GAIT ANALYSIS IN PATIENTS WITH CHRONIC ANTERIOR CRUCIATE LIGAMENT INJURY

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ANALIZA HODA KOD BOLESNIKA SA HRONIČNOM POVREDOM PREDNJIH UKRŠTENIH LIGAMENATA

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ABSTRACT

Anterior cruciate ligament (ACL) injuries are relatively common in young athletes and quite often require surgical reconstruction. The purpose of the ACL reconstruction is to achieve stability in the entire range of motion of the knee and to re-establish a normal gait pattern.

For this study, we examined nineteen adult men. Subjects walked along a pathway at their own speed. Motion curves were obtained based on the kinematic data collected using the OptiTrack system with six infrared cameras. Anterior-posterior tibia translation, as the leading ACL pathological parameter, was indirectly determined by monitoring the difference in the length of the distance between markers positioned at the femoral lateral epicondyle and at the tuberosity of the tibia in space and in the sagittal plane. Additionally, the angle of the internal-external rotation was monitored using the gradient of the tangent line of the motion curve.

Anterior-posterior tibia translation and internal-external rotation were significantly different after reconstruction surgery compared with preoperational measurements. Preoperational measurements included the maximal values of the AP translation and IE rotation in the early stance phase of the gait cycle. An increase of the AP translation and IE rotation values may cause degeneration of the cartilage.

These results reveal that a more precise diagnosis of the ligament instability can be made, providing relevant indicators for the type of treatment.

Keywords: *Gait analysis, ACL injuries, AP shift, IE rotation*

SAŽETAK

U ovoj studiji ispitano je 19 odraslih muškaraca. Pacijenti su se kretali duž putanje kretanja sopstvenom brzinom. Krive kretanja su dobijene na osnovu kinematskih podataka skupljenih korišæenjem OptiTrack sistema sa šest infracrvenih kamera. Anteriorno posteriorna translacija tibie, kao vodeæi pataloški parametar, je indirektno određena praæenjem razlike u dužini rastojanja između markera pozicioniranih na latelarnoj epikondili femura i na tuberozitosu tibie, u prostoru i u sagitalnoj ravni. Takođe, ugao interno eksterne rotacije je praæen korišæenjem gradijenta tangente krive kretanja.

Anteriorno posteriorna translacija tibie i interno eksterna rotacija se znaèajno razlikuju nakon rekonstruktivne operacije prednjeg ukrštenog ligamenta upoređujuæi sa preoperativnim merenjima. Preoperativna merenja ukljuèuju maksimalne vrednosti AP translacije i IE rotacije u ranoj fazi ciklusa hoda. Poveæanje vrednosti AP translacije i IE rotacije mogu dovesti do degenerativnog procesa na hrskavici.

Rezultati dobijeni u ovom istraživanju omoguæavaju precizniju dijagnozu ligamentarne nestabilnosti kolena pružajuæi relevantne pokazatelje za tip leèenja.

Ključne reči: *analiza hoda, ACL povrede, AP translacija, IE rotacija*

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INTRODUCTION

The primary function of the anterior cruciate ligament (ACL) is to control the anterior dislocation of the tibia, preventing hyperextension of the lower leg and disabling excessive axial rotation of the knee during extension [1]. Anterior cruciate ligament injuries are a relatively common in young athletes [2]. The typical orthopaedic treatment involves the surgical reconstruction of the ACL. In the U.S., more than 100 000 reconstructions of the ACL are performed per year. The purpose of the ACL reconstruction is to achieve stability in the entire range of motion of the knee, enabling the patient to perform everyday activities and sports-related activities, and to prevent new chondral and meniscoligamental injuries [3] and early arthritis. Additionally, ACL reconstruction should re-establish the normal gait pattern, which is distorted in patients with chronic ACL rupture. The gait pattern of patients with ACL injuries is changed due to a significant increase in the anterior-posterior (AP) translation of the tibia relative to the femur and internal-external (IE) rotation during specific phases of the gait cycle.

