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Template of instant centers of rotation developed for the knee joint (experimental study)

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Abstract

Relevance There are data in the literature describing the trajectory of displaced center of rotation of the knee joint. However, data on the exact location of instantaneous centers of rotation at various angles of the knee flexion are not available. **Objective** To identify the localization of instantaneous centers of rotation at various angles of the knee flexion and present the results in the form of a template. **Material and methods** The bench testing was performed using a specially developed device that provides fixation of the anatomic cadaver preparation of the lower extremity. The device made it possible to identify the zero instantaneous center of rotation using a radiographic positive marker. Control radiographs were performed to determine the "movement" of instantaneous centers of rotation at every 10° of flexion to reach an angle of 120°. The exact location of instantaneous centers of rotation at different knee flexion angles were obtained with a graphical editor and tibia internal rotation identified during the knee flexion. **Results** The identified instantaneous centers of rotation were applied to the contour of the distal femur to form the template and allow scaling. **Conclusions** The template developed could be useful for computer hexapod assisted orthopaedic surgery in the treatment of knee stiffness, for mechanotherapy and joint replacement.

Keywords: knee joint, kinematics, axis of rotation, instantaneous centers of rotation

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BACKGROUND

Soft tissue procedures alone can fail to eliminate persistent contractures of the knee joint [1, 2, 3]. External fixation devices are used in addition to releases [4, 5, 6]. The complex kinematics of the knee is the main problem that orthopaedic surgeon face with use of external fixation devices (EFD) to restore movements in the knee joint [7]. The movements performed in the knee joint are a combination of sliding, rolling and rotation of the femoral condyles relative to tibia produced simultaneously in three planes (sagittal, vertical, and, minimally, around the frontal plane within 3–5°) [8]. The center of rotation in the knee joint moves during flexion and extension [9, 10]. During passive flexion, the lateral condyle rolls over to accompany the rotation of the tibia, while the medial femoral condyle remains relatively immobile [11]. The vertical axis at which the tibia rotates is located in the medial part of the joint [12]. EFD incorporating a virtual hinge is required to reproduce the complex movements [13]. This group of EFDs includes orthopaedic hexapods based on passive computer navigation [14, 15, 16]. One axis around which rotation will occur can be pre-set with the computer program of the orthopaedic hexapod [17]. The change in the length of the struts can be calculated with use of the variable center of rotation, i.e. with the kinematics of the joint, having the knowledge of localization points of the center of rotation at different angles of flexion and moving the axis of rotation with the computer program of the hexapod. However, publications reporting the findings on the movement of the center of rotation are limited to the description of the trajectory with no indication to the exact location of the instant centers of rotation [18, 19]. The objective was to identify the localization of instant centers of rotation at various angles of the knee flexion and present the results in the form of a template.

MATERIAL AND METHODS

An experimental study was conducted on 12 unpaired non-fixed preparations of the lower limb: 6 male cadavers and 6 female cadavers of individuals who died from causes not related to the musculoskeletal pathology. The lengths of the femoral preparations ranged between 38 and 46 cm (42.3 ± 2.49), the tibial length varied between 33 and 41 cm (37.1 ± 2.44).

The experiment was produced using the original device (Fig. 1a, b) that included a baseboard 1 and a module of three supports 2 (two rings and a half-ring). Lower limb preparations 3 were rigidly fixed with standard transosseous components. An “idle” (without transosseous components) sectoral support 4 was additionally attached to the ring mounted to the femur.

A ring 5 was attached to the middle third of the tibia. A 2-mm nail with a rounded thickening at the end 6 was installed to allow the transport in two planes. A traction rope 7 was attached to the ring, stretched through two blocks mounted to the idle hip support 8 and the ring fixed to the base 9 of the device (Fig. 1, a, b).

