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Original Article

Description of an evaluation system for knee kinematics in ligament lesions, by means of optical tracking and 3D tomography☆,☆☆

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ABSTRACT

Objective: To describe and demonstrate the viability of a method for evaluating knee kinematics, by means of a continuous passive motion (CPM) machine, before and after anterior cruciate ligament (ACL) injury.
Methods: This study was conducted on a knee from a cadaver, in a mechanical pivot-shift simulator, with evaluations using optical tracking, and also using computed tomography.
Results: This study demonstrated the viability of a protocol for measuring the rotation and translation of the knee, using reproducible and objective tools (error < 0.2 mm). The mechanized provocation system of the pivot-shift test was independent of the examiner and always allowed the same angular velocity and traction of 20 N throughout the movement.
Conclusion: The clinical relevance of this method lies in making inferences about the *in vivo* behavior of a knee with an ACL injury and providing greater methodological quality in future studies for measuring surgical techniques with grafts in relatively close positions.

Descrição de sistema de avaliação da cinemática do joelho em lesões ligamentares a partir de rastreamento óptico e tomografia 3D

Palavras-chave:
Articulação do joelho
Ligamento cruzado anterior

RESUMO

Objetivo: Descrever e demonstrar a viabilidade de um método de avaliação da cinemática do joelho, por meio de um aparelho de CPM (*continuous passive motion*), antes e após a lesão do ligamento cruzado anterior (LCA).

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Tomografia computadorizada
por raios X

Métodos: O estudo foi feito em joelho de cadáver, em um simulador mecânico de *pivot-shift* avaliado a partir de rastreamento óptico associado à tomografia computadorizada.
Resultados: Este estudo demonstra a viabilidade de um protocolo de mensuração de rotação e translação do joelho com ferramentas reprodutíveis e objetivas (erro < 0,2 mm). O sistema mecanizado de provocação do teste do *pivot-shift* é independente do examinador e permite sempre a mesma velocidade angular e tração de 20 N por todo o movimento.
Conclusão: Sua relevância clínica está em fazer inferências sobre o comportamento *in vivo* de um joelho com lesão do LCA e proporcionar aos estudos futuros maior qualidade metodológica para a aferição de técnicas cirúrgicas com enxertos em posições relativamente próximas.

Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the orthopedics' surgical procedures most performed today. It has been estimated that approximately 200,000 such procedures are performed in the USA every year.[1]

Despite the large number of studies that have been conducted in relation to ACL reconstruction,[2,3] the rate of excellent or good results ranges from 69% to 95%.[4] Unsatisfactory results may result from persistent instability of the knee and consequent difficulty in returning to the previous level of physical activity.[5–9]

ACL insufficiency is represented by anterior translation of the tibia and by rotational instability of the knee.[10] The pivot shift test is used to evaluate the rotational stability of the knee after ACL injury.[11] Some authors have demonstrated that the presence of a positive pivot shift test is predictive for development of osteoarthrosis and poor functional results.[12–15]

Although the pivot shift test is very specific (close to 100% under anesthesia),[16–19] its result is subjective because it is examiner-dependent. Therefore, it is too imprecise for use in scientific studies.[10,15,18–21]

Musahl et al.[20] demonstrated that the mechanized pivot shift test, which consists of using a continuous passive motion (CPM) machine to perform combined knee movements of internal rotation, valgus rotation and flexion, has greater accuracy than the manual test.

In conjunction with computer-assisted surgery systems, the pivot shift system can be measured satisfactorily and be used to analyze knee stability after different ACL reconstruction techniques.[10,22]

Thus, the present study had the objective of describing a method for kinematic evaluation of the knee before and after ACL injury, by means of technologies that make it possible to objectively assess knee ligament stability.[23]

For this, we present below the mechanized pivot shift apparatus and an optical tracking system in association with computed tomography.

Materials and methods

This experiment was conducted on a knee from a cadaver, in conformity with approval from our institution's Research Ethics Committee. The cadaver's entire lower limb was used, with preservation of the hip and ankle joints.

