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Variations of Femoral Condyle Shape

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A B S T R A C T

The aim of this study is to mathematically approximate the shape of the femoral articulating line and compare radiuses of condylar curves within and between males and females. Ten male and ten female participants were included in the study. Radiuses of medial and lateral condylar curves were calculated from the side view knee X-ray by original mathematical equation. Average radiuses of condylar curves were between 4.5 and 1.7 cm medially, and between 3.2 and 1.8 cm laterally, for 0° and 90° flexion contact point respectively. Males had longer curve radiuses of both condyles (p<0.05). Differences turned out to be statistically insignificant after adjusting to body height. Even small changes in the joint geometry during lifetime could make a joint susceptible to osteoarthritis or injuries. Approximation of the radiuses of femoral condyle curves is a useful method in anthropometric, radiological and virtual calculations of the knee geometry, and other ellipsoidal structures in human body, like wrist, scull segments, dental arches, etc.

Key words: *knee, condylar curves, joint geometry, orthopedics*

Introduction

The knee is the biggest, most complicated and most incongruent joint in human body. Because the knee is located between the body's two longest lever-arms, it sustains high forces, and it is susceptible to chronic diseases and injuries[1]. Although males sustain harder labor and sports activities, the majority of chronic knee diseases and injuries have strong female bias: knee osteoarthritis (OA), anterior crucial ligament rupture, patellar pain syndrome, iliotibial band friction syndrome, tibial stress fractures[2]. It could be speculated that small alterations in the joint shape during lifelong period could make a knee susceptible to those pathological conditions.

The profile shape of the femoral condyles (Figure 1), between 0° – flexion contact point and 90° – flexion contact point, is commonly described as the ellipsoid curve, so-called »evolventa«. Radiuses of the anterior part of the evolventa are longer in comparison to the radiuses of the posterior part of the evolventa. The line which connects the ends of all the radiuses (centers of all curve segments), so called »evoulta« is letter »J« shaped, and it is smaller than the evolventa[3].

Special curving of the femoral condyles is important for the knee mechanics[4]. The geometry of the articular surfaces can affect the location of the contact points during knee motion and ultimately affect the stabilizing of the knee under compressive loads[5].

Studies how to define joint surface geometries have been scarce and, consequently, anthropometric studies on joint surfaces have been rather poor. Also, the development of prostheses that more closely resemble the normal joint anatomy has been unsuccessful. Some re-

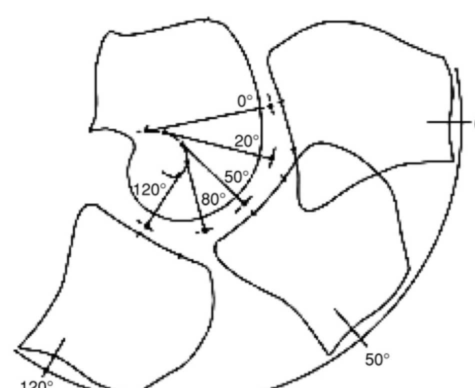

Fig. 1. The schematic sagittal view of the knee.

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searches have chosen cones, arches and hemispheres to model joint surfaces, or at most, they have used a polynomial approximation to mimic knee joint surfaces[6]. All those studies of condylar shape, and almost all employed mathematical models of the knee joint are based on 2D (planar) knee joint description.

Aim of this paper was to mathematically approximate the femoral articulating line and calculate the radiuses of medial and lateral condylar curves.

Participants and Methods

Participants

Twenty healthy Caucasian participants, ten males and ten females, were included in the study. The participants were consistent sample of volunteers from the student population of the city of Sarajevo. All participants willingly took part in this study and signed an informed consent after the explanation of the test procedure. The study was performed during September 2004 at Department for Orthopedics and Traumatology, University Hospital Center Sarajevo.

Inclusion criteria were: age 20–32 years, non-obese person; body mass index (BMI)<25 kg/m^2, negative history of right knee injury, complains of pattelofemoral pain symptoms, or neurological or neuromuscular disorders, full range of right knee active motions, and grade 5 of hamstrings and quadriceps muscle force, negative Lachman's, posterior drawer, varus/valgus, and McMuray's tests[7] and absence of any X-ray visible changes of the right knee. The average age of participants was 24.45±4.56 years and there was no statistically significant difference between genders (t-test, p=0.385) (Table 1).

