and direction in which examined bone differ from the basal, healthy one. The black contour illustrates basal bone, the colorful spectrum shows the shape of the bone to be compared (legend on the right side in *Figure 2*).

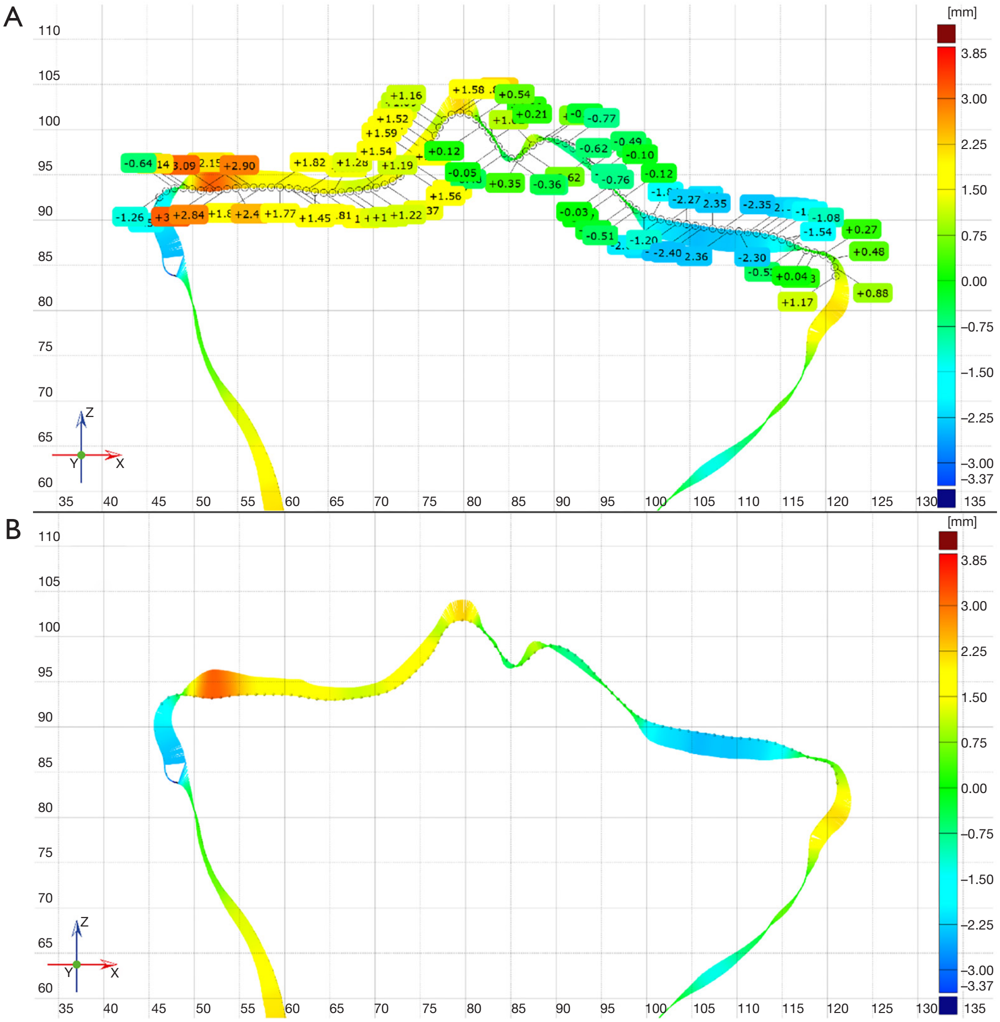

Figure 2 Example of a cloud of measurements points in 2D cross-section in case of female left bone: (A) with visible measurement points, (B) without points—only visualization.

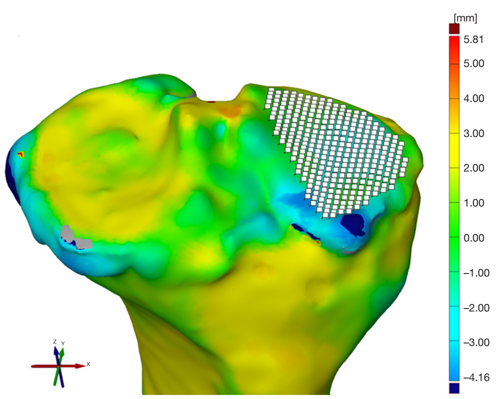

Figure 3 Example of a map of deformation with the cloud of measurements points in the case of lateral female plateau from left bone.