As inclusion criteria, the knee selected did not present any previous ACL injury or other ligament injuries, there was no moderate or severe osteoarthrosis and there was no evidence of fracturing or displaced alignment of the mechanical axis of the limb.

Before the experiment was started, deinsertion and muscle sectioning were performed in order to enable full knee range of motion, as follows: tenotomy of the adductor mass at its origin in the pubis; sectioning of the quadriceps and hamstring muscles at their origin; and tenotomy of the calcaneal tendon.

Instrumented pivot shift and rotational stability of the knee

The mechanical pivot shift simulator was developed in the Biomechanics Laboratory (LIM-41), starting from a CPM machine (Carci, Ortomed 4060; ANVISA: 10314290029) similar to the model used and validated by Bedi et al.[24]

The pelvis was stabilized on the surgical table and the hip and knee were allowed to have full ranges of motion. No support using bands and the femur or tibia level was provided.

The CPM device was designed to allow 15° of internal ankle rotation, for both the left and for the right lower limbs. Axial compression of the ankle was performed at an angular velocity of 1.62°/s, from maximum extension to 50° of knee flexion[20] (Fig. 1).

The moment of internal and valgus rotation of the knee was determined by means of a system of cables and pulleys coupled to the CPM device. The point of traction on the tibia was defined by means of a titanium pin fixed perpendicularly to the tuberosity of tibia, of length 10 cm. The traction of the titanium pin was perpendicular to the axis of the tibia and had the same force vector of 20 N[25] throughout the flexion–extension movement (0–50°)[20] (Fig. 2).

Measurement of the anterior translation of the tibia

The anterior translation of the tibia was measured by means of a spring dynamometer (Sandes) using the same titanium pin presented previously, after prior calibration using a universal mechanical test machine (Kratos, model 5002; Cotia, Brazil).

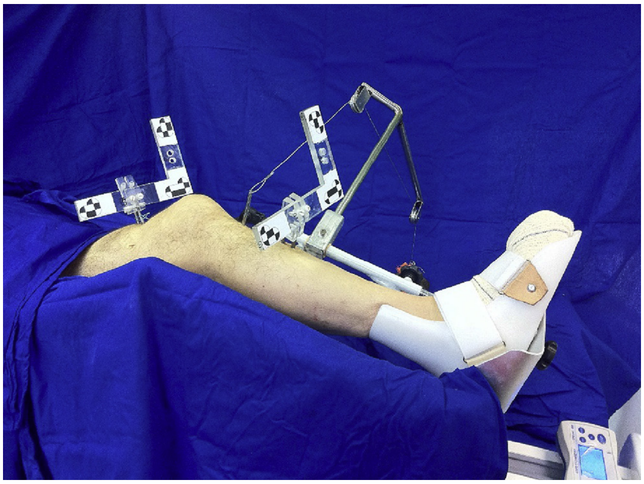

Fig. 1 – Mechanized pivot shift system.

The vertical force applied, in accordance with the study by Bedi et al.,[26] was 68 N with the knee flexed at 30°.

Optical tracking system

The tracking system (MicronTracker 2, model H40) made it possible to obtain the spatial positioning of the femur and tibia through identifying optical markers and determining the knee translation and rotation movements.

Three optical markers were distributed along two L-shaped acrylic pieces and were fixed to the femur and tibia using two titanium pins, in order to create a rigid system (Fig. 3).

A computer routine was developed (using the manufacturer's library, in the Basic language) in order to recognize and save the three-dimensional data (XYZ) that was captured by the cameras of the optical tracking system in real time (15 Hz, with measurement precision of 0.2 mm, according to the manufacturer) (Fig. 4).

The central point of the knee, which was used as a reference point for calculating the knee rotation and translation,

Fig. 2 – Traction system using cables and pulleys.