The aim of the study is to present a more precise and objective method of gait analysis before and after surgery in patients with ACL rupture.

MATERIALS AND METHODS

Nineteen adult men volunteered to perform the gait analysis test. The mean height of the subjects was 183.33±2.24 cm, mean weight 86±3.48 kg, and mean age 29.89±1.73. The subjects were recreational or professional athletes with a history of arthroscopic reconstruction of the ACL after a severe knee injury; the reconstruction involved the use of the semitendinosus and gracilis muscle tendons as nthe autograftdiagnosis . Test analysis and surgery were performed at the Kragujevac Clinical Centre (Clinic for Orthopedics and Traumatology).

The Shelbourne Knee Center rehabilitation protocol was used for postoperative rehabilitation.

Kinematic data were collected using an OptiTrack (Natural Point, Inc., Oregon, www.naturalpoint.com) system with six infrared cameras (V100:R2) and a resolution of 640×480 pixels and ARENA software (Natural Point, Inc., Oregon, www.naturalpoint.com) [4]. Cameras were placed along the pathway, and the positions of markers that were placed at characteristic landmarks on subjects' lower limbs were recorded (Fig. 1a). Four markers, which were placed at the great trochanter region (RVT), femoral lateral epicondyle (LEF), tuberosity of the tibia (TT) and the region of the centre of the ankle joint (CSZ) (Fig. 1b), were used.

Subjects walked along the pathway for approximately 5.00 m at their own speed. The signal at the knee with the deficient AC ligament was recorded first, and then the procedure was repeated for the healthy knee. Every subject was asked to perform this task four times.

To determine preoperative tibia translation along the AP direction, gait analysis was performed the day before surgery. Relevant motion curves were registered for fluorescent markers attached at the femoral lateral epicondyle (LEF) and tuberosity of the tibia (TT) for both the deficient and healthy knee. The test was repeated 15 days later and then after 6 weeks. The results used in this study are the results obtained after 6 weeks.

The subjects' motion was visualised as 3D curves, which were exported from the ARENA software in standard VICON .c3d format and further processed in Matlab (MathWorks, Inc., USA, www.mathworks.com) [5] and Catia V5 (Dassault Systemes, France, www.3ds.com) [6]. The LEF motion curve represents distal femoral movements, and the TT motion curve provides data for tibial shift and IE rotation.

The key functional gait phases were identified using the motion curve of the ankle joint centre in sagittal plane (Fig. 2). From the beginning of the curve, there is a descent to the local minimum, labelled as the heel strike, followed by

Motion curve of the great trochanter region
Motion curve of the femoral lateral epycondile
Motion curve of the tuberosity of the tibia
Motion curve of the center of the ankle joint
RVT *region of the great trochanter,*
LEF *lateral epycondil of the femur,*
TT *tuberosity of the tibia, and*
CSZ *centre of the ankle joint,*

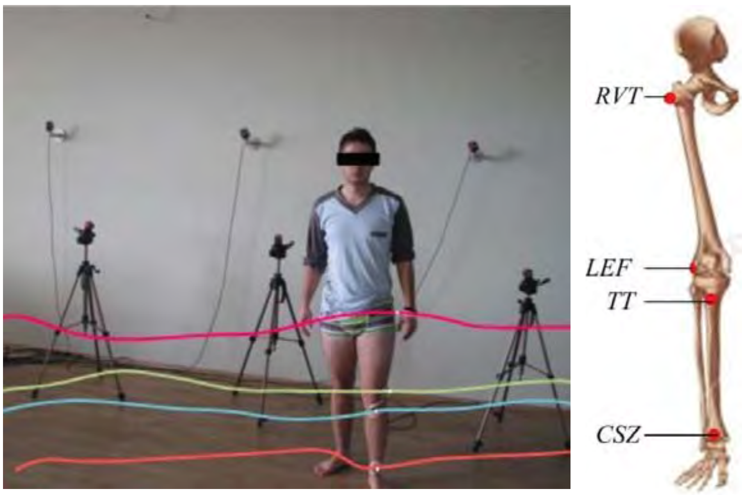


Figure 1. Experimental set-up

a.) **b.**)