3D dimensions' analysis

The differences in dimension over the entire surface of the plateau were measured by generating a deformation map on whole geometry. Again, in this case, all 3D models were compared to the basic one. Then the set of measurement points was generated and calculated separately for the medial and lateral plateau. In this case measurement points were created at an equal distance of 1.20 mm (*Figure 3*).

Plateau surface area

The surface area for each plateau separately was measured using the SpaceClaim module for ANSYS software. The surface area was determined according to the highest points

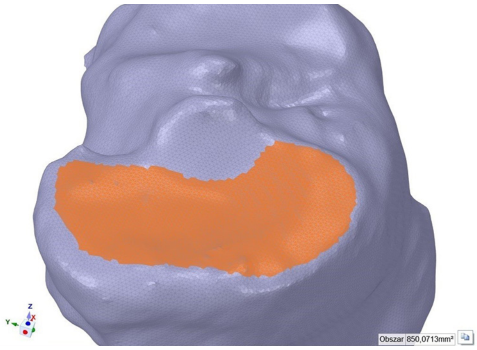

Figure 4 Example of measurement of plateau surface area.

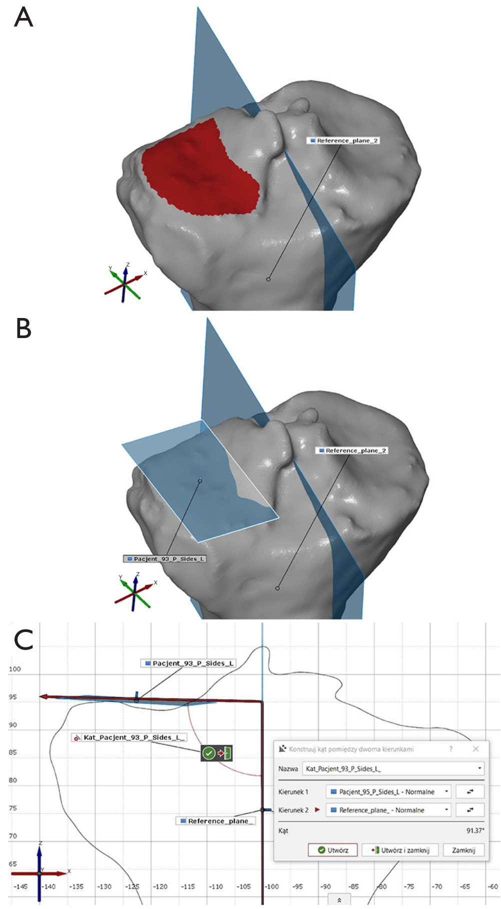

Figure 5 The angle of inclination of the plateau. (A) Measurement area; (B) visualization of the plane on which the measuring line is determined; (C) the determined angle analyzed—between the reference plane and the plateau plane.

of geometry as compared to the lowest points in the plateau area (*Figure 4*).

The angle of inclination of the plateau

To measure the angle of inclination of the plateau at first bones were aligned like in section "2D dimensions analysis" and "3D dimensions' analysis". The orientation of the reference plane is based on the center axis of the bone. Two reference planes were added—one in ZY-axis (*Figure 5A*) and second—in ZX-axis (*Figure 5B,5C*). The last step was the measurement of the angle between the reference plane and planes of the plateau. An example of the measured angles is shown in *Figure 6*. The procedure was the same for every single 3D mesh. Every comparison used the same reference plane.

Statistical analysis

Data obtained by measurements were tested using a single factor analysis of variance (ANOVA) test statistical significance assumed at a level of P<0.05. Statistical analysis was the determination of mean and median and standard deviation (SD). The fille area limits are the minimum and maximum values.

Results

Bone width

An averaged measured width in varus knees for the female was: 72.25±3.35 mm for the left knees and 72.17±2.49 mm for the right knees. An averaged measured width in men's varus knees was: 82.27±2.07 mm for the left knees and 82.80±2.16 mm. Results are illustrated in *Figure 6*.

2D dimensions' analysis

Graphical illustrations of calculated 2D deviations at cross-section analysis are shown in *Figure 7*.

