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Determination of spatial position of tibial graft using X-ray images after anterior cruciate ligament reconstruction

Određivanje prostornog položaja grafta golenjače korišćenjem rendgenskog snimka posle rekonstrukcije prednjeg ukrštenog ligamenta

Aleksandar Djuričin*†, Slobodan Tabaković‡, Milan Zeljković‡, Zoran Milojević‡, Radojka Jokšić Mazinjanin*†, Vukadin Milankov*§

University of Novi Sad, *Faculty of Medicine, ‡Faculty of Technical Sciences, Novi Sad, Serbia; University Clinical Center of Vojvodina, †Department of Emergency Medicine, Novi Sad, Serbia; §Institute for Child and Youth Health Care of Vojvodina, Department of Surgery, Novi Sad, Serbia

Abstract

Background/Aim. Anterior cruciate ligament reconstruction is one of the most commonly performed knee surgeries in young adults. The success of this procedure largely depends on the proper formation of the tunnel, which is obtained by drilling the tibia and which serves to position and fix the graft. The aim of the study was to present a method for determining the spatial position of the graft based on only two standard X-rays. **Methods.** The study was performed on a group of 15 patients in whom the developed software applied the measurement of the angle of the tunnel in the tibia based on the selection of characteristic points on two standard X-rays of the knee (anterior-posterior and lateral projection). The obtained results were compared with the results of measuring the angle of the tunnel in the tibia on knee images by computed tomography (CT) in all patients. **Results.** The drilling angle measured in CT scans was, on average, somewhat greater (59.07° ± 5.61°) than the angle measured by applying a developed application (58.65° ± 5.89°). The obtained results indicated minimal differences without statistical significance in the measurements of the angle of the tunnel in the tibia using the developed software and on CT images (Wilcoxon test: Z = -1.363; *p* = 0.173). **Conclusion.** The presented method and developed software are suitable for everyday clinical applications in terms of precision and usability and can be used to assess the position of tunnels in the tibia in the process of determining the success of surgery or in preparing patients for revision surgery.

Key words:
anterior cruciate ligament reconstruction; computer-aided design; orthopedic procedures; radiography; tibia.

Apstrakt

Uvod/Cilj. Rekonstrukcija prednjeg ukrštenog ligamenta jedan je od najčešće izvođenih hirurških zahvata kolena kod mladih osoba. Uspešnost tog zahvata u velikoj meri zavisi od pravilnog formiranja tunela koji se dobija bušenjem golenjače i koji služi za pozicioniranje i fiksiranje kalema. Cilj rada bio je da se prikaže metoda za određivanje prostornog položaja grafta na osnovu samo dva standardna rendgenska snimka. **Metode.** Istraživanje je izvršeno na grupi od 15 pacijenata kod kojih je razvijenim softverom primenjeno merenje ugla tunela u golenjači, na osnovu selekcije karakterističnih tačaka na dva standardna rendgenska snimka kolena (prednje-zadnja i bočna projekcija). Dobijeni rezultati upoređeni su sa rezultatima merenja ugla tunela u golenjači na snimcima kolena kompjuterizovanom tomografijom (KT) kod svih pacijenata. **Rezultati.** Ugao bušenja meren na KT snimcima u proseku je bio nešto veći (59,07° ± 5,61°) od ugla merenog primenom razvijene aplikacije (58,65° ± 5,89°). Dobijeni rezultati ukazuju na minimalne razlike, bez statističke značajnosti, u merenjima ugla tunela u golenjači, primenom razvijenog softvera i na KT snimcima (*Wilcoxon test*: Z = -1,363; *p* = 0,173). **Zaključak.** Prezentovana metoda i razvijeni softver pogodni su za svakodnevnu kliničku primenu sa stanovištva preciznosti i upotrebljivosti i mogu se primeniti za procenu položaja tunela u golenjači u procesu utvrđivanja uspešnosti operativnog zahvata ili u sklopu pripreme pacijenta za revizionu operaciju.

Ključne reči:
ligament, prednji, ukršteni, rekonstrukcija; kompjuterski podržan dizajn; ortopedske procedure; radiografija; tibija.

