This full text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication.

Measurement of Knee Articulation Looseness by Videofluoroscopy Image Analysis: CINARTRO

Franco Simini
Núcleo de Ingeniería Biomedica
Facultades de Medicina e Ingeniería
Universidad de la República - Montevideo, Uruguay
simini@fing.edu.uy

Dario Santos
Departamento de Rehabilitación y Medicina Física (UIBLH)
Hospital de Clínicas, Facultad de Medicina
Universidad de la República - Montevideo, Uruguay
dsantos@hc.edu.uy

José Artigas
Núcleo de Ingeniería Biomedica
Facultades de Medicina e Ingeniería
Universidad de la República - Montevideo, Uruguay
chetear@gmail.com

Verónica Gigirey
Departamento de Imagenología
Hospital de Clínicas, Facultad de Medicina
Universidad de la República - Montevideo, Uruguay
verogigirey@gmail.com

Luis Dibarboure
Departamento de Imagenología
Hospital de Clínicas, Facultad de Medicina
Universidad de la República - Montevideo, Uruguay
srad@hc.edu.uy

Luis Francescoli
Clínica de Ortopedia y Traumatología
Facultad de Medicina
Universidad de la República - Montevideo, Uruguay
l.francescoli@me.com

Abstract—**The yearly incidence of injured Anterior Cruciate Ligament is one every 3000 persons. Usual clinical evaluation methods are qualitative and thus of limited value for precise follow-up either after surgical or conservative medical conduct. Additionally, routine Anterior Cruciate Ligament evaluation is static, overlooking any dynamic behavior of the knee. In research settings, several methods are used to evaluate knee articulation during movement, such as the Tibio Femoral Contact Point migration or the Instantaneous Centre of Rotation displacement and even the Moment Arm variations during extension. We have devised a novel instrument based on 30 images extracted from knee extension videofluoroscopy, which are interactively analyzed to allow automatic determination of kinematics parameters. The instrument, called CINARTRO, compares values with the contralateral knee and produces a standard Clinical Document Architecture file ready for Electronic Medical Record systems. Proof of concept of CINARTRO was set up using videofluroscopy and computer devices. To correct the "pin cushion" effect of X ray intensifiers, a 10 mm apart lead sphere phantom was developed to calibrate images. To validate the interactive selection of anatomical points on X ray images, a cadaveric leg was marked with lead markers and compared with points marked on the blind image, giving good precision measurements. Anterior Cruciate Ligament and contralateral parameters are given for a series of 6 patients, otherwise healthy amateur and professional soccer players.**

Keywords— Knee Kinematics; Tibio Femoral Contact Point; Quadriceps Moment Arm, CINARTRO.

I. Introduction

The knee articulation (KA) is a very complex structure of the human body, with several functions such as ensuring static stability during full extension of the leg, shortening of the leg to allow movement and adaptation to ground irregularities during gait and running [1]. Until recently, clinical evaluation of movement is the result of subjective appraisal, highly dependent upon the observer. A few quantitative and therefore objective methods have been suggested, all circumscribed to research settings, such as the determination of the Tibio Femoral Contact Point (TFCP) and its migration over the tibial plateau during flexo/extension [2] [3].

The knee is subject to continuous movements and exercises in everyday life. After the rupture of the Anterior Cruciate Ligament (ACL) the knee joint kinematics are altered [1]. The yearly incidence of injured ACL is one every 3000 persons, which implies an ample field of clinical work. In the economy, it accounts for over a billion dollars in surgical and rehabilitation costs only in the USA [4].

We have developed a way to enhance the subjective test with quantitative methods [5] [6] [7]. The aim of CINARTRO [5] (named as the contraction of “CINE” which stands for ”KINEMATICS” and ARTRO for “ARTHRO”) is the collection of data and images to be processed into numerical results to help determine the condition of the patient after an ACL surgery [6]. Videofluoroscopy (VFC) images are the input to the software, which interacts with the user to produce a relevant clinical report for the patient's medical record. We describe in the present paper the proof of concept of CINARTRO including calibration with phantom and cadaveric limb, as well as results obtained measuring the degree of tightness of a series of patients.

II. Specifications of the Instrument

A. Use Cases of the Instrument to be Designed

• After an ACL lesion and either a surgical reconstruction or rehabilitation, the main concern of the surgeon or physiotherapist is to count on reliable and objective elements on which to base decisions during follow-up [8] [9].

