Gender Differences in Knee Kinematics and its Possible Consequences

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Aim
To analyze anatomic and kinematic characteristics of male and female knees in the sagittal plane.

Methods
Ten healthy male and 10 healthy female participants performed extension of their right lower leg in non-weight bearing and weight bearing conditions. The centers of knee joint motion were obtained by videographic motion analysis, and radii of condylar curves were calculated from digitalized X-ray scan. The Knee Roll software was made for this purpose.

Results
The extension of the knee in non-weight loaded and weight loaded conditions is a combination of rolling and sliding joint surface motion with 6:5 ratio, in both genders. During the last 20° of the extension of weight loaded male knee, rolling/sliding ratio changed to 8:1 (P<0.05). Average radii 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. Gender differences in the radii of condylar curves, after the adjusting to body height were insignificant.

Conclusion
A higher proportion of joint surface sliding with consecutive anterior tibial displacement in women indicates more strain during knee extension, potentially making the female anterior cruciate ligament tend and susceptible to injury. The gender differences in the knee kinematics are probably the consequence of different soft tissue structure or its activity, because no difference in the sagittal shape of femoral condyles was noted.

The knee is the largest and most complicated joint in the human body with discongruent but very functional articular surfaces. In spite of large forces at the ends of the two longest lever arms in the human body, the knee becomes a fixed straight rod in terminal extension, able to bear body weight without muscle effort. During the knee motions, flexion, and extension, there is a discrepancy between non-circular leg motions and circular motions of the cruciate ligaments and their insertions. As one of the links rotates on the other (Fig. 1), at any instant in time there is a point which has zero velocity and constitutes the instantaneous center of motion (ICM).

ICM path measurements provide valuable information about characteristics of the knee kinematics (1). If the ICM lies on the joint contact surface, there is pure rolling, and if the ICM is infinitesimally far from the joint contact surface, there is a pure sliding joint motion. However, a wide ICM path is characteristic of the knee varus and a narrow ICM path of the knee valgus. Both wide and narrow ICM paths normalize after implantation of a knee endoprosthesis (2). The anterior cruciate ligament (LCA) injury can affect the knee ICM pathway as well (3).

In everyday activities, the knee extension occurs almost always in the weight bearing
conditions. It is more likely to expect the altered joint kinematics and knee joint symptoms during weight loaded than non-weight loaded conditions. Even small changes in the joint kinematics during lifetime could make a joint susceptible to osteoarthritis or injuries.

Although males sustain harder labor and sports activities, strong female bias in the knee osteoarthritis (OA) and rupture of the anterior cruciate ligament (4,5) is evident. So far, there is no adequate explanation for this difference. A higher percentage of sliding component during female knee extension than during male knee extension might be one of the reasons for the strong female bias in the majority of knee pathology.

The aim of this work was to analyze anatomic and kinematic characteristics of male and female knees in the sagittal plane. Videographic motion analysis was used in the determination of the ICM path and rolling/sliding ratio during the knee extension. Additionally, the radii of medial and lateral condylar curves were calculated from the knee side view X-rays.

The knee extension was analyzed in non-weight bearing and weight bearing conditions, to reveal the influence of the weight bearing and increased muscle activity on the patterns of the knee joint motion.

**Subjects and Methods**

**Participants**

Twenty healthy Caucasian participants, 10 men and 10 women, were included in the study. They were sample of volunteers from the student population of the city of Sarajevo. The study was approved by the Ethics Committee of the Ljubljana Medical Faculty. Participation in this study was voluntary and all participants signed an informed consent after the explanation of the test procedure. The study was performed during September 2004 at Department of Orthopedics and Traumatology, Clinical Center, University of Sarajevo. The inclusion criteria were: age 20-32 years; non-obese person, body mass index (BMI) <25 kg/m²; negative history of right knee injury, complaints of patellofemoral pain, or neurological or neuromuscular disorders; full range of right knee active motions, and grade 5 of hamstrings and quadriceps muscle force (6); negative Lachman’s, posterior drawer, varus/valgus, and McMurry’s tests (7), and the absence of any X-ray visible changes of the right knee. The average age of the participants was 24.45±4.56 years and there was no statistically significant difference between genders (t test, \( P = 0.385 \) (Table 1).