Correspondence to: Slobodan Tabaković, Faculty of Technical Sciences, Dositej Obradović Square 6, 21 000 Novi Sad, Serbia. E-mail: tabak@uns.ac.rs

Introduction

The anterior cruciate ligament (ACL) is one of the four most important ligaments responsible for knee stability in a stationary position and when in motion. It prevents anterior tibial movement in relation to the femur and plays a significant part in ensuring lateral and rotational knee stability (Figure 1) [1].

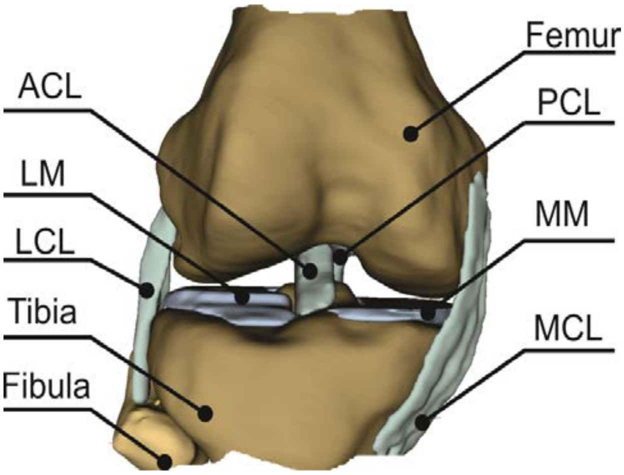


Fig. 1 – Ligamentous apparatus of the knee joint.

ACL – anterior cruciate ligament; LM – lateral meniscus; LCL – lateral collateral ligament; PCL – posterior cruciate ligament; MM – medial meniscus; MCL – medial collateral ligament.

Successful ACL reconstruction by arthroscopic surgery reduces total treatment costs, shortens the rehabilitation period, and enables the quicker return of the patients to their everyday activities [2].

In the last three decades, the middle third of the patellar ligament has been used in ACL reconstruction as a replacement for the damaged one. This technique has become a "gold standard" over time [3]. However, semitendinosus and gracilis muscle tendons have been used in the last decade, as well as allografts; bone-patellar tendon-bone allograft is the most frequently used, while Achilles tendon allograft and the iliotibial band are rarely used [4]. Allografts are being used more frequently due to the increased number of recurrent ACL reconstructions and their numerous advantages in practical use. Some of the advantages are the following: there are no local complications in the region of autograft harvest (pain, crepitation, weakness of femoral muscle, etc.); the timing of surgery is shortened; a smaller incision after embedding the autograft is required; rehabilitation is easier and faster. Due to all these reasons, the allograft is a lot more economically efficient [5]. Each of these techniques has its advantages and disadvantages and is the subject of numerous research and a topic of controversy [6–8].

Despite the development of surgical techniques and rehabilitation, revision surgery is required in some patients due to unfavorable outcomes of ACL reconstruction.

The causes that result in recurrent knee instability after ligament reconstruction are failure of surgical technique, problems in relation to the used graft, and undetected knee instability. Improper graft position is considered the most frequent cause of early recurrent instability, i.e., the position of the tunnel created by drilling with the aim of graft positioning and fixating that is not at its anatomical site [9, 10]. Since graft position depends on the femoral and tibial tunnel placement, there is a popular belief that drilling the tunnels in the position within their anatomical insertion during ACL reconstruction is necessary. In that way, anatomical ACL reconstruction could be achieved, stability and normal knee kinematics regained, and the patient would recover more quickly [11].

Most surgeons who deal with this issue determine graft position (i.e., the tunnel where the graft is situated) in the tibia by measuring according to standard X-ray images: anterior-posterior and lateral projection, which certainly is not precise enough [12, 13]. The position of the graft can also be determined by analyzing images of computed tomography (CT) or magnetic resonance (MRI) along with spatial reconstruction in the knee region or by creating a specialized application that determines spatial graft position using standard X-ray images, which is the goal of this research.

The aim of the study was to present a method for determining the spatial position of the graft based on only two standard X-rays, as opposed to CT or MRI imaging which are more expensive, and patients are exposed to lower doses of ionizing radiation compared to CT imaging. Furthermore, specialized software has been developed for everyday clinical applications, and it can be used to assess the position of tunnels in the tibia in the process of determining the success of surgery or in preparing patients for revision surgery.