Methods

The side view X-ray of the right knee in extended position was reproduced in real size on the computer digitalized scan (Vidar VXR-12 CCD scanner, 600 dpi, 256 gray levels[8], CorelDRAW 9®, Microsoft, Seattle, USA).

The tangents were drawn on the medial and lateral condylar curves at 0° and 90° articular contact points.

The anterior distal part (fourth quadrant) and posterior proximal part (second quadrant) of the femoral condyles are quarters of a circle, with diameters approximately 4 and 2 cm diameters, respectively (Figure 2).

The »third quadrant«, posterior distal part of the femoral condyles, which articulates with tibia in a range of knee flexion from 0° up to 90°, is quarter of ellipsoidal curve[9–11]. It is mathematically defined with its wider and narrower diameters A and B respectively (Figure 3).

The lines perpendicular to the two neighboring tangents at spots M and N determine the center of the curve (circle, ellipse), and the radius (Ra) of that curve segment (Figure 4).

Radiuses (distances between evolventa and evoluta) were calculated for each 10° segment of the medial and lateral condylar curves.

$$X_R = [Y\alpha_{+10} - Y\alpha + tg(90-\alpha)X\alpha - tg(80-\alpha)X\alpha_{+10}] / [tg(90-\alpha) - tg(80-\alpha)]$$

$$Y_R = tg(90-\alpha)X_R + Y\alpha - tg(90-\alpha)X\alpha$$

$$X\alpha = A/(1+(B^2/(tg\ \alpha)^2\ A^2))^{1/2}$$

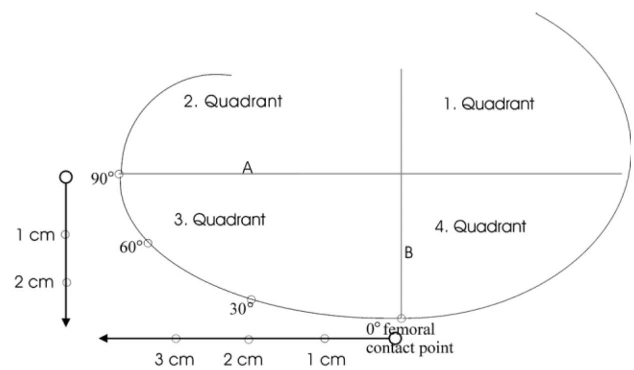

Fig. 2. Femoral condyle contours in sagittal plane divided in quarters.

TABLE 1
AGE, HEIGHT AND BODY MASS OF PARTICIPANTS

Subject No.	Male			Female		
	Age (years)	Height (cm)	Mass (kg)	Age (years)	Height (cm)	Mass (kg)
1	31	190	88	20	169	61
2	32	187	85	22	175	56
3	24	180	80	29	169	55
4	20	182	71	20	178	59
5	20	180	75	20	176	62
6	23	179	80	20	165	58
7	27	180	81	23	169	59
8	32	176	67	24	168	58
9	24	187	73	26	174	58
10	21	183	81	32	169	58
X±SD	25.4±4.8	182±4.3	78±6.5	23.6±4.2	171±4.2	58±2.1

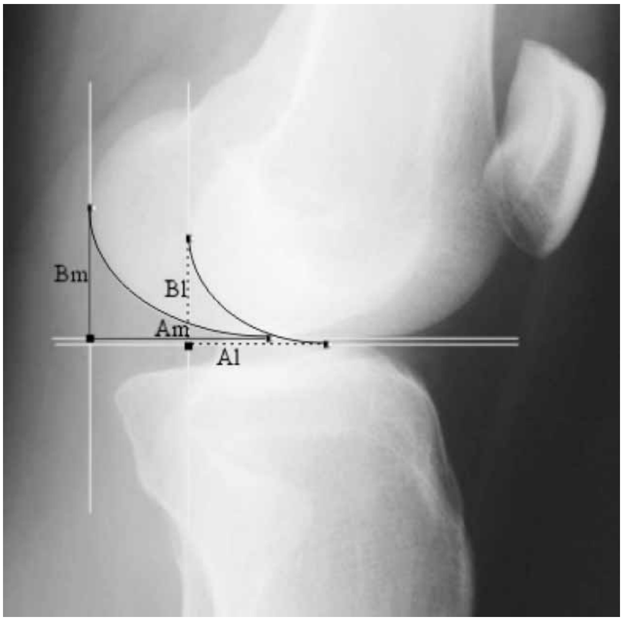

Fig. 3. Side view knee X-ray with outlined femoral articulating contours and diameters of ellipse, A and B, medially (solid lines) and laterally (dotted lines).