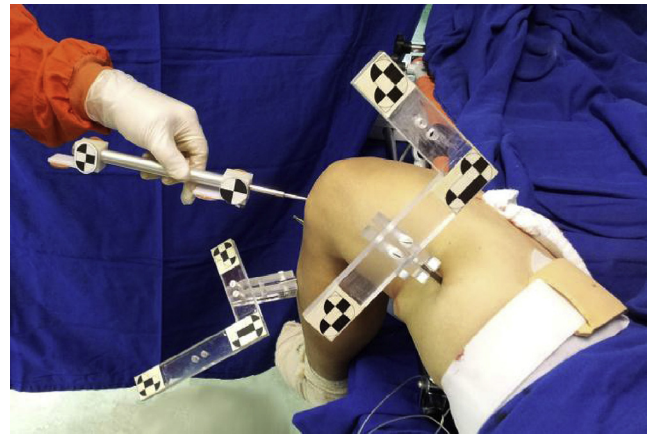

Fig. 3 – L-shaped optical markers on the femur and tibia.

was defined from computed tomography on the entire limb after the tests had been finished (Fig. 5).

For there to be correspondence between the optical tracking system and the computed tomography, radiodense filaments were included in the central positions of the optical markers (Fig. 6).

The knee movement was calculated from rotation and translation matrices between the coordinate systems of the camera and tomography and the coordinate systems positioned on the barium markers and on the center of the knee. At this point, coordinate systems were created for the tibia and femur. One of the axes coincided with the respective axis of each bone: one horizontal and the other vertical. These two coordinate systems were determined, for each time instant, by the coordinate systems of the markers.

The rotation around the axes and the translation of the central point of the knee were obtained by means of the rotation and translation matrix between the femoral and tibial coordinate systems. This procedure was developed using the GNU Octave computer software.

Protocol

The tests were carried out in two stages: before and after dissection, under direct viewing of the ACL at its origin and insertion.

At each stage, three measurements of the anterior translation of the tibia were made using a manual dynamometer (68 N) and three measurements of knee flexion–extension were made using the mechanized pivot shift, as described earlier.

Results

The knee used was the right knee of a 45-year-old male cadaver.

The central points of the knee (distal femur and proximal tibia) were captured three-dimensionally (Fig. 7) along the knee flexion and extension and were analyzed in the time domain.

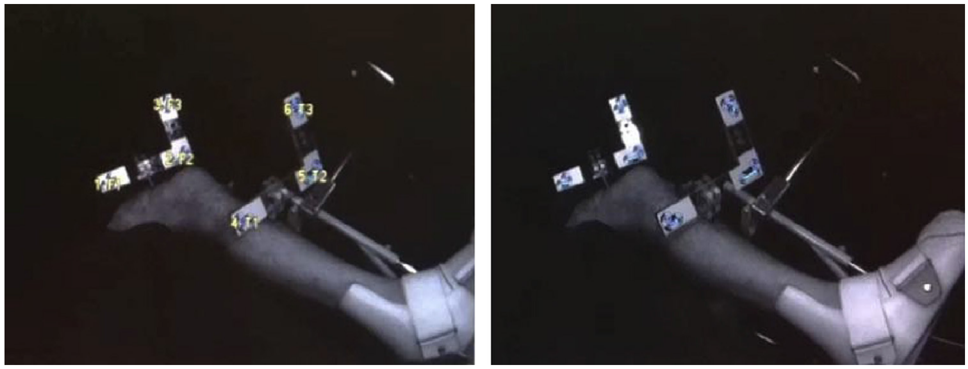

Fig. 4 – Three-dimensional identification of the optical markers.