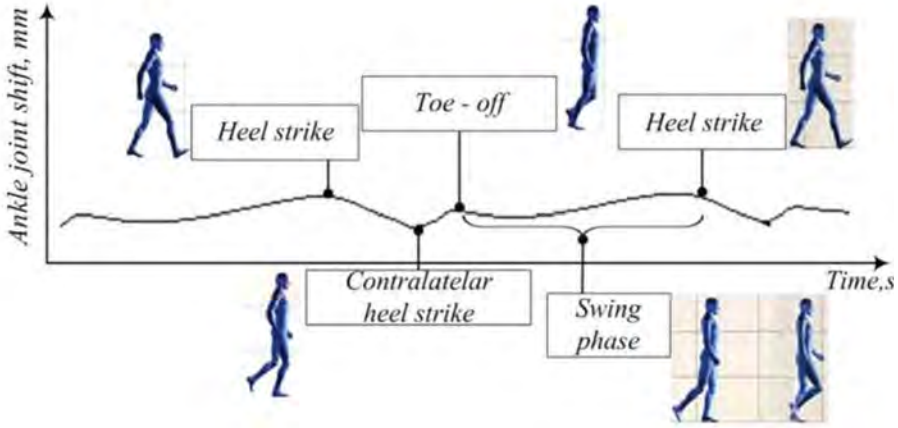


Figure 2. The key functional gait phases of the motion curve of the ankle joint centre

the contralateral heel strike. This is followed by a continuous curve increase, marked as the toe-off point in the next maximum. From the local maximum, the motion curve extends almost horizontally, denoting the swing phase, after which the decline to the next local minimum begins, labelled as the new heel strike of the same leg. The values that define shift of the tibia relative to the femur are given s a function of time, e.g., defined as a percentage of the gait cycle relative to time.

For indirect determination of the AP-tibia translation, we monitored the differences in the distance between LEF and TT points (Fig. 3) in space and in the sagittal plane, as well as the tibia shift along the AP axis. The shortest distance between LEF and TT points was determined using collected data for markers positions in space from .c3d file, such as:

- the spatial distance between LEF and TT

$$PDP = \sqrt{(x_{TT} - x_{LEF})^2 + (y_{TT} - y_{LEF})^2 + (z_{TT} - z_{LEF})^2}, \quad (1)$$

and

- the distance between LEF and TT in the sagittal plane

$$DPSR = \sqrt{(y_{TT} - y_{LEF})^2 + (z_{TT} - z_{LEF})^2}, \quad (2)$$

where x is the AP direction and z is the superior–inferior direction.

Based on the definitions of the distance between LEF and TT in space and in the relevant planes, differences in length are determined as:

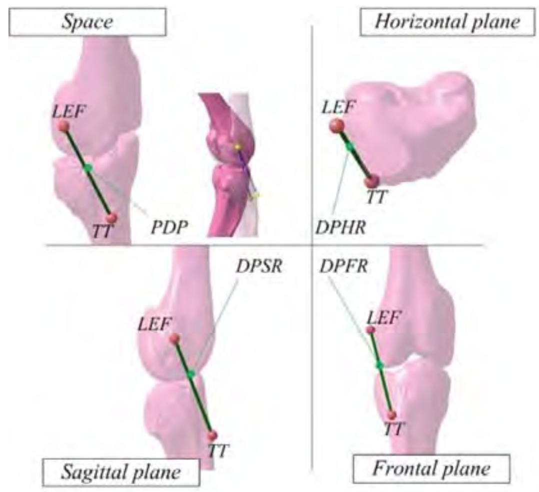
- the spatial difference in the lengths of the distance between LEF and PP