$$Y\alpha = B/(1+(A^2(\mathrm{tg}\ \alpha)^2/B^2))^{1/2};\ \alpha = 0°, 10°, 20°, 30° \ldots 90°$$

$$R\alpha = [(X\alpha - X_R)^2 + (Y\alpha - Y_R)^2]^{1/2}$$

Derived equation is based on the calculation of coordinates of ellipse and its tangent contact spot, and intersection spot between lines perpendicular on two neighboring tangents at contact spots[12].

The »Knee Roll« is original software[13] based on above described equations, and its output is a radius of the condylar curve (Ra) for each 10° segment, from 0° up to 90° articulating point.

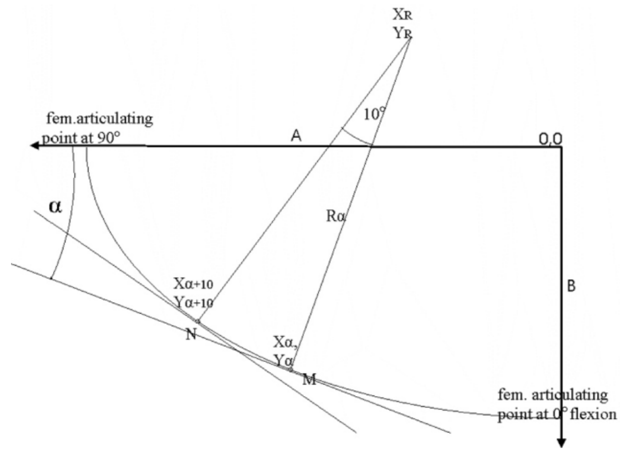

Fig. 4. Radius of condylar curve (Ra) is defined with angle a and diameters of ellipse A, B.

The Independent samples t-test (equal variance, normal distribution) was used for the analyses of differences of Ra, Icr and the rolling percentage between males and females, with p=0.05 as a cut off value[14]. The Wilcoxon's non-parametric unimpaired test was employed to confirm results of t-test. The sum of ranks in one group out of 78–132 interval (10, 10 sample) pointed to a difference between the examined groups (p<0.05). The collected data were processed by Microsoft Excel® (Microsoft, Seattle, USA) software.

Results

When analyzing medial and lateral condylar curve radiuses, from 0° to 90° flexion contact point, it has to be noticed that the all radiuses reduce. Otherwise, the anterior part of femoral condyles is less curved than the posterior.

TABLE 2
RADIUSES OF MEDIAL CONDYLAR CURVE

Knee angle	Male (mm)	Female (mm)	Total sample (mm)	p*	Sum of male ranks**
0°	46.2±8.8	44.4±5.1	45.3±6.7	0.590	98
10°	42.2±6.6	41.3±4.2	41.7±5.3	0.729	96
20°	36.1±3.8	36.3±3.0	36.2±3.3	0.884	105
30°	30.2±2.2	31.1±2.4	30.7±2.2	0.364	118
40°	25.3±2.1	26.6±2.5	26.0±2.3	0.212	122
50°	21.7±2.5	23.2±2.6	22.4±2.6	0.227	129
60°	19.2±2.8	20.7±2.8	19.9±2.8	0.250	119
70°	17.7±3.0	19.1±2.8	18.4±2.8	0.279	117
80°	17.0±3.0	18.4±2.8	17.7±2.9	0.296	118
90°	16.5±2.9	17.8±2.7	17.2±2.8	0.293	118

* probability p<0.05 (Independent Samples Test with two tailed distribution)
** sum of ranks in male group for medial condyle (Wilcoxon's test) out of 78–132 interval

TABLE 3
RADIUSES OF LATERAL CONDYLAR CURVE

Knee angle	Male (mm)	Female (mm)	Total sample (mm)	p*	Sum of male ranks**
0°	31.7±2.6	30.7±7.1	31.2±5.1	0.691	109
10°	30.6±2.3	29.3±5.3	29.9±3.9	0.463	131
20°	28.9±1.8	27.0±2.9	27.9±2.5	0.101	120
30°	26.7±1.6	24.5±2.4	25.6±1.7	0.117	129
40°	24.7±1.9	22.3±1.3	23.5±1.9	0.070	130
50°	22.9±2.2	20.6±2.0	21.7±2.3	0.070	131
60°	21.5±2.4	19.2±2.5	20.3±2.6	0.051	132
70°	20.6±2.6	18.3±2.8	19.4±2.8	0.074	132
80°	20.1±2.7	17.8±2.9	19.0±2.9	0.088	121
90°	19.5±2.6	17.3±2.8	18.4±2.8	0.089	121