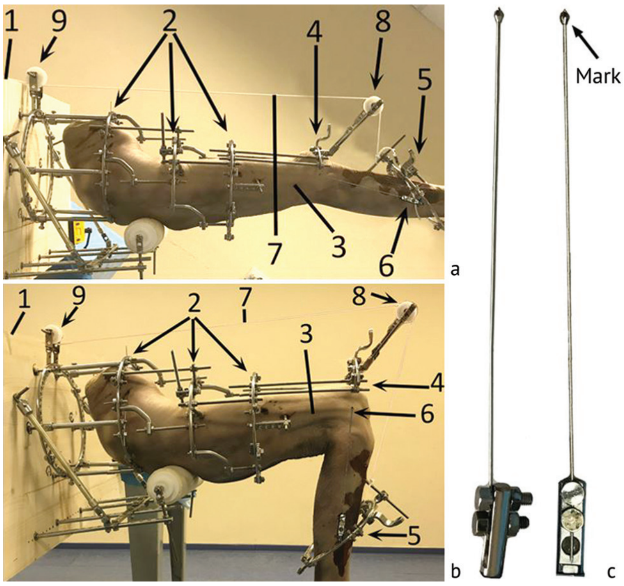

Fig. 1 A device for identifying instant centers of rotation of the knee joint. Explanations in the text

The experiment was performed as follows. A mark (a rounded thickening at the end of a 2 mm rod) was set under radiological control using a mobile "Arman 9L5" device in the projection of the zero instant center with the limb extended. The point of intersection of the posterior cortical bone of the femur and the line of the intercondylar notch (the Blumensaat line) was taken as the zero instant center (Fig. 2, a). With the mark located at the indicated point, the tibia was bent by loosening the tension of the cable. Lateral radiographic views of the knee joint were produced at every 10° flexion reaching 120° flexion. The resulting 12 radiographs were adjusted with the Adobe Photoshop 2021 editing software and layered on top of each other to allow the contours of the distal femur coincide (Fig. 2, b). Then the location of the marks on each of the radiographs was determined (Fig. 2, c). To do this, a longitudinal line was drawn along the posterior cortical bone on the radiograph, and a transverse line was drawn at a right angle at the intersection with the Blumensaat line. Both lines intersected at the mark set at the point of zero instant center (zero mark). Then a rectangle was drawn from the center of the zero mark to the center of the study one using AdobePhotoshop editing software. For instance, Figure 2, d shows the location of the mark (i.e., the instant center) with the knee flexed at 80°. The editing software represented the length and width of the rectangle in pixels (pix) (Fig. 2, d). Measurements of each mark obtained in pixels were tabulated for statistical analysis.