$$d_{PDP} = (PDP)_i - \min(PDP)_i, \quad (3)$$

and

- the difference in lengths of the distance between LEF and PP in the sagittal plane

$$d_{DPSR} = (DPSR)_i - \min(DPSR)_i. \quad (4)$$



LEF *-lateral epycondil of the femur,*
TT*- tuberosity of the tibia,*
PDP *- distance between LEF and TT points in space,*
DPHR *- distance between LEF and TT points in horizontal plane,*
DPSR *- distance between LEF and TT points in sagittal plane, and*
DPFR *- distance between LEF and TT points in frontal plane.*

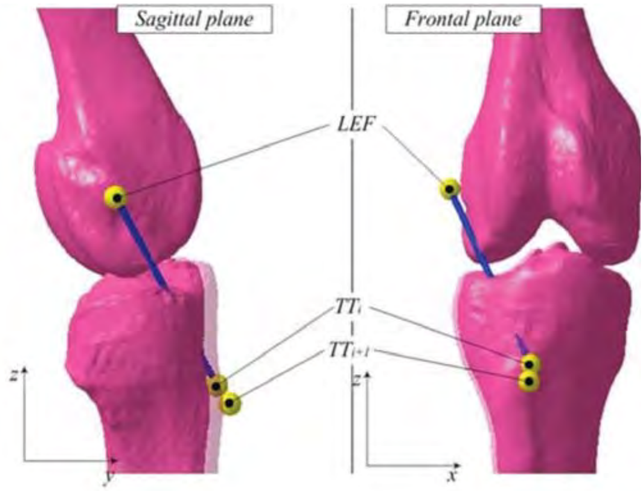
Figure 3. Identification of the distances between LEF and TT in space and in the horizontal, frontal and sagittal planes

The tibia shift along the AP direction (Fig. 4) is determined by successive calculations of the affine coordinates along these directions:

$$d_{TTAP} = (TTAP)_{i+1} - (TTAP)_i \quad (5)$$

The angle of the IE rotation is determined based on definition of the tangent line coefficient of the movement curve and on the definition of the angle between the tangent line and AP axis of the femoral coordinate system (Fig. 5) [7].

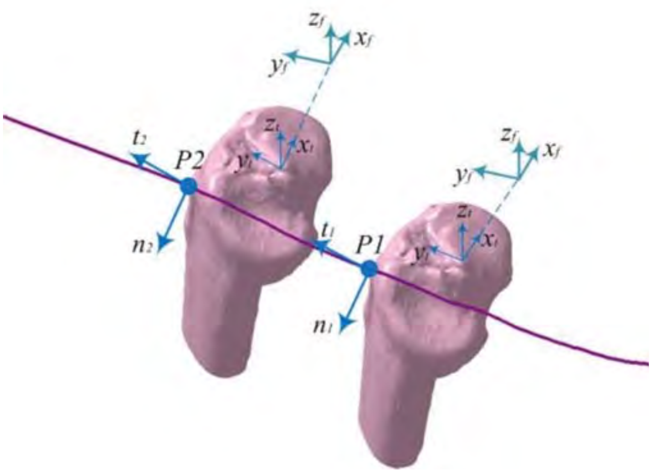
During the motion, the femoral coordinate system is considered the referent coordinate system that does not change its orientation. On the other side, IE tibia rotation occurs during motion. During the motion, i.e., within the stride (point *P1*) (Fig. 5), the tibia rotates at a certain angle relative to femoral coordinate system. On the tibial motion curve at point P1, in this particular moment within the gait cycle, it is possible to define



***LEF** - lateral epycondil of the femur,*
***TT_i**- tuberosity of the tibia in i-th moment, and*
***TT_{i+l}**- tuberosity of the tibia in i+l-th moment.*