* probability $p<0.05$ (Independent samples test with two tailed distribution)

** sum of ranks in male group for lateral condyle (Wilcoxon's test) out of 78–132 interval

The average radiuses of the medial condylar curve decrease from 45 mm, at 0° flexion contact point, to 17 mm, at 90° flexion contact point (Table 2).

In the same interval, the average radiuses of the lateral condylar curve decrease from 31 mm to 18 mm (Table 3). This implies more round shape of lateral condyle in comparison to the medial condyle.

Males have significantly bigger femoral condyles and radiuses of its condylar curves in comparison to females ($p<0.05$). The differences turned out to be statistically insignificant after adjusting to body height (Table 2, 3). That insignificance was very close to the borderline p-value 0.05 on the lateral condyle for segments 40°–70°.

More elliptic medial condyle is bigger, with average dimensions of wider and narrower diameter (A and B) 33 and 24 mm, respectively (Figure 5).

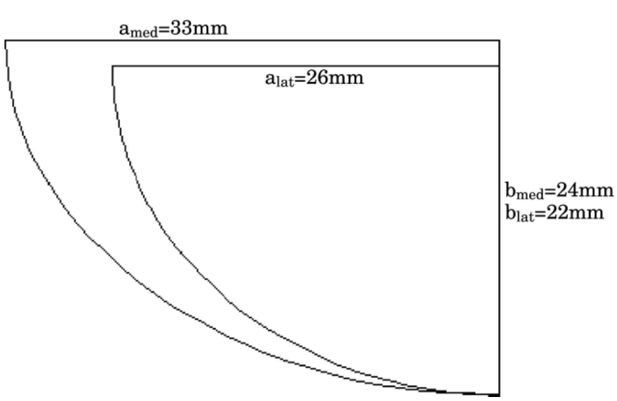

Fig. 5. Elliptic medial, and more round lateral condyle with average A and B diameters.

Discussion

This study has found out that average radiuses of the medial condylar curve, from 0° to 90° flexion contact point, are longer and decrease by more than 2.5 times in comparison to the lateral curve radiuses which decrease less than a half time in the same interval. Otherwise, the medial condyle is bigger and much more oval than the lateral. Similar results were reported by other authors who measured radiuses of the condylar curves[9,10].

Gender differences in radiuses of the condylar curves were noted, as well. Male condyles and their radiuses were larger, but that difference became insignificant for both condyles after adjusting to body height. A relative high deviation of Ra within each segment, approximately a seventh of Ra, even after adjusting to body height, points out that the shape of the condylar curves is probably not equal within or between the examined groups. If the examined groups had been larger, it could have been expected that the radiuses of the condylar curves differed significantly.

Anatomy, shape and structure of joint bodies are base for all biomechanical researches. In equilibrium, shape is result of function and it can help as a model in deductive-analytical analyzing of function and clinical consequences. For instance, the geometry of the articulating contact points, and radiuses of condylar curves determine anatomical center of joint motion. If joint center is infinitesimally far from joint contact surface (Ra=8), there is pure sliding joint motion. If the center of joint motion lies on the surface of the moving limb (Ra=0), there is rolling contact, a condition in which there is no sliding and, therefore, minimum friction losses or wear[15]. Significantly more sliding and arthritis occur at extension contact area[1], where curve diameters are longer. Different shapes of condylar curves could be one of, at least theoretical, explanations for strong medial side bias in knee OA.

