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Videofluoroscopy Instrument to Identify the Tibiofemoral Contact Point Migration for Anterior Cruciate Ligament Reconstruction Follow-up: CINARTRO

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Abstract. We measure the Tibiofemoral contact point migration to offer clinicians a tool to evaluate Anterior Cruciate Ligament reconstruction. The design of the tool includes a C arm with fluoroscopy, image acquisition and processing system, interactive software and report generation for the clinical record. The procedure samples 30 images from the videofluoroscopy describing 2 seconds movements of hanging-to-full-extension of the knee articulation. A geometrical routine implemented in the original equipment (CINARTRO) helps capture tibial plateau and femoral condile profile by interaction with the user. The tightness or looseness of the knee is expressed by the migration given in terms of movement of the femur along the tibial plateau, as a percentage. We automatically create clinical reports in standard Clinical Document Architecture or CDA format. A special phantom was developed to correct the "pin cushion effect" in Rx images. Five cases of broken ACL patients were measured giving meaningful results for clinical follow up. Tibiofemoral contact point migration was measured as 60% of the tibial plateau, with standard deviation of 6% for healthy knees, 4% when injured and 1% after reconstruction.

1. Introduction

The knee articulation (KA) is responsible for two contradictory functions: static stability during full extension and adaptation to ground irregularities during gait and running [1]. Clinical appraisal of movement is subjective, which has led to the need of objective measurements. To this end, several methods have been suggested, albeit all circumscribed within research settings and not currently in clinical use. Clinicians look at the looseness or tightness of the knee during flexion and extension but have no objective measure of either of them.

In the presence of Anterior Cruciate Ligament (ACL) injury there is a need for clinical assessment. According to Benjaminse et al. [2] the main function of the ACL is to prevent tibial translation forward, with respect to the femur. Therefore a loose KA is found for ACL injured patients. A reconstructed KA after ACL injury should recover at least part of the contention with no excess stiffness. Diagnostic tests to confirm ACL tears (and knee looseness) include the Lachman test, the pivot shift test and the use of the KT 1000/2000 arthrometer [3]. Magnetic resonance imaging is also used, because it provides the fine soft tissue detail necessary to confirm a diagnosis [4].

The normal knee bends with respect to a migrating fulcrum or centre of rotation. The ACL injured KA behaves differently. One method to objectively describe this state of tightness/looseness was described by Baltzopoulos [5] which consists of determining the contact point between the femur condile and the tibial plateau, which was called the "Tibiofemoral (TF) contact point". Baltzopoulos measures the migration of this TF contact point during flexo/extension on the tibial plateau [6]. This determination of knee artrokynematics could be used as an objective method to evaluate ACL reconstruction [7] and the first clinical applications have been described [8]. TF contact point migration data also helps to put in place rehabilitation strategies and to monitor them, as well as to give feedback to the surgeon. An alternative method to objectively record the tightness/looseness of the knee was published by Rouleaux, as the mechanical centre of rotation [9] derived from two adjacent videofluoroscopy images during flexo/extension. More related to mechanical engineering practice, this method of the geometrical centre of rotation has little clinical significance though, because the instantaneous fulcrum is located within the femoral condile. We set ourselves the goal of developing a methodology and a clinical instrument for ACL follow-up, based on our prior medical device development experience [10]. The present paper reports on the implementation of the Baltzopoulos method as a medical instrument prototype (which we called CINARTRO), while development of software according to the Rouleaux method are at present under way. Clinical application was performed on five patients before and after surgery. The goal of the present applied research is that of obtaining a dynamic and functional evidence of knee movement as opposed to conventional static imaging studies, such as MRI, CT and RX, to guide clinical management.

2. Rationale and specification of the instrument

2.1 Relevance of the instrument designed

The incidence of ACL lesions is estimated as 1 every 3000 population, which accounts for over a billion US dollars in surgical and rehabilitation costs only in the USA [11]. This overall cost is equivalent to US dollars 10.000 for every injured person including 6 months of rehabilitation [12]. Surgery and rehabilitation restore the stability and the complex movement of the knee. The main concern of the surgeon is to count on reliable and objective elements to evaluate the postoperative functional restoration. The physiotherapist, moreover, is interested in periodic knee functional measurements as his or her rehabilitation work progresses, and in particular the relative movement of femur and tibia, whether too tight or too loose.