• The instrument to be designed will add quantitative input to the traditional clinical approach of gait observation and tests such as the one described by Lachman using the arthroformetre, (e.g.: KT-1000 y KT- 2000) [10].

• In addition to the usual static clinical imaging studies such as X rays, CT scans and MR, which may show anatomical structures in great detail, the user needs to evaluate the dynamic aspects, i.e. the essence of knee joint function [11]. CINARTRO has to analyze moving images to produce kinematics parameters of clinical value [6].

• The instrument to be designed should document knee kinematics characteristics in the Electronic Clinical Record.

• Since CINARTRO is based on X ray equipment of different geometries, it must compensate distortion for all of them.

• CINARTRO version 1 is specified to study in open chain [12] leaving for later versions the capture and analysis of the body loaded knee joint movement walking up and down on a standard step [13].

B. Specifications of CINARTRO Software

The Software to be developed should be able to read DICOM images produced by the X-ray equipment, either the C-arm or other real time X-ray equipment. Based on this information, it must produce clinically relevant evidence according to the following specifications:

• Display of VFC series of images

• Interactive point definition to determine the extremities of the Tibial Plateau, the Femoral Condyle, the Patella Extremity and the Tuberosity Notch. Figure 3 shows an example of this.

• Automatic spline determination of the Femoral Condyle from the three points spotted by the user.

• Automatic calculation of the TFCP as the midpoint of the Tibial Plateau to Femoral Condyle distance, in every image, following the Baltzopoulos method [3], [14].

• Automatic calculation of the Moment Arm as the distance between the "*Patella Notch to Tibial Tuberosity*" segment and a center of rotation. As a proxy for the moving instantaneous center of rotation, we have used the TFCP [15], [16].

• Automatic calculation of the Moment Arm as the distance between the same "*Patella Notch to Tibial Tuberosity*" segment and the actual instantaneous center of rotation [5]

• When displaying the subsequent image, the software [17] suggests all the fiducial points in plausible positions, determined from the previous image points and a Tibia movement extrapolation. In open chain movements, the Femur points suggested by the software are in the same place as in the previous image, since the Femur is fixed, the patient being seated.

• Once the series of VFC images is interactively processed by the operator, the software calculates the TFCP migration as a percentage of the Tibial Plateau dimension.

• The software must generate a clinical report in two formats: PDF (Portable Document Format) and CDA (Clinical Document Architecture) for Electronic Clinical Record interoperability.

III. Design of CINARTRO

A. Building Block of the Instrument CINARTRO

To record a moving joint we chose a sequence of VFC images at a rate of 15 images per second during a two-second extension movement. This method has the advantage over conventional Roentgen moving film analysis (once known as RSA – Roentgen Stereo Photographic Analysis) in the much lower ionizing radiation delivered to the patient. The disadvantage of using VFC is the optical distortion inflicted to the image by the curvature of the image intensifier [3]. Using clinical VFC available for angiocardiographic or gastroscopic dynamic exploration, the overall dosis delivered was 250 microGy (J/Kg) absorbed for every two seconds movement. We used a C arm (Angiostar Plus, SIEMENS) to obtain VFC series, as shown in Figure 1. The images are recorded in DICOM format, with single images ready for further processing in Bit Map Picture (BMP). We designed an original software to process the series of images, which consists of an interactive application to allow the user to select fiducial points on the images. The CINARTRO software shows on the image the homothetic places coming from the previous one to help the operator by suggesting points to be either confirmed or modified. The eleven anatomical points prompted by the software are shown in the left column of Figure 3. The first five points include three points on the Femoral Condyle and the two Tibial Plateau extremities. The second group includes two pairs of bone surface points to determine the flexion angle of the image. Finally the last group comprises the Patella Extremity and the Anterior Tuberosity Notch, to allow the software define the quadriceps ligament direction, and thus the Moment Arm.

Fig. 1. C-arm used to obtain videofluoroscopic (VFC) images of a moving knee joint. Note the subject seated in proximity of the image intensifier with a hanging leg. When ordered, the patient extends the leg while VFC is performed. Both legs are imaged this way the first time, only the injured one after surgery and during follow-up.