Methods

Surgery

ACL reconstruction was performed in a group of patients using a bone-patellar tendon-bone graft. During the surgery, the patients were lying on the back with their legs on the arthroscopic leg holder, in general, spinal, or epidural anesthesia. After the graft was harvested, the processing began. Simultaneously, arthroscopy was performed to verify ACL tear and detect possible joint lesions (osteochondral lesion, loose joint body, meniscus injury, chondromalacia of cartilage). After that, the tunnel was drilled through the tibia and femur using a drill of 9 mm or 10 mm in diameter. When the drilling of the tunnel was finished, the graft was inserted and fixated by cannulated screws of dimensions 8 × 25 mm. Finally, graft position and its relation to the walls of the intercondylar fossa in the position of the maximum extension were checked once again by arthroscopy. The study was approved by the Ethics Committee of the Faculty of Medicine in Novi Sad, Serbia (N° 01-39/137/1 from 03 February, 2017).

Determination of graft angle

The determination of spatial graft angle was based on X-ray images of the knee region in two orthogonal projections (in the sagittal and coronal planes). Given that the patient's knee position and orientation can never be ideal due to the measuring angles, the first phase of determining graft spatial angles involved placing orthogonal projections in the scans in the proper position. The procedure involved the determination of common points that enable precise projection definitions of the appropriate knee surfaces. Based on the clinical procedure for evaluating the tunnel angle, the procedure which defines the specific points on the tibial plateau and tunnel has been accepted (Figure 2). Figure 3 shows separate points with the planes they define and the appropriate angles they form with the graft axis.

The reference coordinate system (point P) was set at the intersection point of the tunnel where the graft was positioned and in the plane of the tibial plateau. To harmonize projections, this plane needed to be seen as a horizontal line in both projections (*x*-*y* plane). The first step in this procedure was to evaluate tibial plateau angles in both projections concerning the horizontal axis (angles γ and δ) (Figure 3).

With the rotation of plateau and tunnel projections around the coordinate system starting point (P) for the previously evaluated angles, the connected projections were obtained (Figure 4a). These modified views display the coordinates of the graft endpoint: from the front view, *x* and *z* coordinates, whereas the *y* coordinate was obtained from the lateral view. The graft intersection point with the tibial plateau (coordinate start) represents the other point that determines the tunnel axis (Figure 4b).

The tunnel drilling angle (sagittal angle – α) was calculated between the generated spatial graft line and its projection into the *x*-*y* plane. Transversal angle (β) was calculated between the graft line projection into the *x*-*y* plane and a unit vector in the direction of the *y*-axis (Figure 4b). In order to see the drilling angle in its full size from the lateral view, it was necessary for the transversal angle to be 0º, i.e., to make a scan in the *y*-*z* plane so that the rays were normal on the drilling plane. Given that graft is required to be as close as possible to the anatomical position,

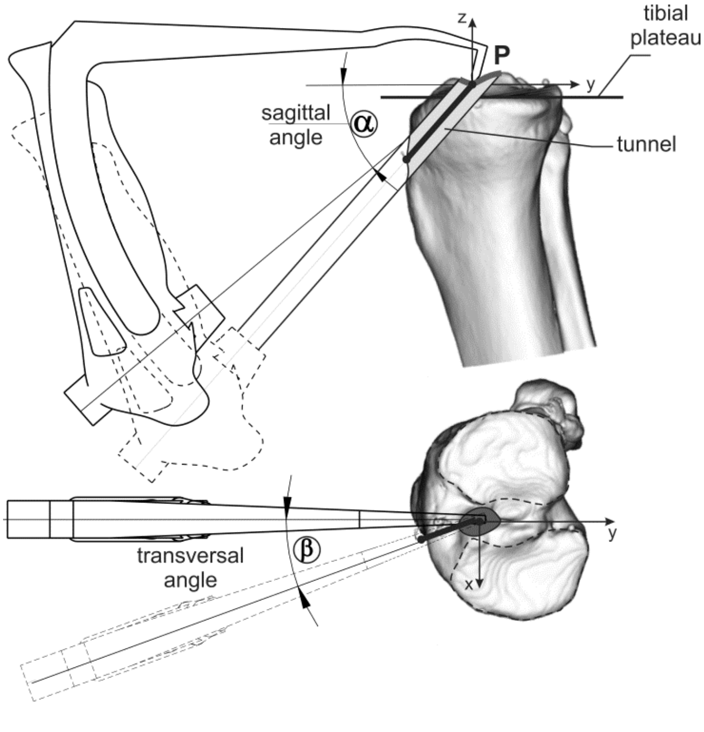


Fig. 2 – Graft insertion parameters.