Female varus knees showed much bigger variability in tibial plateau dimensions according to sides of the body than male ones, these differences were statistically significant (P=0.03).

In comparison the varus bones to our base bone, created in the first part of our study, only male right knees differ significantly (P=0.018) (*Table 1*).

3D dimensions' analysis

Results of the created map of deviations show average differences in the whole area of the plateau (*Figure 8*). In

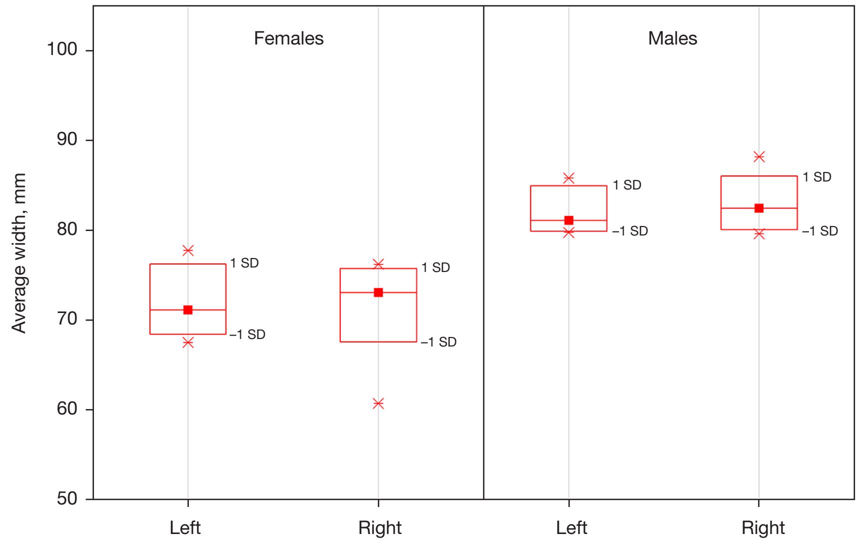

Figure 6 Average bone width. SD, standard deviation.

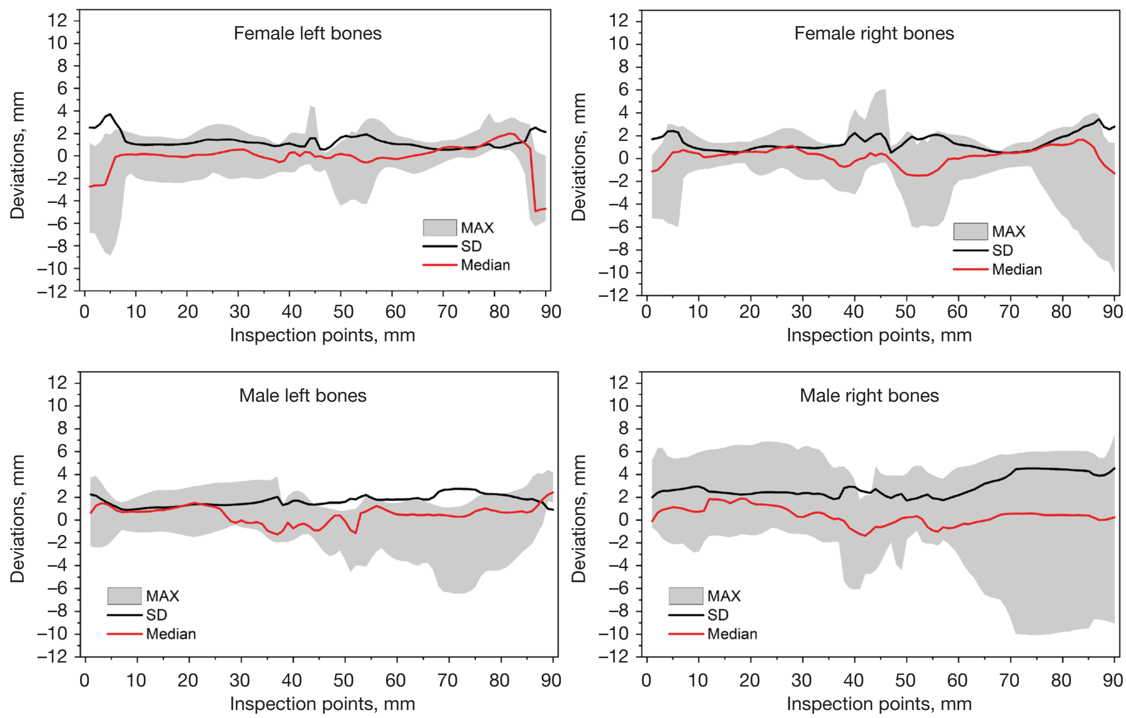

Figure 7 Graphical illustrations of 2D deviations of the tibial plateau. SD, standard deviation.

comparison between the basal bone and bones with OA, variability in 3D dimensions was statistically significant only for lateral condyles in male's right knees (P=0.025).