B. Image Quality Control to reduce Pin Cushion Effect

In order to correct the pin cushion distortion effect, we have designed a plastic device [17] with lead spheres separated by 10 mm in a two dimensional regular pattern (Figure 2). We called the device "Phantom" and it was placed in the same plane as the sagittal plane the patients would be located subsequently. Due to the VFC characteristics, the X-ray image taken of the Phantom pattern appears distorted. By matching the theoretical position of every lead sphere with their real position, the software [3] [20] is able to correct the operator-defined fiducial points. We have put in practice the method published by Baltzopoulos [3] which minimizes a global error function with linear algebra methods, and thus obtains a set of parameters for the transformation of the VFC point coordinates into "corrected" points. The same transformation derived from the Phantom image is later applied to all operator selected points on patient knee joint images. The image analysis is therefore free from major geometrical distortion.

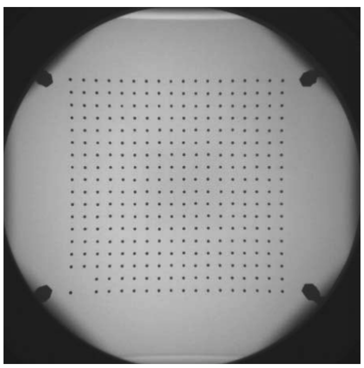

Fig. 2. Phantom specially designed and built to obtain a distorted image of the lead sphere pattern. Depending on the position of points on the VFC images, they are corrected accordingly. Spheres are 1 mm in diameter and spaced 10 mm from each other. Image obtained with Angiostar Plus, SIEMENS.

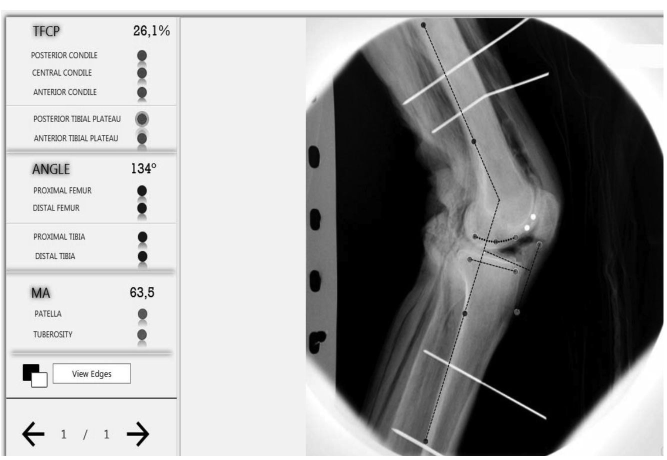

Fig. 3. Screen of CINARTRO software. On the left side the fiducial points are displayed and the operator click on one of them before marking the image on the right. As the points are marked, the software displays in bold characters on the left side of the screen, the angle of the Femoral-Tibial extension and the Moment Arm (MA) once the Tibio Femoral Contact Point is automatically determined and shown on the very image.

The error in TFCP migration was found to be less than 2% of the Tibial Plateau dimension in case the pincushion effect was not corrected [21]. A TFCP measurement of 40% of Tibial Plateau extension, with an uncertainty of 2% can be made better with pincushion distortion correction. After correction the error has no practical relevance in direct and derived measurements.

IV. RESULTS USING CINARTRO

A. Validation of Operator Point Marking

In order to verify that the operator marks the anatomical point correctly, we surgically prepared a cadaveric lower limb with lead sphere in the exact places of the Tibial Plateau extremities and along the Femoral Condyle. Similarly, spheres were also implanted at the lower end of the Patella and at the Tuberosity Notch, as shown in Figures 3 and 4.

In addition, the cadaveric limb was marked with steel rods to measure the flexion angle, as a check for the angle measured by CINARTRO software extracting information from the images.

Comparing cadaveric marked points with operator selection on blind images, the mean difference between series is 5% for the TFCP migration [22]. Similarly, the MA values obtained differ by a mean value of 3% [22].

Fig. 4. X ray of a knee joint taken by CINARTRO experimental set up. Note the Tibial Plateau highlighted by 2 points and 5 points of the Femur Condyle contour. The surgeon also put one lead sphere at the Patella extremity and one lead sphere on the Tuberosity Notch. Also note the perpendicular rods embedded into the bones.

B. Use of CINARTRO to Evaluate Patients

We used CINARTRO to evaluate ACL reconstruction of six subjects, after securing Ethics Committee project approval. Table 1 shows the results in terms of percentage of the Tibial Plateau to normalize dimensions across patients. The MA is increased when the ACL is injured, returning to close to normal after reconstruction.