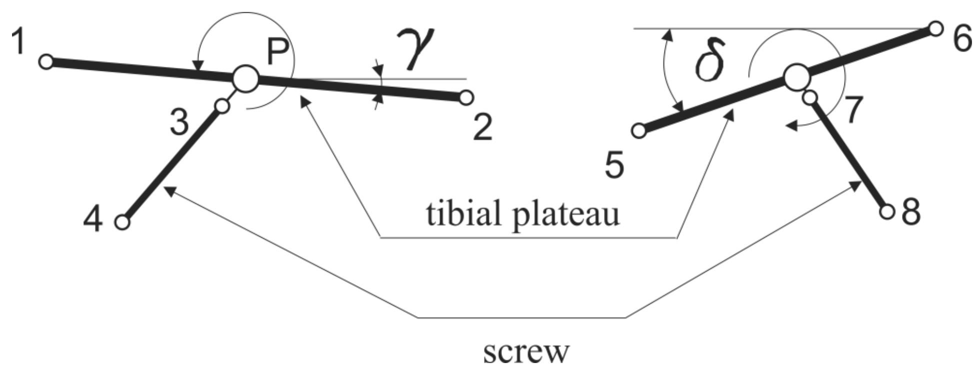


Fig. 3 – Defining the plane of the tibial plateau and tunnel axis.

the transversal angle was always different from 0º during the procedure. Such influences on the results of measurement are shown in Figure 5 as the projection values of sagittal, functioning as transversal angle, for the values from 0º to 90º. It can be seen in the figure that the sagittal angle for the value 0º was in its real size. The projected angle grows for other values; therefore, it was expected that X-ray images generated from the lateral view would show a bigger projected angle α_P between the graft and tibial plateau than the real drilling angle α. Consequently, inaccurate results were obtained, which may be misleading for a physician.

The mathematical procedure of sagittal angle calculation (α) based on the known projected sagittal angle in the lateral view (α_P) and transversal angle (β) shown in Figure 4 has been defined by the expressions (1)–(5).

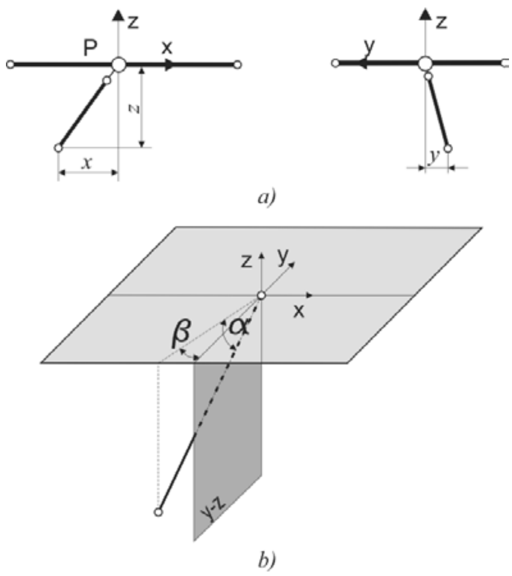


Fig. 4 – a) and b) – Principle of setting the selected parameters from X-ray images.
For details, see "Determination of graft angle" in Methods.