The desired instrument to address these needs should add quantitative input to the traditional clinical approach of gait observation and tests such as the one described by Lachman using the arthrometre, (e.g.: KT-1000 y KT- 2000) [2]. For ACL reconstruction evaluation, usual clinical practice includes imaging studies such as X rays, CT scans and NMR, all of which are purely static evaluations. Although anatomical structures may be shown in great detail, no dynamic aspects are considered, which are part of the essence of knee functions. The instrument to be designed should record, evaluate and quantify kinematic characteristics of the KA.

2.2 Specification of the instrument to be designed

There are no instruments available today to spot quantitatively the TF contact point during knee joint movement, to be used in patient care. The instrument to be designed should compare the injured knee with the other knee and the injured knee prior and after surgery, as well as at set intervals during rehabilitation.

The instrument should determine TF contact point migration during flexo-extension and should create a document for the Electronic Clinical Record of the patient, as well as a hard copy. The details of the determination should be decided by the specialist during an interactive software application. The instrument should show both the injured and contra-lateral knee joints images and TF contact point determinations, allowing reference and comparison. Additionally, the instrument should include ways to follow-up a knee joint being reeducated over the months and years. The instrument was called CINARTRO to suggest kinematics (“CIN”) and joint (“ARTROS”), to study KA movement.

2.3 Experimental set up and design of the instrument
In order to obtain a proof of concept and to validate the method, an experimental set up was build to analyze results on real data. To this end the following elements were connected:

- C-arm Xray equipment with video data acquisition
- Data acquisition hardware to digitize the videofluoroscopy images
- Software to determine the fiducial points in every image (tibial plateau and femur condile)
- Software to calculate TF contact point in every image
- Software to calculate the percentage of migration of TF contact point with respect to tibial plateau length

The method used consists of obtaining a series of 30 Xray images during extension and 30 images during flexion. The overall doses delivered by the C-arm was 250 microGy (J/Kg) absorbed every 2 seconds movement.

3. Project and building blocks
To tackle the clinical need for the instrument specified, we suggest a configuration such as the one represented in Figure 1. A C-arm apparatus gives standard sequences of images to be processed off line. The video film obtained is transformed into a series of 30 still images, evenly distributed from hanging leg position to full extension. Every image is shown to the operator in an off line environment with a Graphical User Interface (GUI) [13]. In this image the user is asked to identify the following five points: tibial plateau extremities and three points on the femoral condile profile. The central point is the furthest point on the femur “distalwise” and the other two are approximately one cm apart on either side, on the profile, as shown in Figure 4.

The five points for each image are processed by CINARTRO to find the shortest segment between the tibial plateau (straight line) and the curved femoral condile. The three femoral points are fitted to a circumference, and the software calculates by simple geometry the distance from the condile to the tibial plateau. Once the segment going from tibia to femur is known, its mid point is defined as the TF contact point. One TF contact point is calculated for each one of the 30 images. The projection of the TF contact point onto the tibial plateau is taken by the software as the position of TF contact point. We express this position as a percentage of the tibial plateau segment, from back to front (posterior-anterior wise). A projection at the very back of the tibial plateau is 0% and a projection at the foremost end is labelled 100% which is a way to unify measurements amongst anatomically different individuals.

CINARTRO builds a graph of the TF contact points in terms of percentage of tibial plateau with respect to the angle of extension (from 0 degrees to 90 degrees, the latter being full extension). The comparison of this graphical representation of (a) contralateral healthy, (b) injured and (c) reconstructed movements is the evidence that CINARTRO gives the clinician on the KA kinematics (Figure 2) of a single individual. Once the TF contact point migration is determined in the three situations -injured, healthy contralateral and reconstructed- data are stored and a clinical report is created, in which free text can be added by the operator.

We build a phantom consisting of a matrix of lead spheres (3 mm diameter, 1 cm apart) to be placed between the X ray emitter and the fluoroscope, thus allowing spatial calibration of the software. Figure 3 shows the phantom developed to calibrate videofluoroscopy derived images. In order to record exact dimensions, prior to the study of each patient, we obtain a phantom image and identify a few points at random to deduce a correction factor for all coordinates of the 30 images.