The shape of knee condyles has been studied comprehensively in relation to osteoarthritis (OA) etiology and treatment. The relation between joint shape and OA has not been fully elucidated and few empirical data exist. It is well accepted that an alteration in joint shape occurs as a result of OA. Indeed, one feature of the original Kellgren and Lawrence OA scoring system was an alteration in bony contours at X ray. It has also been hypothesized that joint shape, influencing joint biomechanics, could increase the risk of OA. Bone remodeling and altering of joint shape have a role in the etiology of OA[16]. Yoshioka[17] has studied the shape of distal femur and noted a large natural variation in shapes that could be involved in the genesis of the knee OA. More recently, Cooke[18] has presented evidence that varus and valgus deformities can result from the shape of distal femur and proximal tibia that precede any OA change and have suggested that such deformities may be risk factors for knee OA. It has been also suggested that bone remodeling may be a response to OA in an attempt at joint repair and stabilization forming a „negative feed back«, that could slow the progress of OA. This is supported by the observation that marginal osteophytes decrease varus-valgus instabilities[18] and may also decrease anterior-posterior translation.

In paleopathologic comparative analysis, Shepstone[20] has related the shape of medial condyle to knee OA.

The group with eburnated medial condyles had relatively broader condyles (especially the medial condyle), a narrower intercondylar notch with a more medial rather than lateral, anterior twist, a straighter and less concave lateral edge to the lateral condyle and a more symmetric patellar groove

The shape of the distal femur may, therefore be very pertinent in etiology of knee OA. To the best of our knowledge, a quantitative analysis of the shape of the distal femur (rather then an analysis of individual morphological measurement) has not been conducted with respect to knee OA.

It is not known what has early happened, primary knee OA or mechanical disorder. The fact is that in OA biomechanical relations are compromised, and one makes other worse.

The method described in this research could be employed in analyzing of arthritic, eburnated knee condyles, as well, in a manner to compare radiuses of the destructed condyles with the clinical and radiological severity score of the knee OA.

The current study offers the mathematical approximation of the shape of femoral condyles by the original equation for calculating the radiuses of femoral curves. It could be applied in the anthropometric, biomechanical, radiological and virtual calculations of the knee joint geometry.

Comprehensive anthropometric characteristics of the knee are always topical, especially in improving the aloplastic knee constructions, treatment of the knee instability and prevention of knee arthritis. A lack of experimental data needed in the determination of the model system parameters, including the detailed geometry of the articular surfaces, is the main reason why the mathematical knee modeling has not finished as yet. Without complete mathematical knee model is not possible to solve rather common problems of current knee endorpostheses: loosening, wear, abrasion, pitting, fracture, radiolucency, insufficient range of motions[9].

Additionally, the equation for the Ra calculating can be employed in other anthropometric analyses of the ellipsoidal or parabolic structures in human body, like wrist, segments of scull, dental arches, etc.

In orthodontics, the ellipsoidal shape of palatinal and dental arches enables anthropometric analyses of dental arches curving (Lundstrom, Moyers), gnatometric analyses of jaw deformities and malocclusions[21]. It can be used in the design of fixed and removable orthodontic appliances[22,23], as well.

Limitations of this study could be a relatively small number of participants and the way of data collection. But, in spite of the mentioned limitations, curve delineation is an approximation accurate only to 1–2 mm[10].

The exact numerical descriptions of the femoral condyle shapes from this study could be helpful in describing mathematical knee models, designing knee endoprostheses, and developing commercial motion analyzing systems.

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VARIJACIJE OBLIKA FEMORALNIH KONDILA

S A Ž E T A K

Cilj ovog rada je matematički aproksimirati oblike femoralnih zglobnih linija i usporediti radiuse kondilarnih krivulja unutar i između muškaraca i žena. U studiju je uključeno deset muških i deset ženskih sudionika. Radijusi medijalnih i lateralnih kondilarnih krivulja izračunati su pomoću originalnih matematičkih formula, a na osnovu bočnih rendgenskih snimki koljena. Prosječni radiusi kondilarnih krivulja iznosili su za kontaktne točke 0° fleksije 4.5 cm medijalno i 3.2 cm lateralno, a za kontaktne točke 90° fleksije 1.7 cm medijalno i 1.8 cm lateralno. Muškarci su imali duže radijuse krivulja oba kondila ($p<0.05$). Nakon usklađivanja sa tjelesnom visinom razlike su se pokazale statistički beznačajnima. Male promjene u geometriji zgloba za vrijeme života mogu učiniti zglob podložnim osteoartritisu i ozljedama. Aproksimizacija radijusa femoralnih kondilarnih krivulja je korisna metoda u antropometrijskim, radiološkim i virtualnim izračunima geometrije koljena te ostalim elipsoidnim strukturama u ljudskom tijelu kao što su zapešće, segmenti lubanje, zubni lukovi itd.