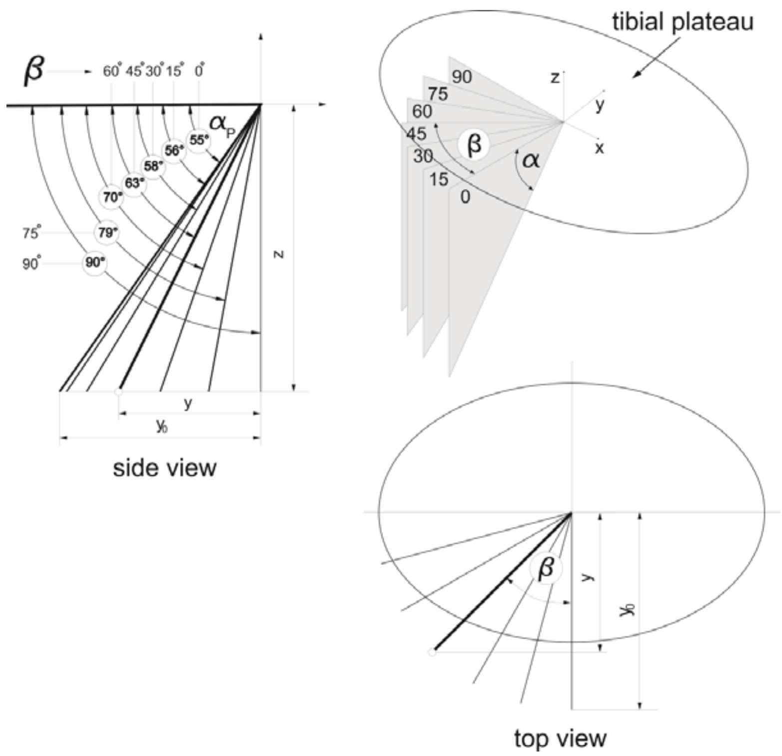


Fig. 5 – Correlation between sagittal angle α, transversal angle β, and projected sagittal angle α_P.
For details, see "Determination of graft angle" in Methods.

$\tan \alpha_p = z / y$ (1)

$y = y_0 \cos \beta$ (2)

$\tan \alpha = z / y_0$ (3)

$\tan \alpha = (z/1)/(y/\cos \beta) =$

$(z \cos \beta) / y = \tan \alpha_p \cos \beta$ (4)

$\alpha = \tan^{-1} (\tan \alpha_p \cos \beta)$ (5)

Structure of software

The development of adequate software that will confirm the success of the method for determining the graft insertion parameters comprises the formation of programming sections with the aim of applying the method described in the previous chapter, as well as the user interface that enables precise defining of specific tibial points, measurement of specific angles and their mathematical processing. For the automatization of these activities by applying the programming language C++ in the development environment Visual Studio 2010, a suitable programming solution has been developed. As verified software support for the development of image processing software in medicine and 3D graphics, Visualization Toolkit (VTK) library has been chosen for implementing the manipulation functions for graphic elements, as well as measurements of desired sizes in the images. VTK library possesses a large number of classes with functions that enable the following: loading and manipulating various scan formats; a high-resolution 3D display. Figure 6a shows a dialogue window, which is part of the user interface of the developed software solution with the parameters for selecting specific points; Figure 6b shows the output with the calculated parameters.

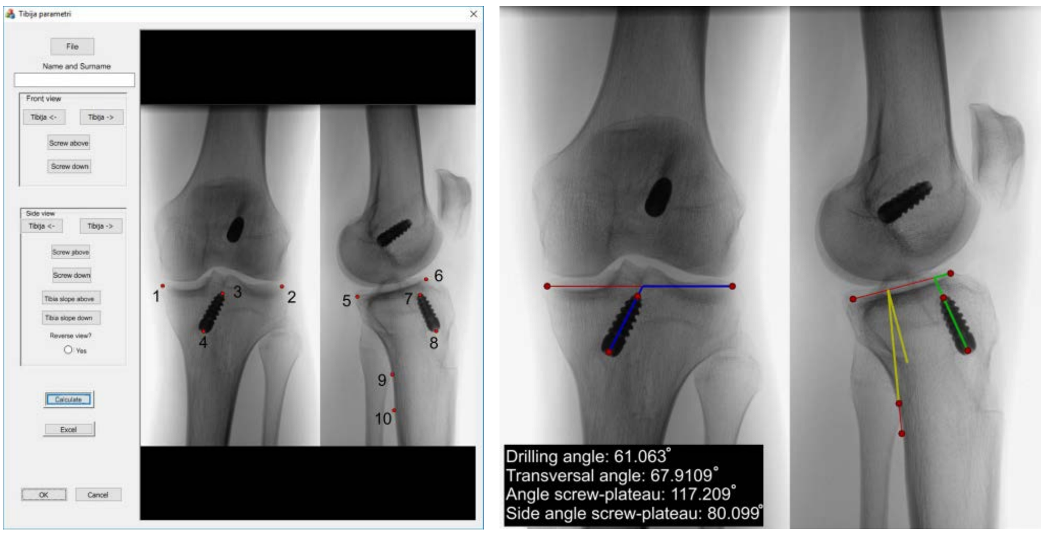
Figure 6a shows ten specific points in X-ray images chosen during the parameter calculation as follows: starting and end points of the tibial plateau in both images (points 1, 2, 5, and 6); starting and end graft points in both projections (points 3, 4, 7, and 8); points seen in the lateral image belonging to the tibial plateau angle (posterior tibial slope) (points 9 and 10). A created application enables detailed enlargement in the images during the selection of the appropriate points so that they can be selected as precisely as possible. Figure 6b shows the application output after calculation. It is a new image consisting of original images with the marked selected points, lines generated based on these points, and the calculated angles which are significant for the research. The angles are marked with the appropriate color, whereas the calculated values of the angles and their relationship at the tibial plateau in both projections from the graft intersection point with the tibial plateau are shown at the bottom of the image. The application enables exporting of the calculated values to the MS Excel table for further analysis and statistical processing.