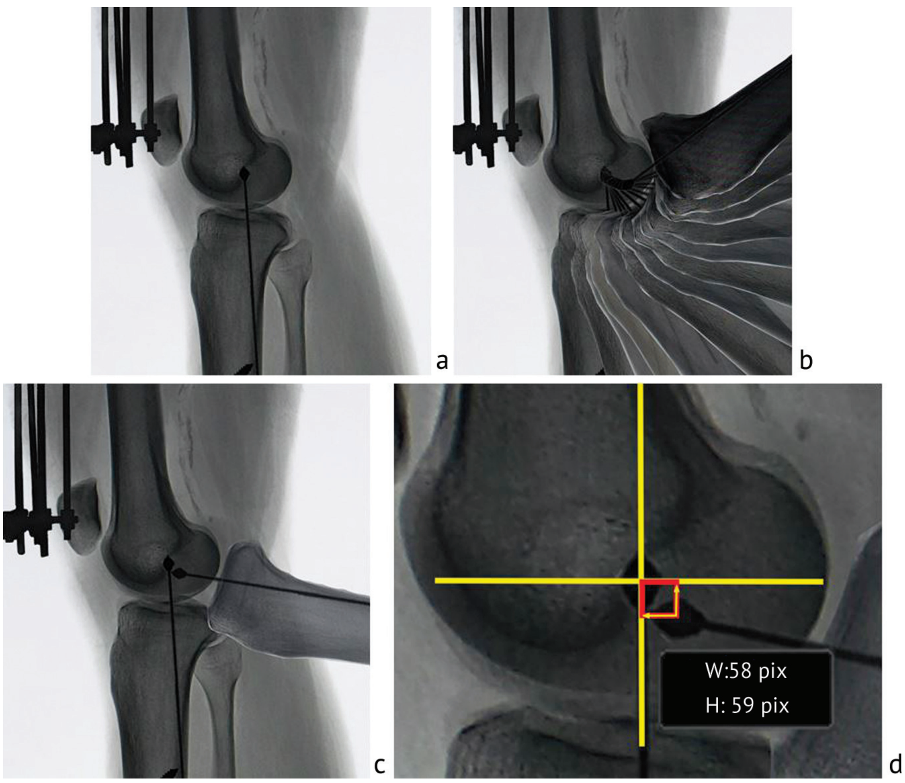

Fig. 2 The experiment was performed by: (a) placing a mark at the point of intersection of the posterior cortical bone and the Blumensaat line; (b) staged radiographs adjusted with editing software; (c) radiograph of the knee flexed at 80°; (d) identifying the position of the mark under study relative to the mark located in the zero position

Internal rotation of the tibia was measured with the knee flexed at 10, 30, 60, 90 and 120 degrees. For that, a threaded rod was attached to the sectoral support to be parallel at the extension to the half-pin inserted into the anterior tibia. Then the tibia was passively flexed and the angle between the threaded rod on the free sector and the half-pin placed in the tibia was measured (Fig. 3). Measurements of the rotation angle were recorded and tabulated for statistical analysis.

The study of each preparation was repeated 5 times to obtain statistically significant data. A total of 60 series of experiments were performed. Statistical data analysis was performed using Statistica v10.1 computer program. The Mann-Whitney U-test was used to identify statistically significant differences between preparations of male and female subjects.

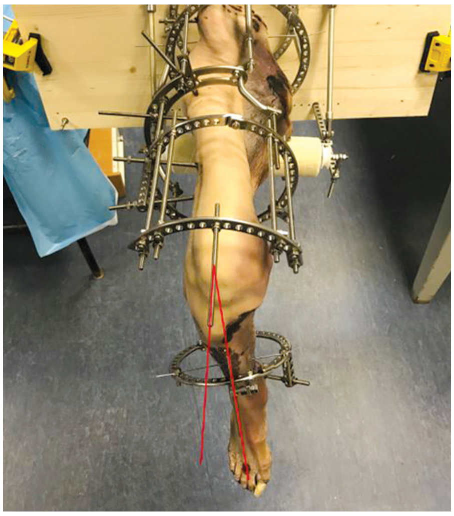

Fig. 3 Identifying tibial rotation

RESULTS

Quantitative data obtained during the experiment to determine the instant centers of rotation on 12 unpaired non-fixed preparations of the lower extremities are presented in Table 1.

No statistically significant differences were found in tibial preparations of males and females ($p \geq 0.05$). The average tibia rotation with the tibia flexed are presented in Table 2. No statistically significant differences were found in measurements of the internal rotation of the tibia between the preparations of males and females ($p \geq 0.05$).

Based on the data in Table 1, a template was created (Fig. 4) with localization points of instant centers of rotation marked at flexion from 0 to 120°. The template included the average internal rotation of the tibia at various angles of knee flexion based on the data presented in Table 2. The anatomical shape of the distal femur was identical in the preparations and differed by size only. The template can be used to determine the instant centers of rotation of a bone of any size by scaling. An example of scaling is shown in Figure 5.