There was no statistically significant differences between sides for both genders and between ganders in varus knees (*Table 2*). Quite big differences were found in female population in medial condyles for both sides of the body (*Table 2*). In *Figure 9* are shown diagram results for each gender. Results of the created map of deviations show average differences in the whole area of the plateau (*Figure 8*).

Table 1 Results of the calculations for varus bones

Gender	Condyle	P			
		2D dimensions analysis	3D dimensions analysis	Plateau surface area	Angle of inclination
Female left	Medial	0.51	0.062	0.74	0.08
	Lateral		0.57	0.26	–
Female right	Medial	–	0.086	0.96	–
	Lateral		0.77	0.8	0.44
Male left	Medial	–	0.8	0.45	0.002
	Lateral		0.47	0.5	0.6
Male right	Medial	0.018	0.13	0.0046	0.95
	Lateral		0.025	0.005	0.77

P, P value of U Mann-Whitney test, significance P<0.05.

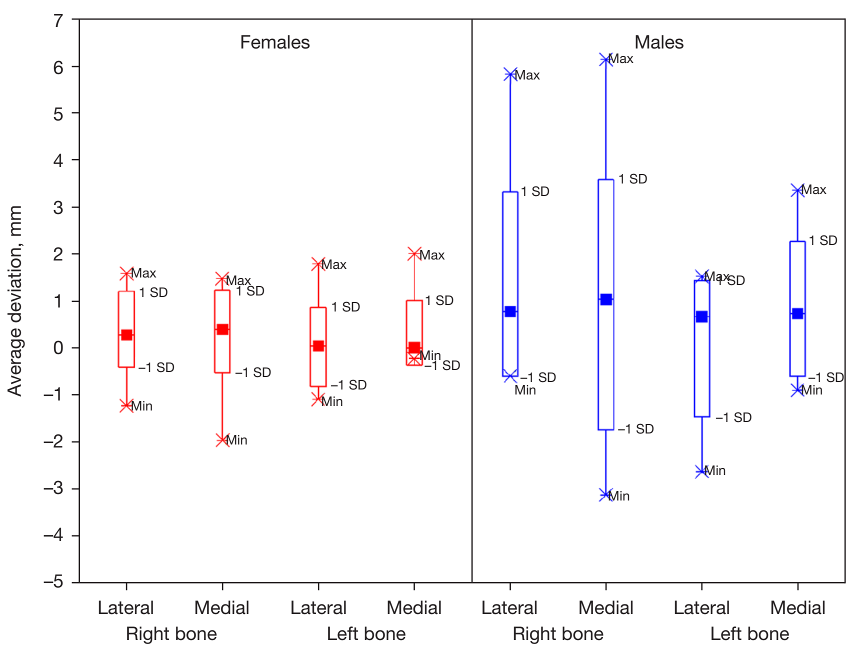

Figure 8 The average dimensional difference for each plateau for each gender. SD, standard deviation.

Plateau surface area

In comparison the degenerative knees to the most average, healthy knee there were significant differences in the measured surface area of male's right knees for both condyles: for the medial P=0.0046, for lateral P=0.005 (*Table 1*). Male varus knees had a statistically bigger (P=0.028) surface area for all measured condyles. The final results of measurement of the surface area of each plateau are shown in *Figure 10*.