**Procedure**

Four photoreflective markers were drawn on the lateral side of the naked right leg near the greater trochanter (A), lateral condyle (B), apex of fibula (C) and lateral malleolus (D), away from its bony prominences to minimize skin movement artifacts (8). Markers in the regions of the lateral condyle and lateral malleolus were X-ray reflective.

While sitting with legs freely bending (non-weight loaded condition/open kinetic chain), participants extended the right lower leg (90°-0°). The participants were instructed to hold their torso straight and not to use their hands while elevating the right lower leg.
Additionally, they rose from the squatting position to the standing position. During the examination they were barefoot, with 3 cm distance between the right and the left foot and the knees, and they were instructed not to use their arms when rising. The motion of the right leg was recorded by 4.2 Megapixel digital camera set on a camera tripod at a two-meter distance. The side view X-ray of the right lower leg, knee, supracondylar femoral area, and both X-ray reflective markers, was reproduced on a single scan.

**Mathematical Background of Knee Kinematics**

The part of the femur which articulates with the tibia in the range of knee extension from 90° up to 0° is a quarter of the ellipse (9-11). It is mathematically defined by its wider and narrower diameters, A and B, respectively. Lines perpendicular on the two neighboring tangents at spots M and N determine the center of the curve and radius of that segment of curve – Ra (Fig. 2).

The ellipse diameters A and B, distance between “D” marker and “B” marker, and distances between “D” marker and the tibial contact point at 0° and 90° – (T₀ and T₉₀), were captured from the side view X-ray. The radii – Rα were calculated for each 10° segment of the medial and lateral condylar curves.

Linear velocities in the directions of x and y axes of the coordinate system (Vₓ, Vᵧ), and angular velocity (ω) of the moving marker were acquired from the digitalized knee motion.

Distance from “D” marker to the ICM is expressed as X, and distance between the ICM and the joint contact line is expressed as Icr (Fig. 3):

\[
V_x = \alpha \cdot X, \quad V_y = \omega \cdot X
\]

\[
X = [(V_x/\alpha)^2 + (V_y/\omega)^2]^{1/2},
\]

\[
\alpha = T_0 + [T_0 - T_90] (\alpha/90),
\]

\[
I_{cr} = X - \alpha
\]

The Icr distances were calculated through 90°-0° knee extension in non-weight and weight loaded conditions.

Sf is the displacement (arc length) between the contact points on the femoral surface and St is the displacement between the contact points on the tibial surface.

The variables Sf and St are approximated by

\[
S_f = \int_{\alpha}^{90} (R_\alpha - I_{cr}) \cdot d\alpha \quad \text{and} \quad S_t = \int_{\alpha}^{90} R_\alpha \cdot d\alpha.
\]

![Figure 2. The radius of condylar curve – Rα, defined with points M and N and angle α.](image)

![Figure 3. Mathematical model used for the estimation of the instantaneous center of motion (ICM) and the distance between the instantaneous center of motion and joint contact line (Icr).](image)
where, $R$ is the average value of radii of medial and lateral condylar curve (Fig. 2), $I_{cr}$ is the distance from the ICM to the femoral contact point (Fig. 3), and $\alpha$ is the angle of extension at the observed moment (frame) with 10° successive angles. Therefore, the percentage of rolling is defined by equation

$$\%\text{rolling} = \frac{S_f}{S_f + (S_f - S_t)} \cdot 100\% \quad (12).$$

**Computer Data Processing – the “Knee Roll” Software**

The knee extension event was recorded by the digital camera, and the video clip was downloaded into the computer. After removing the sequences out of 90° to 0° knee extension, the Windows Media Player® (Microsoft, Seattle, WA, USA) file was converted into the chain of MotionBMP® (Microsoft, Seattle, WA, USA) files (frames). This was just like creating animated cartoons where a drawing was moved a fraction of a millimeter and every time the drawing was moved a picture was taken. Each sequence (frame) had all four markers visible.

Marker recognition was the most demanding part of this software. The success of automatic recognizing depended on the choice of reflective marker size. In this system, the reflective markers were the brightest objects and the threshold could be set to automatically discriminate the markers. The cluster of “pixels”, seen above the threshold, formed the centroids of the markers, which were automatically computed in the two dimensional image plane of the camera. The difficulty with the system was that every marker had to be visible in all frames all the time. An additional problem was the determination of marker centroid (single pixel defined with x and y coordinates) because the software recognized the marker as a cloud of more or less white spots (RGB more than 235). The software was able to remove small random digitizing errors or “noise” from the transformed image sequence. Such problems are significantly reduced with different filter options (Prewitt, Laplacian, Gaussian, Median). Coordinate values of all markers in each frame were recalculated according to the position of marker “B” in the first frame of each clip (superposition). Referent line for angle and angular velocity measurements was the direction marker “A” to marker “B” in the first frame.