Table 1

Results of identified location of instant centers of rotation (length and width of rectangles)

Flexion	Length, pix			P value	Width, pix			P value
	M	F	M+F		M	F	M+F	
10°	5 [4;5]	4.5 [4;5]	5.0 [4;5]	≥ 0.05	1 [0;1]	1 [0;1]	1 [0;1]	≥ 0.05
20°	14 [13;16]	15 [14;17]	15 [14;17]	≥ 0.05	1 [1;2]	1.5 [1;2]	1 [1;2]	≥ 0.05
30°	28 [26;29]	28 [25;29]	28 [25;29]	≥ 0.05	3 [3;4]	3 [2;4]	3[3;4]	≥ 0.05
40°	35 [33;38]	34.5 [33;37]	35 [33;37]	≥ 0.05	6.5 [6;8]	7 [6;7]	7[6;7,5]	≥ 0.05
50°	39 [38;41]	38 [37;40]	39 [37;41]	≥ 0.05	14.5 [13;15]	14 [13;15]	14 [13;15]	≥ 0.05
60°	48 [44;49]	46 [43;49]	47 [44;49]	≥ 0.05	33 [31;34]	31,5 [30;34]	32 [30;34]	≥ 0.05
70°	55 [53;57]	53 [51;55]	54 [51;56]	≥ 0.05	48 [46;50]	49 [46;50]	48.5 [46;50]	≥ 0.05
80°	58 [56;60]	58 [56;59]	58 [56;59]	≥ 0.05	60 [58;61]	60 [59;61]	60 [59;61]	≥ 0.05
90°	66 [65;68]	66 [64;68]	66 [64;68]	≥ 0.05	75 [72;76]	73.5 [72;75]	74 [72;76]	≥ 0.05
100°	71 [69;74]	71.5 [69;73]	71 [69;73]	≥ 0.05	88 [87;89]	87 [86;88]	87 [86;89]	≥ 0.05
110°	77 [75;79]	75 [74;78]	76 [74;79]	≥ 0.05	101 [100;102]	100 [99;101]	101 [100;102]	≥ 0.05
120°	71 [70;74]	70 [68;73]	71 [68;74]	≥ 0.05	119 [117;121]	118 [117;120]	119 [117;121]	≥ 0.05

The table shows median values, lower and upper quartiles.

Table 2

Measurements of tibial rotation

Flexion	Rotation (degrees)			P value
	M	F	M + F	
10°	5 [4; 5]	4.5 [3; 5]	5 [4;5]	≥ 0.05
30°	8 [8; 9]	8 [7.5; 8]	8 [7.75; 8.5]	≥ 0.05
60°	13.75 [13; 14]	13 [12; 14]	13.25 [12.5; 14]	≥ 0.05
90°	17.25 [16; 18]	16.25 [16; 17]	16.75 [16; 17.75]	≥ 0.05
120°	20.25 [19.5; 21]	20 [19.5; 20]	20 [19.5; 20.75]	≥ 0.05

The table shows median values, lower and upper quartiles.

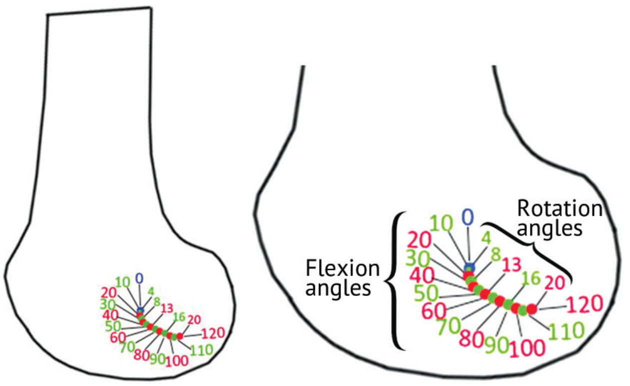

Fig. 4 Template with instant centers of rotation and rotation measurements marked at various angles of knee flexion