The angle of inclination of the plateau

Angles of inclination differ significantly between knees with OA and healthy knees in the male population for the medial condyle plateau in left knees, in female population for the lateral condyle in left knees and medial condyle in right knees (*Table 1*). A significant difference between

Table 2 Results of the calculations. Comparison of the degenerative knees to the healthy knees

Gender	Condyle	2D dimensions analysis (mm)			3D dimensions analysis (mm^2)			Plateau surface area (mm^2)			Angle of inclination (degrees)		
		Mean ± SD	Min/Max	P	Mean ± SD	Min/Max	P	Mean ± SD	Min/Max	P	Mean ± SD	Min/Max	P
Female left	Medial	−0.03±1.28	−2.2/2	0.03*	0.33±0.69	−0.22/2	0.79**	864±145	695/1,128		79±3.6	75/86	0.001**
	Lateral				0.02±0.84	−1.1/1.8	0.37*	612±84	534/799		86±3.7	77/92	
Female right	Medial	0.14±1.39	−2.9/2.2		0.35±0.8	−1.9/1.5	0.34*	821±131	609/1,139	0.53*	78±2.4	73/82	0.29*
	Lateral				0.39±0.8	−1.2/1.6	0.88**	624±79	445/748	0.27*	89±3.2	83/95	0.03*
Male left	Medial	0.3±1.7	−2.5/2.4	0.9*	0.8±1.43	−0.9/3.3	0.38**	1020±162	815/1,257	0.028**	80±1.7	78/83	0.01**
	Lateral				−0.02±1.45	−2.6/1.5	0.99*	830±292	561/1,514		89±5.5	76/94	
Male right	Medial	0.37±2.88	−4.3/5.5		0.91±2.66	−3.12/6.15	0.79**	1137±221	855/1,606	0.24*	77±8.5	55/83	0.16*
	Lateral				1.36±1.96	−0.6/5.8	0.34*	795±78	662/905	0.48*	89±4.5	80/94	0.74*

P, P value of U Mann-Whitney test, significance P<0.05. Marked with * when tested between sides within same gender; marked ** when tested between single-name condyles within same gender. SD, standard deviation; min, minimum; max, maximum.

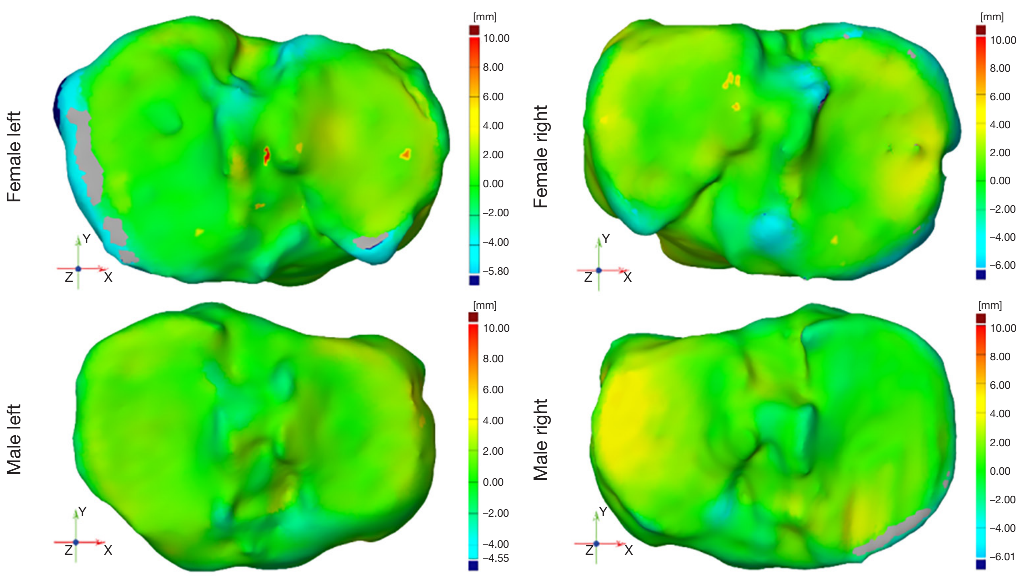

Figure 9 Graphical illustrations of 3D deviations of the tibial plateau.

degenerative knees was observed for medial and lateral condyles in female knees according to side of the body, and for medial condyles in male population, as males had lower angle values. Results of calculated average angles of inclination of a plateau concerning the central axis are shown in *Figure 11*.