Figure 4. Tibial translation along the AP and mediolateral (ML) axes

the tangent axis on the curve *t1* and corresponding normal axis *n1*. In the next moment (point *P2*), the tibia rotates at some other angle according to the referent femoral coordinate system. Accordingly, on the tibial motion curve at the point *P2*, we define tangent axis on the curve *t2* and corresponding normal axis *n2*. These axes, together with their corresponding binormals, form the tibial frame of reference. At the point P1:



***xf**- mediolateral axis of the femur,*
***yf**- anteroposterior axis of the femur,*
***zf**- superior - inferior axis of the femur.*
***xt** - mediolateral axis of the tibia.*
***yt** - anteroposterior axis of the tibia.*
***zt** - superior - inferior axis of the tibia,*
***ti, t2** - tangent line of the curve at the point PI, e.g. P2, and*
***n1n2** - normal line of the curve at the point PI, e.g. P2.*

Figure 5. Internal-external rotation of the tibia

$$x_{t1} \perp y_{t1} \text{ and } t_1 \perp n_1 \Rightarrow x_{t1} \parallel n_1 \text{ and } y_{t1} \parallel t_1 \quad (6)$$

Analogous to the previous expression, for point P2:

$$x_{t2} \perp y_{t2} \text{ and } t_2 \perp n_2 \Rightarrow x_{t2} \parallel n_2 \text{ and } y_{t2} \parallel t_2 \quad (7)$$

The previous two expressions show that for any point *i*:

$$x_{ti} \perp y_{ti} \text{ and } t_i \perp n_i \Rightarrow x_{ti} \parallel n_i \text{ and } y_{ti} \parallel t_i \quad (8)$$

By defining the position of the tangent to the curve, it is possible to define the normal position and consequently the orientation of the coordinate system of the tibia. Given the curve of the real function *f*, the direction of the tangent *t* at point *$P(x_i, f(x_i))$* has the same gradient as the curve function *f*, defined as:

$$t = f'(x_i) = \frac{dy_i}{dx_i} \quad (9)$$

The angle between the tangent to the tibial motion curve and the AP femoral axis is identical to the angle between the normal to the curve and ML femoral axes:

$$angle(t, y_f) = angle(n, x_f) \quad (10)$$

This angle defines IE tibia rotation and represents one of the key parameters for the diagnosis of ACL rupture.