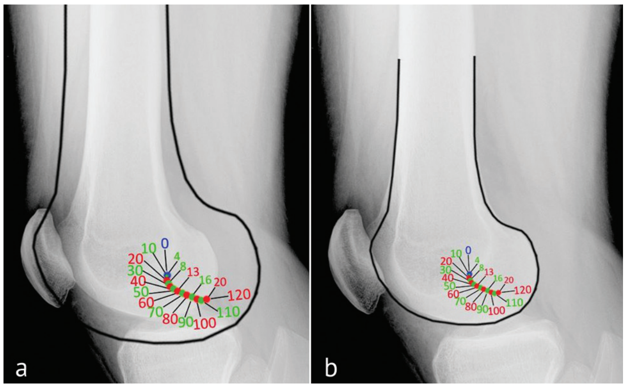

Fig. 5 Template scaling: (a) before scaling; (b) after scaling

DISCUSSION

With the discovery of radiography, the method of midperpendiculars developed by Rouleaux [10] was used to find the instant center of rotation. The method allowed tracking and schematic display of the trajectory of movement of instant centers (Fig. 6, a). Similar data on the trajectory of movement of the center of rotation (Fig. 6, b) could be obtained by spatial measurements of movements using a special device developed by N.M. Kalyadin, V.A. Shirokov and O.V. Oganesyan [18, 20]. Comparing their data with those obtained by the Rouleaux method, the authors came to the conclusion that the geometric shape of the trajectory of movement of instant centers in the projection of the condyles remained unchanged with small deviations in size and the location being associated with different size of the condyles.

The results of spatial measurements were analyzed in the form of a cyclogram obtained from recording movements with four markers (seven-segment arrays) placed on the medial and lateral aspects of the joint [18, 20]. The authors could describe the shape of the trajectory of the center of rotation that was similar to the contour of the posterior portion of the femoral condyles. However, the data obtained on the shape of the trajectory were not enough for use in clinical practice. The method of spatial measurements was rather descriptive in nature and could demonstrate the trajectory of the centers transport.

The method of median perpendiculars is a simple and sensitive method that can be used if the knee movements are considered as one-plane sliding of the condyles relative to each other [21]. Even if we represent the movements in this way and draw a median perpendicular, it would be unclear to which flexion angle the instant center corresponds. It is also unclear whether the point found corresponds to the true spatial location of the instant center in the lateral projection of the condyles. Constructing multiple perpendiculars and connecting the points obtained, one can build a trajectory and evaluate the shape that is located "somewhere in the projection of the distal femoral condyles." And this is not taking into account the fact that even the slightest inaccuracies with segments or marking points drawn can lead to defaults and downgrade the relevance of the data obtained [22].

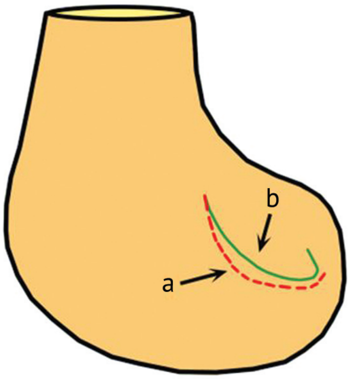

Fig. 6 Trajectory of movement of the center of rotation: (a) reported by Rouleaux (red dotted line) (being similar to Soudan K. et al., 1979); (b) data of spatial measurements (green solid line) (being similar to Oganesyan O.V., 2004)

The method we developed is based on the fact that the control mark moves in accordance with the movement of the center of rotation with increasing flexion. In contrast to the previously described methods, the technique we offered to perform staged (every 10°) radiographs of the knee joint allows assessment of the trajectory of movement and identification of the location of instant centers of rotation on the lateral view of the femoral condyles. The review of the specialized literature showed that this study is the first to describe the location of instant centers of rotation at various flexion angles. Analysis of the literature on tibial rotation at the knee flexion revealed the data being similar to our findings. A. McPherson et al. (2005) reported 4.1° internal rotation of the tibia at 10° flexion, 8.9° at 30° flexion, 13.4° at 60° flexion, 16.2° at 90° flexion and 18.3° at 120° flexion [23]. J. Victor et al. reported that the internal rotation reaches 20° at passive flexion of tibia of 130° [24].

CONCLUSION

The template of instant centers of rotation and an additional indication to rotation can facilitate practical use of the data obtained. The template can primarily be useful for computer hexapod assisted orthopaedic surgery aimed at developing the knee motion. The template can also be used to improve devices employed in rehabilitation mechanotherapy and joint replacement procedures.

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