The final result for each participant was stored as txt file (Fig. 4).

The “Knee Roll” was developed in the object-oriented programming language C# 2.0 for Microsoft 9X and XP® (Microsoft, Seattle, WA, USA). The software requires minimally 256 MB RAM and 2.2 GHz Pentium CPU.

**Statistical Methods**

The independent samples t test (equal variance, normal distribution) was used for the analyses of differences of $R$, $I_{cr}$, and the rolling percentage between men and women, with $P=0.05$ as a cut off value (13).

The collected data were processed by Microsoft Excel® software (Microsoft, Seattle, WA, USA).

**Results**

Gender $R$ differences were noted for each 10° slices at both condyles. The differences turned out to be statistically insignificant after adjusting to body height (Table 2). This insignificance was very close to borderline $P$ value of 0.05 on the lateral condyle for segments 40-70°.

The distances between the ICM and the articular contact point ($I_{cr}$) varied between 13 mm and 29 mm in non-weight and weight loaded conditions. The exception was male group during terminal rising from the squat position, where $I_{cr}$ was 6 mm (Fig. 5).

On average, men had the ICM closer to the articular contact point than women (19.7 ± 8.9 mm and 20.1 ± 6.5 mm for men and women, re-
This difference became statistically significant only in the last 10° of the extension during the closed kinetic chain (\(P<0.001\)). In weight-bearing condition, the ICM was 6 mm closer to the articular line than in non-weight-bearing condition (22.8 ±8.6 mm and 17.1 ±6.6 mm for non-weight and weight loaded conditions, respectively).

Rolling was a dominant joint surface motion during knee extension. In the non-weight bearing conditions (open kinetic chain), there was about 54 ±10% of rolling, with no gender differences. In the closed kinetic chain (weight-bearing condition), there was 58 ±10% of rolling (Table 3). The rest was sliding.

During weight loaded extension from 90° to 0°, men had more rolling (62.5 ±9.5%) than women (54.7 ±8.2%). That difference was statistically significant only for the 20-10° segment (\(P=0.049\)), and for 10-0° segment (\(P<0.001\)) of weight loaded extension.

The knee extension is a combination of rolling and sliding with 6:5 ratio, independent of gender or weight loaded conditions. The exception is the terminal extension weight loaded male knee, where the ratio was 8:1. Otherwise, whereas female knee equally rolls and slides in the terminal extension, the male knee practically just rolls into extended position of the weight bearing leg.

![Figure 5](image-url)
Discussion

This study found gender differences in the radii of condylar curves, but after adjusting to the body height these differences became insignificant. Relatively high standard deviation of \( R_a \) within each segment, points to the differences in the shape of the condylar curves within or between the examined groups.

On average, the ICM path in non-weight-bearing conditions was more distant to the joint line in comparison with weight-bearing conditions. Men had the ICM path closer to the joint contact line than women, especially during the last 20 degrees of the loaded knee extension (Fig. 5). Due to the different lcr distances, men had about 12\%, whereas women had 44\% of sliding motion during the terminal weight-bearing extension. In all other situations the percentage of rolling remained relatively constant – about 55\% (Table 3).

There is a gender difference in the knee kinematics – women have a higher percentage of sliding component than men, significantly higher only during the terminal extension phase in the closed kinetic chain.

Rising from a sitting position is taken as one of the most difficult and mechanically demanding functional operations for the knee. If the standing position is to be regarded as fully functional, an individual must be able to rise without help. Rising from a low position (squat) requires a far greater movement in knees and a higher total exertion of strength (14). Such activity will express the majority of kinematic characteristics of the knee in weight bearing condition. Even small changes in the joint kinematics during lifetime could make the knee joint susceptible to osteoarthritis or injuries. Some gender differences in lower leg kinematics could be used as biomechanical explanation of higher incidence of pathological conditions in the female knees.