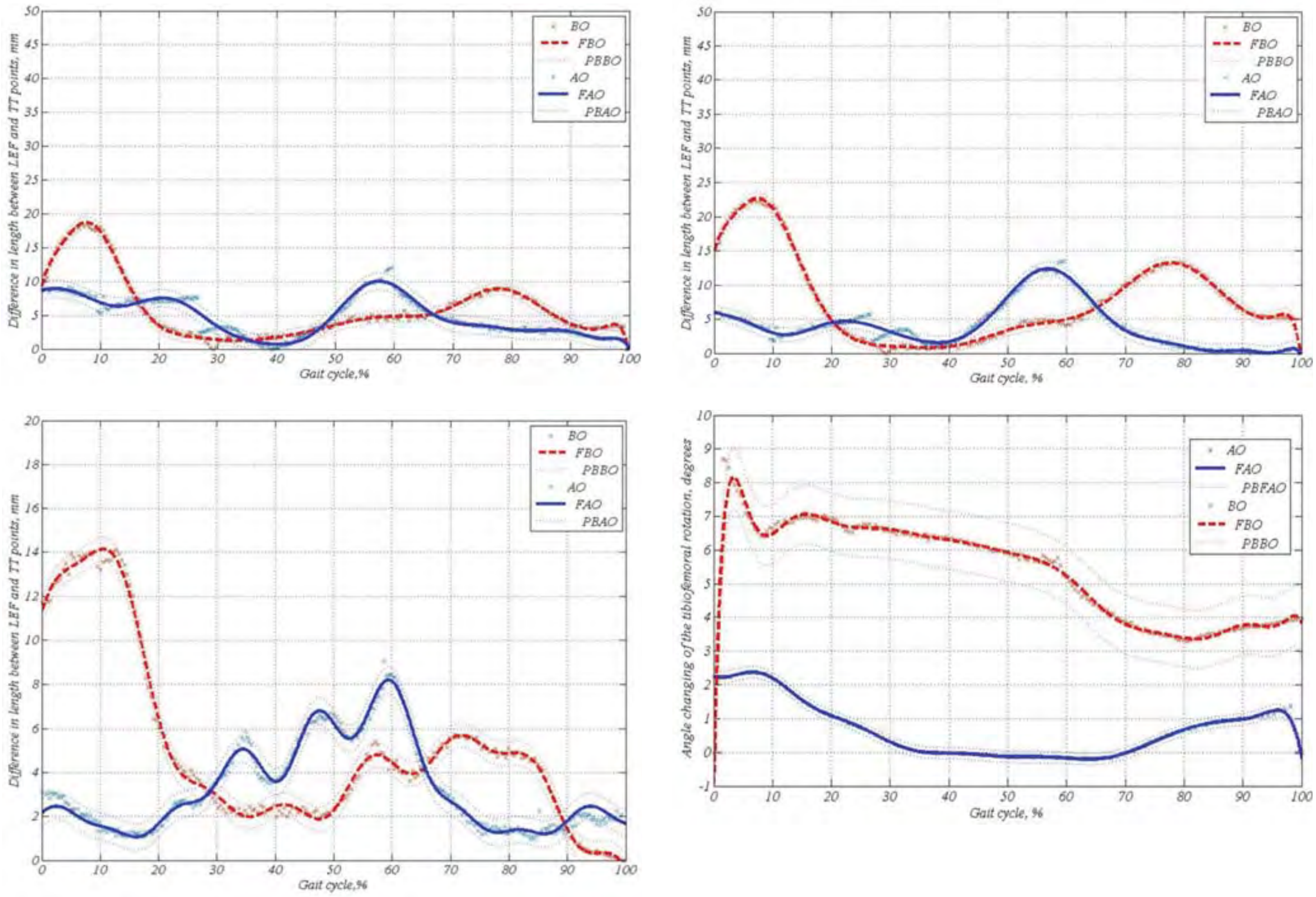
RESULTS

The horizontal axis represents the percentage distribution of the gait cycle, and the vertical axis represents the difference in lengths between LEF and TT in millimetres for tibia shift (Fig. 6a-c) and the difference of the change in IE angle rotation (Fig. 6d).

The curves on the diagrams obtained from the preoperational measurement results indicate that a large difference in lengths between the LEF and TT points along the AP axis occurs at the beginning of the gait cycle, just before the heel strike (Fig. 6a-c). The mean spatial value and its standard deviation of LF-TT lengths was 7.378±1.673 mm (Tab. 1). In the sagittal plane, this value is 11.064±1.961 mm, and along the AP axis, it is 6.619±1.447 mm (Tab. 1).

Curves on diagrams show that the patients' gait patterns have lower amplitudes after surgery, and the intensity of the LEF-TT length changes is decreased. The maximal spatial length change in our investigation corresponds to a heel strike of 4.179±0.886 mm (Tab.1). Additionally, the maximal shifts in sagittal plane occur in this part of the gait cycle, with approximate values of 5.748±0.859 mm, and an approximate value of 3.0901±0.511 mm along the AP direction (Tab. 1).

A diagram of the change in angle of the tibiofemoral rotation (Fig .6d) shows maximal rotation at the beginning of the gait cycle, when maximal tibial translation along the AP axis occurs, with a mean value and standard deviation of 6.169±0.711°. After surgery, this value decreases to 2.382±0.477° (Tab. 1).