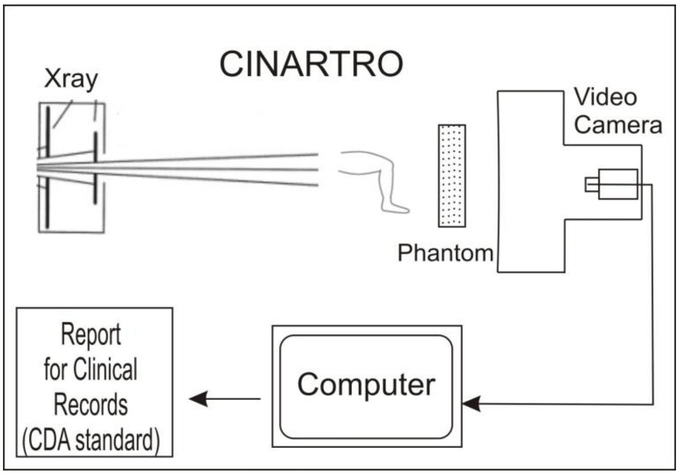


Figure 1. Block diagram of CINARTRO. Serial X ray images are obtained during extension. Fiducial points are marked for every image, allowing the Tibiofemoral (TF) contact point to be determined in each one of the 30 "hanging-to-extension" images. The clinical report shows the migration of the TF contact point projection along the tibial plateau.

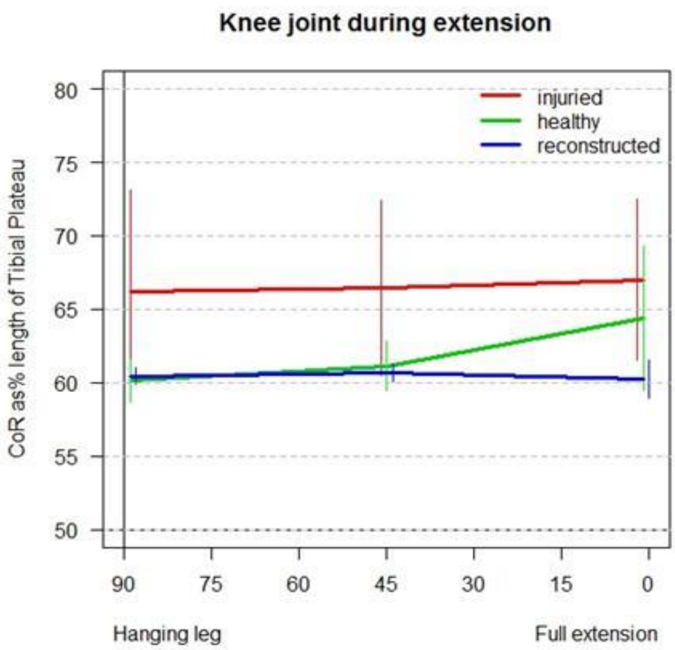
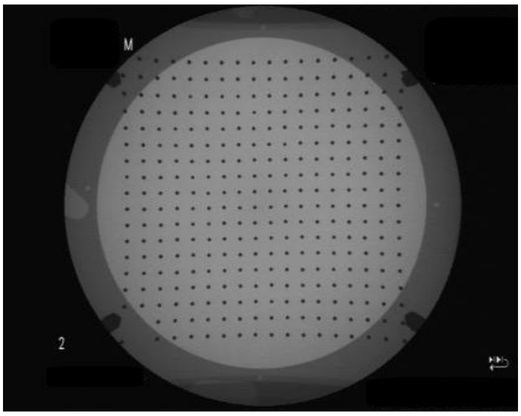


Figure 2. CINARTRO presentation of Tibiofemoral (TF) contact point migration as extension progresses, with respect to tibial plateau segment length. This case is the mean of several patients, but the same graphical format is created for each individual, with the same coordinates and values. Reprinted from Santos, et al. [14]

(a)



(b)

Figure 3. (a) Phantom for CINARTRO made with hard acrylic material. Anatomical pieces (Femur and Tibia) are included in the foreground to show the scale. Note the 324 lead spheres of 1 mm, spaced 1 cm apart, embedded in the hard acrylic. The dimensions are 18 cm by 18 cm. **(b)** Rx image of the Phantom, used to calibrate and correct the C-arm distortion. Note the "pin cushion effect" as spheres -originally in a straight line- appear on a curved line showing the X-ray system distortion.

4. Clinical Results Using CINARTRO

CINARTRO was used to evaluate ACL reconstruction of five subjects, after securing Ethics Committee approval of the "Hospital de Clinicas". The patients were instructed to sit with their knee close to the C-arm. Patients performed extension/flexion movements in 2+2 seconds for a total of three repetitions, recorded by videofluoroscopy. This procedure was performed for the injured knee and the contralateral knee before surgery. Six months later, a third data set is obtained only for the reconstructed knee. Videofluoroscopy sequences were fragmented into 30 images, evenly distributed over the extension movement. No images are analyzed during flexion because we assume that the principal function of the ACL is tibial forward constraint [2]. Figure 4 shows one of the 30 images with the points marked by the operator. The information of both segments (straight line for tibial plateau and three points curve for the femoral condile profile) is used to determine the TF contact point according to the Baltzopoulos method [5].