Comparison of the obtained spatial drilling angle with CT images

To verify the newly developed software, the spatial determination of the graft position in the tibia was realized by processing standard X-rays (anterior-posterior and lateral projection) in 15 patients in whom the ACL reconstruction was performed. High-resolution digital radiograms were made using the Shimadzu Sonialvision Safire II. The same images were imported into the software developed for the analysis of graft spatial position in the tibia.

We used CT as a control method to determine the exact position of the graft in the tibia. The latest generation CT machine was used for this purpose (Siemens Somatom Emotion 16).

Tibial reconstruction using CT scans and applying 3D Doctor software has been performed to make a comparison of the drilling angle and carry out verification, with the result of achieving 3D models of the tibia and screws. Tibial and screw models generated in this manner are imported into the AutoCAD programming system, which enables precise measurement (with the unlimited possibility of image enlargement and measurement reading with more than ten decimal values) of the drilling angle.



a) b)

Fig. 6 – Developed application dialogue box display with selection parameters. For details, see "Structure of software" in Methods.

Results

A tunnel angle analysis has been carried out in a group of 15 patients with the aim of method verification for determining the tibial angle and functionality of the user interface of the programming system in the process of defining the specific points.

The obtained results are shown in Table 1. The first column represents the projected angle values measured based on the X-ray image, whereas the second and the third columns show a transversal drilling angle and the angle obtained using a developed computer program. A column with the values of the drilling angle based on the CT knee scan has been inserted into Table 1 to confirm the validity of the mathematical expression that describes the relationship between the real value of the drilling angle and the projected angle value.

Data in Table 2 shows that the drilling angle measured in CT scans, on average, is somewhat greater (59.07° ± 5.61°) than the angle measured by applying a developed application (58.65° ± 5.89°). CT drilling angle ranged from 45°– 68°, while during measurement using the application, it ranged from 42.94°– 67.93°. The median value was a half degree higher during measurement using the application. The distribution of measurement angles while measuring using both techniques is negatively asymmetrical, which indicates that the drilling angle values were higher than the mean value in a larger number of patients.

Wilcoxon test results (Z = -1.363; p = 0.173) showed that an error occurring during the determination of the spatial position of the tibial graft after ACL reconstruction by using a developed computer program has no statistical significance, and computer determination of tibial graft provides the same results as CT images.

Discussion

Although primary arthroscopic ACL reconstruction has reached until today a significant level of precision and is routinely performed, there are still a number of patients who are not completely satisfied with the outcome of surgical treatment and need reoperation. It is essential to find all the causes responsible for the unsatisfactory result of the primary reconstruction of this ligament in order to make a good preoperative preparation of the revision operation and thus reduce the number of complications to a minimum.