(BO: Changes in lengths (or changes of the IE angle) between LEF and TT points before surgery, FBO: Fitted curve of the changes in lengths (or changes of the IE angle) between LEF and TT points before surgery, PFBO: Confidence boundary of the fitted curve of the changes in lengths (or changes of the IE angle) between LEF and TT points before surgery, AO: Changes in lengths (or changes of the IE angle) between LEF and TT points after surgery, FAO: Fitted curve of the changes in lengths (or changes of the IE angle) between LEF and TT points after surgery, and PFAO: Confidence boundary to the fitted curve of the changes in lengths (or change of the IE angle) between LEF and TT points before surgery)

Figure 6. Changes in lengths between LEF and TT: a) spatial, b) in the sagittal plane, c) along the AP axis, and d) changes in the angle of the IE rotation

	Before operation	*After operation*
Spatial distance between LEF and TT points	*7.378±1.673 mm*	*4.179±0.886 mm*
Distance between LEF and TT points in the sagittal plane	*11.064±1.961 mm*	*5.748±0.859 mm*
Tibia shift along the AP axis	*6.619±1.447 mm*	*3.0901±0.511 mm*
IE tibia rotation	*6.169 °±0.711*	*2.382±0.477°*

Table 1. Mean value and standard deviation

DISCUSSION

We used a Sstudent's t-test to demonstrate the statistical significance of the difference of the related patterns between the preoperational and post-operational period. The test shows that there is a significant difference in the spatial distance between LEF and PP, the distance between LEF and PP in the sagittal plane, the tibial shift along the AP axis, and in IE rotation before and after operation. The threshold of the significance was computed as $p<0.01$ for a certainty of $P>99\%$. The character of the change is non-random and was the result of differences between pathological preoperational and corrected post-operational gait patterns.

The results of this study show that the reconstruction of the AC ligament reduces tibial translation to an acceptable level in space, and consequently in each plane and along all directions, simultaneously reducing the IE rotation of the tibia. Static knee stability tests (such as the Lachman test) are considered standard for determination of AC ligament deficiency, and these are based on the surgeon's personal impression. In contrast, in vivo studies of the knee joint stability are much more suitable for diagnosing clinical AC ligament deficiency as well as for the estimation of the positive effects of the surgery because they are based on calculations of the real shifts [8].

To achieve the functional role of the AC ligament, it is critical to determine the gait cycle phases that induce pathological kinematics of the knee joint with a deficient AC ligament. Assuming that the AC ligament and posterior cruciate ligament are rigid bodies, knee motion combines two different motions, gliding and rolling [9]. The gliding phase is very important for the determination of the rotation and translation values. During this phase, in patients with chronic ACL rupture, tibial translation is increased in the AP direction, as is IE rotation, which is clearly observed in diagrams (Fig. 6).

The restoration of tibiofemoral kinematics is based on decreasing tibial IE rotation and AP translation. In other words, at the beginning of the gait cycle (heel strike), in the gliding phase, tibial rotation and tibial translation along the AP direction achieve their maximal values. A stable knee joint assumes small values of IE rotation and AP translation of the tibia. An increase in those values that exceeds usual (physiological) measurements serves as a clinically clear symptom of AC ligament deficiency, whose further deterioration may cause cartilage degeneration [10,11,12,13].

Using in vitro and in vivo experiments, numerous researchers have recorded tibial translation along the AP direction, as well as an increased angle of IE rotation, which are related to a deficiency of the AC ligament [8,9,14,15]. The results of the studies published so far [7], [10], [16] confirm the findings in our study, shown in Figure 6. The maximal values of AP tibial translation and IE rotation occurred in the early stance phase. After ligament reconstruction, translation and rotation values were decreased, e.g., the amplitudes of the curves were smaller.

The limitations of this study are related to measurement errors and data noise coming from the skin and soft tissue motion. This problem is widely recognised [9], [16] and is common for non-invasive approaches in which IC cameras and fluorescent (reflective) markers are used. However, the clinical benefits of the methodology far exceed the imprecision of the measured values. Using the same clinical position for the leg markers may minimise these errors, providing a more precise clinical picture [8].

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