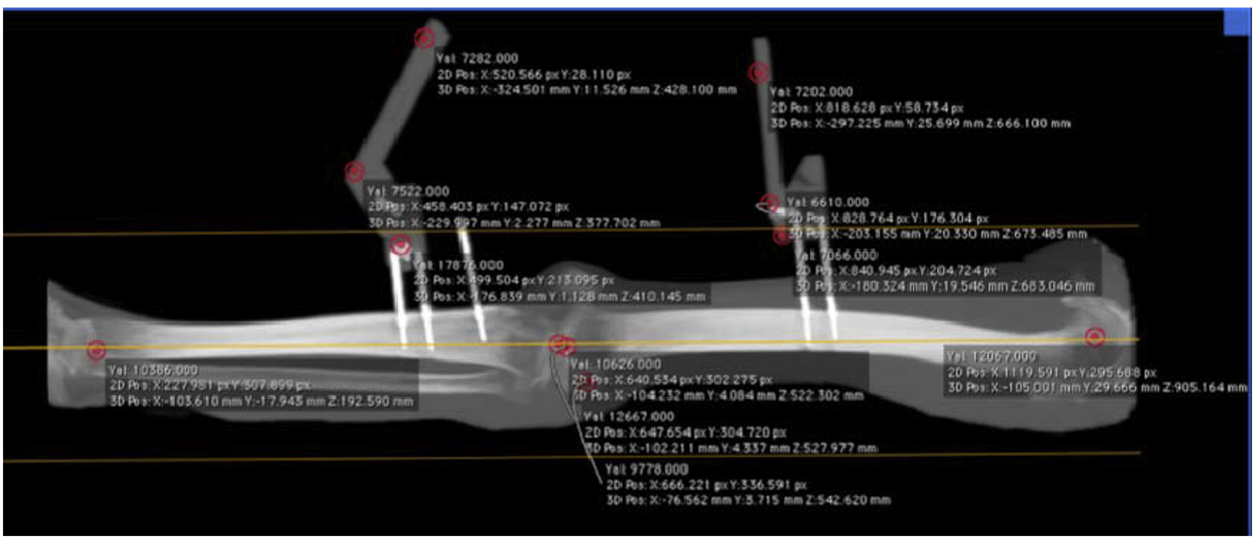

Fig. 5 – Mechanical axis of the lower limb: three-dimensional points at the center of the femoral head and ankle. Radiodense and optical markers on the femur and tibia.

The increase in the distance between the positions of the center of the femur and the center of the tibia, between maximum extension and maximum flexion of the knee represents the pivot shift phenomenon (Fig. 8, red line).

Fig. 9 shows the anterior translation of the tibia with the knee flexed at 30° in relation to the femur, before and after 68 N or 15 lb[25] of traction through the titanium pin, perpendicularly to the tibia.

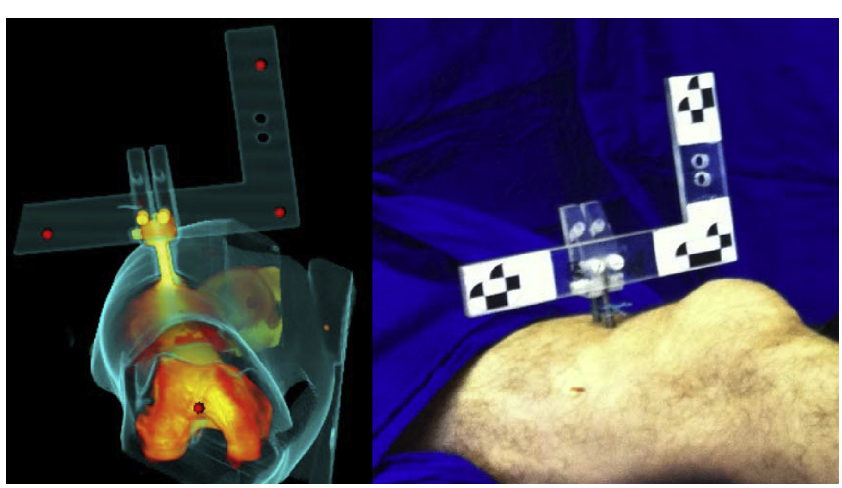

Fig. 6 – Correspondence between the radiodense and optical markers.