Discussion

OA disease process is about premature wear and degeneration of joint tissue. Destruction in most cases begins with the medial compartment of the knee joint, which leads to a distortion of the limb axis. The main goal of the treatment of OA of the knee joint is to stop its progression, relieve pain, improve functional capacity and improve the quality of life of patients. HTO is one of the methods of surgical treatment in the treatment of OA of the knee. This treatment allows even distribution of pressure forces on the articular surfaces, relieving the sick joint compartment and reducing pain. One of the observed intraoperative complications is lateral hinge or intra-articular fracture and treatment failure. That fact made us thinking about possible

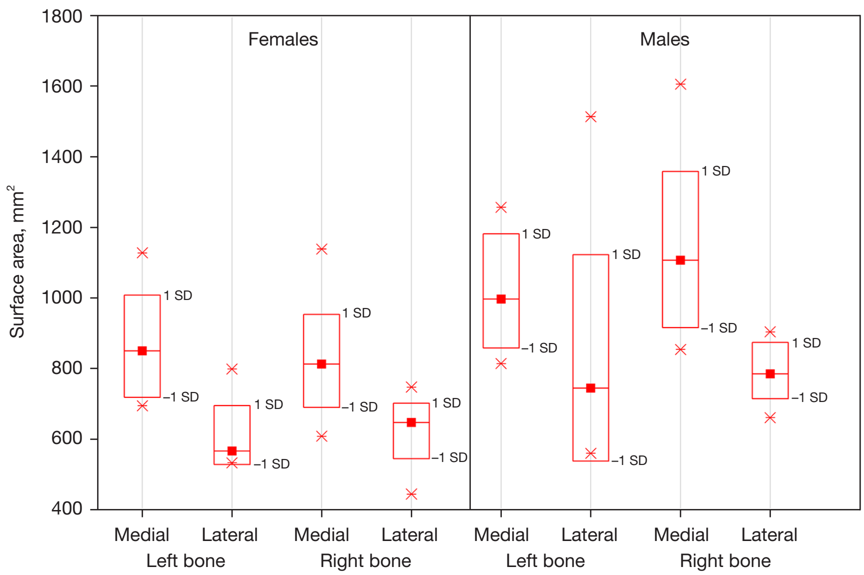

Figure 10 Results of measurements of the average surface area of each plateau. SD, standard deviation.

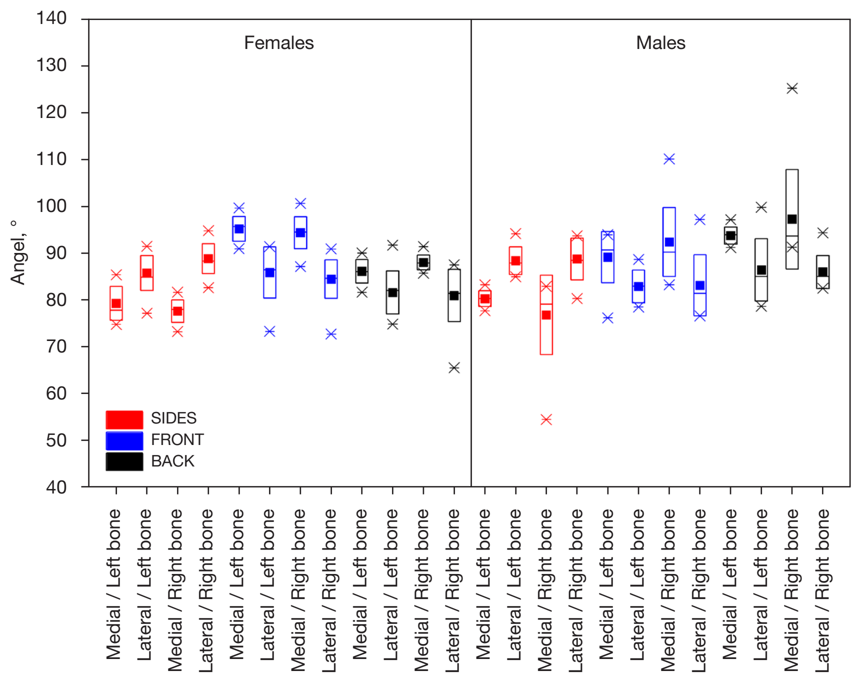

Figure 11 Diagram of calculated angles of inclination of the plateau.

bone structure overloads and prompted us to investigate the exact model of deformation of the proximal tibia in the course of degenerative disease. We assumed two basic possible models: the first with the assumption of collapse of the medial compartment, the second one assumed a simultaneous elevation of the side compartment.