In order to achieve the projected postoperative outcome and knee stability during ACL reconstruction, it is necessary to position the graft properly and incorporate its ends into the created femoral and tibial tunnels ensuring isometry during movements. The most common reason for instability, even after surgery, is bad graft position, and as many authors say,

Table 1

Measurement results for 15 patients

Patient number	Projected angle, X-ray α_P[°]	Transversal angle, X-ray β[°]	Drilling angle, application α[°]	Drilling angle, computed tomography α[°]
1	71	45	65	65
2	68	48	58.9	58
3	81	67	67.9	68
4	68	46	59.8	61
5	74	60	60.2	61
6	49	36	42.9	45
7	71	59	56.2	55
8	60	45	50.8	51
9	79	65	65.3	64
10	70	51	60.0	61
11	71	53	60.2	61
12	69	52	58.1	59
13	67	49	57.1	58
14	73	58	60.0	61
15	68	49	58.4	58

Table 2

Descriptive statistics for the drilling angle α[°] measured using computed tomography (CT) and developed computer application

	CT	Application
Mean value	59.07	58.65
Standard deviation	5.61	5.89
Minimum	45	42.94
First quarter	58	57.09
Median value	61	59.82
Third quarter	61	60.2
Maximum	68	67.93
Wilcoxon test: Z = -1.363; p = 0.173		

improper femoral tunnel placement is a more common cause [14, 15–17]. However, improper tibial tunnel placement also results in recurrent instability.

Most surgeons who deal with this issue determine graft position (i.e., the tunnel where the graft is situated) in the tibia by measuring according to standard X-ray images, anterior-posterior and lateral projection, which is certainly not precise enough [12, 13], given that the results mainly depend on the morphology of bones and current position of the patient's extremities. The position of the graft can be most accurately determined from CT images, especially if 3D or multiplanar reconstruction is performed [16-18]. However, the high doses of radiation to which patients are exposed, as well as the cost of taking images, make it impossible to apply this method in everyday, routine clinical practice. Analysis of the position of the graft in the femur and tibia can also be performed via MRI unless metal lentils are used to fix the ends of the graft [15].

After ACL reconstruction, graft angle is one of the fundamental parameters in surgical outcome evaluation. The application of X-ray images in such determination, by its nature, provides plane (2D) scans with a relatively high error of orientation and positioning of the patient's knee, which results in an error occurring during graft angle measurement. The second method, using CT scans, is significantly more complex, more expensive [18], and less favorable for the patients due to its negative effects of radiation. Therefore, the application of X-ray images is the optimal method, accompanied by the formation of a suitable methodology for the determination of spatial graft angle.

The value of the transversal angle has a significant influence on the projection of the drilling angle; therefore, suitable mathematical transformation preceded by transversal angle evaluation from the X-ray image is necessary for the calculation of the real sagittal angle value.

Verification of the results obtained with the developed application was performed on a group of 15 patients, in whom, in addition to X-rays, CT images were also made. Tibial reconstruction using CT scans and applying 3D Doctor software has been performed to make a comparison of the drilling angle and carry out verification, with the result of achieving 3D models of the tibia and screws. A high level of automatization is achieved in this manner during this study phase, and subjective errors made by users while performing CT scan analysis are avoided. Tibial and screw models generated in this manner are imported into the AutoCAD programming system, which enables precise measurement of the drilling angle. The analysis of the obtained results showed that the drilling angle measured on CT images is, on average, slightly larger (59.07° ± 5.61°) than the angle measured by applying a developed application (58.65° ± 5.89°). This deviation from the results can be explained by the fact that during X-ray imaging, it is difficult to place the tibia in the ideal position so that the tibial plateau can be seen as a line.

A potential weakness of this experimental-clinical study lies in the fact that most authors regard CT or MRI evaluation as being more precise than radiographic measurement; therefore, clinical studies should include a larger number of ACL images made by using these techniques and introduce additional comparison criteria comprising the time of imaging and image reconstruction, price of diagnostics, etc.

One of the main aims of the study, part of which was presented in the paper, was to form a quick and economically efficient method for the determination of tibial graft position after surgery and the evaluation of reconstruction outcome based on that. A standard radiogram with appropriate software support was used as a basis for the created method. The obtained results are comparable with the measurement results using CT scans and suitable for clinical use on a daily basis from the standpoint of accuracy and usability.

Conclusion

Comparing the results obtained by measuring tibial tunnel angles after ACL reconstruction, one can reach a conclusion that the method of using X-ray images and software developed in accordance with them has the applicable value.

According to data obtained in this study, it has been concluded that this procedure may be applied to the determination of tibial tunnel placement as part of the preparation for revision surgery, i.e., in patients that still feel pain and knee instability after surgery.

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