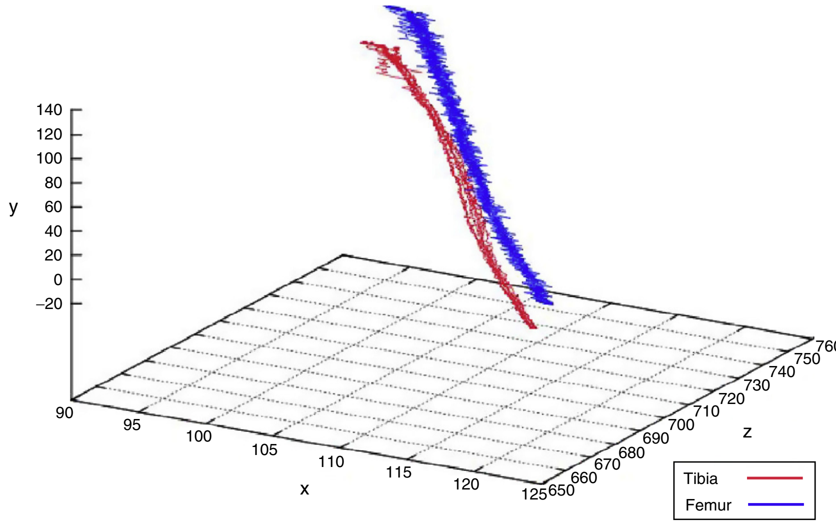

Fig. 7 – Graphical representation of knee movement in the space of the central points of the femur and tibia.

Fig. 10 shows a polar graph representing the combined translation and rotation movements of the tibia, in relation to the femur during knee flexion and extension.

Discussion

The main contribution of this study is that it shows the viability of a protocol for measuring knee translation and rotation using objective and reproducible tools (error < 0.2 mm). Moreover, the technology that was developed for correlating between the optical and tomographic systems and the computational methodology for describing the movement are Brazilian intellectual property.

Lane et al.[10] reported that a clinical grading system describing knee stability in terms of knee glide, knee clunking and gross stability is valuable for experienced orthopedists. However, this system is subjective and not reproducible between surgeons and, for this reason, should not be used in scientific studies.[27]

The mechanized challenge system of the pivot shift test is independent of the examiner and always allows the same angular velocity and traction of 20 N throughout the movement. Because the test is mechanized, this also reduces the risk of bias and increases the internal validity of such studies.[28] Consequently, the quality and representativeness of these studies are also increased.

Another important technical note relating to the present methodology relates to the use of tomography for defining the center of knee rotation. This selection can be made after the end of the experiment and it is possible, for example, to define the translation of the tibia in relation

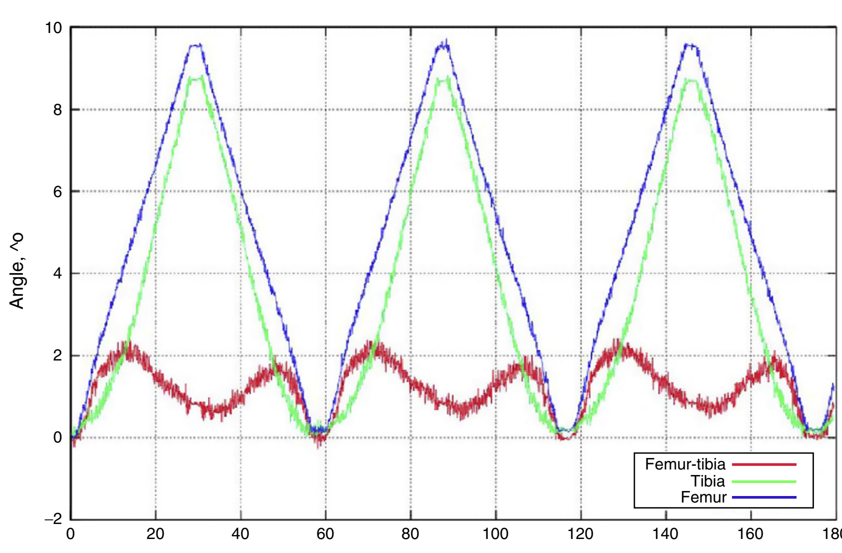

Fig. 8 – Graphical representation of the pivot shift phenomenon (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