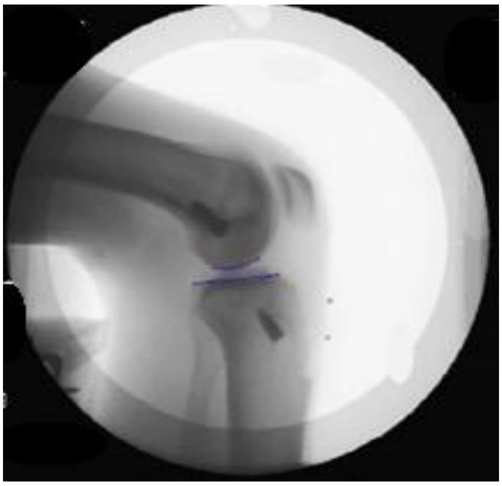


Figure 4. X ray of a knee joint taken by CINARTRO. Note the tibial plateau highlighted by 2 points selected by the user with the software and 3 points of the femur condile profile. The TF contact point is determined as the midpoint of the shortest segment between femur and tibial plateau.

Five male patients were studied (25 ± 3.6 years, range 18-35 years), all with an isolated tear of the ACL three months earlier (no ligament nor meniscal injury); all had a closed knee injury. As inclusion criterion, all patients had a score of the International Knee Documentation Committee (IKDC) of grade "A". Additionally all patients had a healthy contralateral knee.

Bone-patellar tendon-bone surgical technique was used for all patients. The first X-ray exploration was done the day before surgery and the second was performed six months after reconstruction only on the reconstructed knee [14].

In order to evaluate the surgical procedure and its effect on everyday life, the Lysholm-Tegner score [15] was enquired by questioning before and after reconstruction. The contralateral KA had a LT score of 100%, also assigned to the pre-lesion KA, both based on patient memory. Before and after reconstruction, the scores were 60% and 97%, respectively, suggesting that surgery was successful.

As a sample for the clinical use of CINARTRO, we estimated the mean TF contact point excursion of the five patient group. In healthy condition TF contact point was located 62% (SD 6%) with respect to the tibial plateau, as measured on the contralateral healthy knee (Table 1). After ACL lesion, this measurement is 61% (SD 4%) and finally, after ACL reconstruction surgery, it was 60% (SD 1%).

TABLE 1 – EVALUATION OF ANTERIOR CRUCIATE LIGAMENT (ACL) RECONSTRUCTION BY TIBIOFEMORAL CONTACT POINT MIGRATION PRIOR AND AFTER SURGERY.

	Healthy*	Injured	Reconstructed
Patient	MTFCP**	MTFCP	MTFCP
1	62%	57%	61%
2	56%	59%	60%
3	60%	61%	61%
4	61%	68%	61%
5	71%	59%	58%
mean	62% (SD 6%)	61% (SD 4%)	60% (SD 1%)

* Healthy contralateral knee. ** MTFCP: Migration of Tibiofemoral contact point (% with respect to tibial plateau from back to front in sagittal plane as shown in Figure. 3)

5. Discussion

Clinical practice of ACL reconstruction follow-up has demanded for many years a practical instrument to benefit from the results published by research in KA kinematics. On one side, current research has explained the dynamics of the consequences of ACL rupture and has described the partial reconstruction obtained with different surgical techniques. This explanation remained within the realm of academic work, while clinicians had no other way to record the evolution of a repaired ACL but static images and their observation of the patient with limited displacement tests such as the KT1000.

By developing CINARTRO we are suggesting an objective procedure to record the result of ACL reconstructive surgery immediately after inflammation disappears, and later at intervals during physiotherapy and rehabilitation. The first five patients studied here with our methodology follow a common pattern, that of being young amateur sportsmen with an ACL injury in an otherwise healthy organism. Subjective evaluation by the patients themselves gives a clear indication of the improvement of their quality of life (Table 1) after reconstructive surgery. Our study has added an objective measurement of knee kinematics by recording the TF contact point migration with respect to the tibial plateau. We are developing -for future versions of the CINARTRO software- the suggestion to the user of the fiducial points detected in the previous image as a first guess to be corrected by fine displacement of the mouse. This will greatly help the determination of the TF contact point on each image of the fluoroscopic series.

The X-ray apparatus used for the preliminary proof of concept of CINARTRO is cumbersome to use and expensive (C arm is originally intended for cardiac procedures). We are working towards the design of a dedicated compact X-ray device, derived from veterinary equipment [16] which will allow us to design a simple, portable CINARTRO.

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