Many authors report about different lower leg kinematics between men and women. For instance, sidestepping and landing motion analysis showed that during gait women have less hip and knee flexion, hip and knee internal rotation, and hip abduction, higher knee valgus and foot pronation angles and increased variability in knee valgus, and internal rotation during sidestepping (15). Also, women land with greater knee flexion angles and greater knee flexion accelerations than men (16). Women demonstrate more ankle dorsiflexion and pronation, hip adduction, flexion and internal rotation, and less trunk lateral flexion than men with generally higher muscle activation in a manner that could increase strain on the LCA (17). Men generate significantly more hamstring muscle torque (18).

As previously mentioned, the ICM path measurements provide valuable information about characteristics of the joint kinematics. For instance, the knee with an acutely torn LCA has the ICM path that shifts suddenly downward and forward between 20° and 40° of flexion and shifts back to its normal position before 90° of flexion (19).

If the instant center lies on the surface of the moving limb, there is rolling contact, a condition in which there is no sliding and, therefore, minimum friction losses or wear (20). In many of the knees in Frankel’s series, it was possible to correlate the site of wear of joint surface cartilage with the findings in the ICM path study. The longer the motion about an abnormal ICM path had been present, the greater was the chance of finding wear at arthroscopy (20). Fourfold increased sliding in the female knee at the most loaded areas could lead to increased wear and could be one of the theoretical reasons for a strong female bias on the knee osteoarthritis.

This study suggests a higher proportion of joint surface sliding in terminal extension with consecutive anterior tibial displacement in women than in men. This probably indicates more strain during terminal knee extension, potentially making the ligament tend and susceptible to injury. The gender differences in the knee kinematics are probably the consequences of different soft tissue structure or its activity, because no difference in the bony articular shape was noted. The majority of authors think that hamstring activation provides deceleration and stability during the knee extension (18,21,22). Hamstrings, by virtue of its posterior force vector, may cause limitation of anterior displacement of the tibia and promote rolling in men at terminal extension (11).

Most of the above mentioned studies were performed by computerized electronic quantification of human motion. There are several systems for such analyses such as APAS, MA, VICON, Kinemetrix, and SIMI. Each system is based on a
digitalized video sequence which is divided into single pictures with captions of characteristic spots on a moving limb. The computerized hardware/software technique provides a means to objectively quantify the dynamic components of movement. Non-invasive motion analyzing systems have been primarily used for quantification of human activities, it has assisted medical professionals, sport scientists, and athletes to understand and analyze movement.

The Knee Roll software has relatively simple usage, and hardware components (ordinary PC and digital camera) are widely available. A combination of videographic and X-ray techniques provides reliable data about the joint surface kinematics without violating the ethical requirements.

With the most appropriate marker selection, frame-to-frame adjusting of center position, marker-recognizing filters, the usage of actual dimensions of both condyles, and calculation of meaningful output usable for biomechanical and clinical interpretation, the Knee Roll software has been designed as a valuable tool in the analysis of knee kinematics.

The limitation of the method and software based on it, are the 2D mathematical model of the knee. However, this 2D mathematical model seems to be sufficient, until 3D knee model, which can be employed in more comprehensive analyses, becomes available.

Schwitalle’s and Frankel’s methods for estimation of the ICM paths (2,20) offered descriptive results. Hollman’s analysis provided numerical results (11), but his study was obtained assuming equal condylar shapes. The Knee Roll software provides numerical results based on the actual shape of femoral condyles, and so overcomes the main limitations of Frankel’s, Schwitalle’s, and Hollman’s studies.

The number of participants in this study (twenty) and their ages (20-32 years) were common for kinematic studies based on healthy participants. The authors of all other similar studies quoted in this work (5,8,11,15-18,20,22) also analyzed between 2 and 25 healthy younger adult volunteers. Completed bone growth after 20 years of age (23) reduces the possible influence of growth differences between participants. Healthy skeletal and neuromuscular systems exclude the influence of pathology on the knee kinematics, making the examined groups of men and women homogenous. This allows including of a relatively small number of participants in such studies.

The current study explains one of the many gender differences in the knee kinematics and relates it theoretically to the most common knee pathology with strong female bias (anterior cruciate ligament rupture and knee osteoarthritis).

A new, comprehensive study based on more participants (with and without knee pathology), matched by age, muscle activity, habits, cartilage status, and diagnosis could explore the influences of each examined factor on normal and altered knee kinematics.

A further step for physicians, biomechanics, mathematicians, and programmers would be the development of a system which would comprise the best features of all described types of software and relate the kinematic parameters to the specific knee conditions, and use it as a diagnostic tool.

References

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