We made a thesis, that if only the medial compartment would collapse due to OA that could explain intraoperative lateral hinge fracture during HTO as a result of overloading the bone structure of lateral compartment. In the study we prove that in degenerative varus knees as the medial compartment collapse, the lateral compartment rises, what is clearly presented in *Figure 2*. There is no study known to us, which would explore exact deformation model in degenerative knees.

Advantages of our study is division according to gender and sides of the body in patients with OA. From hospital database CT scans of degenerative and healthy knees were collected and we studied both, 2D and 3D measurements. Besides being able to quantify the surface deviations, the use of 3D models allows a better understanding a detailed representation and accuracy of the complexity of their anatomical bony structure and remodeling of the structure due to OA. An undoubted advantage of our work is the fact that both stages of the research were validated and standardized in one research center

The limitation of the study, without a doubt, is the analyzed area given the fact that we were analyzing proximal tibial epiphysis, so we couldn't correlate results with the rest part of the bone. It would be very interesting to correlate our results with height or weight, but as we used clinical database, so we could not obtain this data. However as Sharma *et al.* proved body mass index (BMI) is related to severity of OA in varus alignment but not in valgus alignment and it is dependent on specifics of malalignment in the knee, which differ by sex (10).

Our tested group in second part of the study is relatively small, but the trend of changes shown in *Figure 2* is so strong, that we believe our conclusions are authoritative.

Conclusions

In conclusion, the accurate quantification of bilateral asymmetries of the tibia requires both 2D and 3D measurements. The statistically significant differences proved in both parts of our research (9) between healthy and degenerative knees may be useful in pre-operative planning for HTO, so some intraoperative complications can be avoided.

Acknowledgments

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Footnote

Reporting Checklist: The authors have completed the MDAR checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-21-1210/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-21-1210/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). An approval from the Local University Ethical Committee was obtained for the study design and data acquisition from CT scans. Because our study did not disclose any private patient data, individual consent for this retrospective analysis was waived.

References

1. Schröter S, Freude T, Kopp MM, Konstantinidis L, Döbele S, Stöckle U, van Heerwaarden R. Smoking and unstable hinge fractures cause delayed gap filling irrespective of early weight bearing after open wedge osteotomy. Arthroscopy 2015;31:254-65.
2. Jackson JP, Waugh W, Green JP. High tibial osteotomy for osteoarthritis of the knee. J Bone Joint Surg Br 1969;51:88-94.
3. Plochocki JH. Bilateral variation in limb articular surface dimensions. Am J Hum Biol 2004;16:328-33.
4. Radzi S, Uesugi M, Baird A, Mishra S, Schuetz M, Schmutz B. Assessing the bilateral geometrical differences of the tibia--are they the same? Med Eng Phys 2014;36:1618-25.
5. Dargel J, Ninck J, Koebke J, Appell HJ, Pennig D, Hillekamp J. Influence of knee flexion on plantarflexion moments after open or percutaneous Achilles tendon repair. Foot Ankle Int 2009;30:551-7.

6. Eckhoff DG, Jacofsky DJ, Springer BD, Dunbar M, Cherian JJ, Elmallah RK, Mont MA, Greene KA. Bilateral Symmetrical Comparison of Femoral and Tibial Anatomic Features. J Arthroplasty 2016;31:1083-90.
7. Dobbe JG, Pré KJ, Kloen P, Blankevoort L, Streekstra GJ. Computer-assisted and patient-specific 3-D planning and evaluation of a single-cut rotational osteotomy for complex long-bone deformities. Med Biol Eng Comput 2011;49:1363-70.
8. Santoro D, Tantavisut S, Aloj D, Karam MD. Diaphyseal osteotomy after post-traumatic malalignment. Curr Rev Musculoskelet Med 2014;7:312-22.
9. Tomczyk J, Taczała J, Sawicki J, Domżalski M. Assessment of morphological differences of the proximal tibia in healthy knees: analysis of the 3-dimensional mathematical model. Quant Imaging Med Surg 2021;11:4354-64.
10. Sharma L, Lou C, Cahue S, Dunlop DD. The mechanism of the effect of obesity in knee osteoarthritis: the mediating role of malalignment. Arthritis Rheum 2000;43:568-75.

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