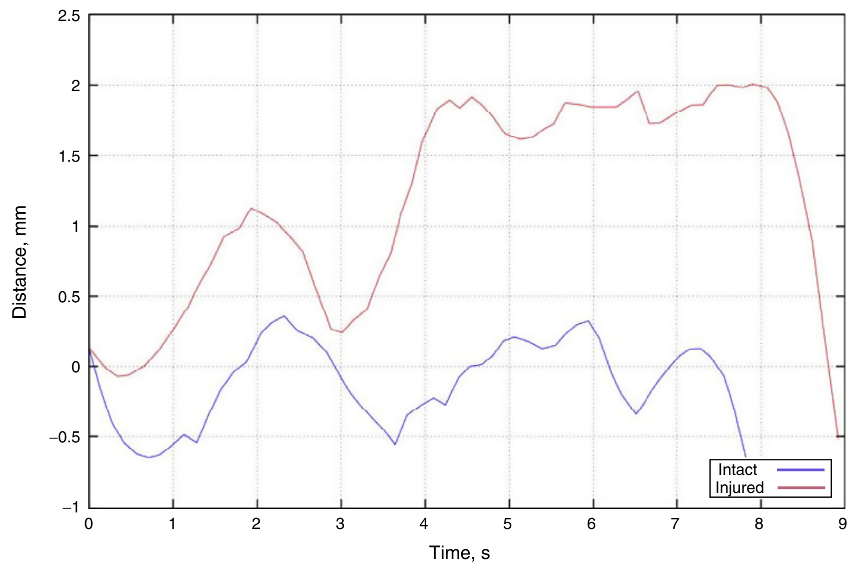

Fig. 9 – Anterior translation of the tibia after traction of 68 N by means of a metal pin in the tibial tuberosity (after 4 s). Blue line – intact ACL; red line – injured ACL. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the femur, in the lateral, medial or intercondylar compartments. Three-dimensional computed tomography also enables reconstruction of the knee in any plane and allows knee alignment and correct measurement of the positions of the femoral and tibial tunnels.[29,30]

The pivot shift phenomenon presented in Fig. 8 is concordant with what was shown by Bull et al.,[31] in which subluxation of the knee occurred at flexion of between 25° and 36°. Other studies have demonstrated reduction of knee subluxation at flexion of between 40° and 44°.[10]

One methodological limitation of biomechanical studies relates to carrying out experiments at time zero, *i.e.* immediately after the surgical procedure for ACL reconstruction. In our study specifically, because no ligament reconstruction was performed, there were no changes to the mechanical properties of grafts during any period of biological integration that could have influenced the analysis on the results presented.

Further studies are desirable, in order to biomechanically analyze the knee with tunnels in different anatomical positions. Cross et al.[32] argued that there was no consensus in the literature regarding where within the original footprint the ACL tunnel should be constructed.

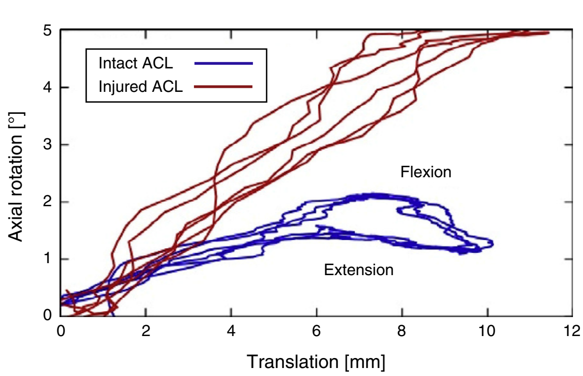

Fig. 10 – Polar representation of the combined translation and rotation of the knee.

Conclusion

The clinical importance of the present study relates to the inferences that can be made regarding the *in vivo* behavior of knees with ACL injuries and the greater methodological quality that can be provided in future studies regarding measurements on surgical techniques with grafts in relatively close positions.

Conflicts of interest

The authors declare no conflicts of interest.

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