TABLE 1 – QUADRICEPS MOMENT ARM OF 6 PATIENTS

Patient Condition	Position of leg			
	135 º Hanging leg	**150 º**	**165 º**	**180 º Fully extended**
Healthy	**39 ±3**	**45 ±5**	**43 ±5**	**44 ±3**
Injured	**47±5**	**51 ±7**	**62 ±5**	**53 ± 4**
Reconstructed	**38 ±3**	**41 ±4**	**40 ±2**	**37 ±2**

Note: All figures given in percentage of Tibial Plateau size.

CINARTRO produces a clinical document, which includes a graphic representation of the TFCP migration and the MA as the extension progresses. Figure 5 is an example of such representation where the migration of the TFCP is shown to span from 42% to 60% of the Tibial Plateau length.

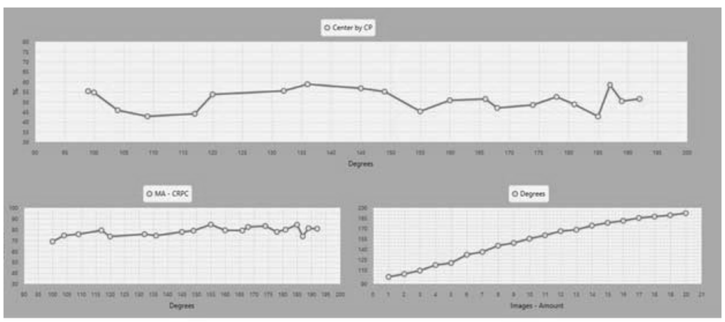

Fig. 5. Clinical results for the Patient Report. The upper graph shows the Tibio Femoral Contact Point (TFCP) migration as a percentage of the Tibial Plateau, during active extension from 90º to 180º (full extension). The lower left is the Moment Arm length, which varies from roughly 60 to 80 mm. The lower right is a check of the limb angle (90º to 180º full extension) and image number (1 to 30) in abscissa.

V. Discussion

When the ACL is repaired, the rehabilitation process aims at strengthening muscular action and neuromuscular control, in order to preserve as much as possible the original functions present prior to the lesion. In particular the initial training phases are critical in strengthening quadriceps without damaging the reconstructed ACL [9]. When the ACL is injured, the quadriceps force is reduced [6]. We have shown here that the MA is slightly increased when ACL is injured (Table 1), a compensation of the reduction in quadriceps strength, trying to keep the Moment constant (remember that Moment is the product of Force by MA). The increase of MA secondary to ACL injury, is shown in the same Table 1 to be reduced after ACL reconstruction. Our interpretation is that the rehabilitation improves the quadriceps strength, a necessary measure to counteract the surgical reduction of MA back to near physiological values. A non-repaired ACL is probably compatible with a weakened quadriceps.

Clinical practice of ACL reconstruction follow-up has demanded for many years a practical instrument to benefit from research in joint kinematics [23]. On one side research explained the dynamics of the consequences of ACL rupture [8] and 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 simple clinical procedure such as the KT1000 or Lachman test. By developing CINARTRO we are suggesting an objective procedure to record the result of ACL reconstructive surgery immediately after inflammation lowers, and later at intervals during physiotherapy and rehabilitation [6].

The X-ray system used for the present preliminary proof of concept of CINARTRO is available but cumbersome to use and expensive (C arm for cardiac procedures). We are working towards the design of a dedicated compact X-ray device, probably derived from veterinary equipment [17], which will allow us to design a simple, portable CINARTRO for routine clinical practice.

Future work will address the measurement of forces involved in the intact/injured/reconstructed ACL settings, to further explore the hypothesis of quadriceps strength reduction with injured ACL to be restored to higher performance muscles with reconstructed (shortened) ACL and MA.

Acknowledgment

The authors thank Dr Ing. Alberto Leardini for inspiring comments on our research which led to the inclusion of pertinent research methodology. Dr. Teresa Camarot, Director of the Rehabilitation and Physical Medicine Department, is acknowledged for support during the research. The authors also thank Dr. Eduardo Olivera for active cooperation from the Anatomy Department. The authors finally thank Florencia Arbío, Braian Elliot, Mauricio Bouza, Williams Olivera and Marcio Rodríguez all Engineering Students as well as Andrés Rey for contributions in procedures and programming tasks. Mrs. Susana Martinez is acknowledged for excellent administrative support.

References

[1] A. Benjaminse, A. Gokeler, and C. P. van der Schans, "Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis.," *J. Orthop. Sports Phys. Ther.*, vol. 36, no. 5, pp. 267–288, May 2006.

[2] B. M. You, P. Siy, W. Anderst, and S. Tashman, "In vivo measurement of 3-D skeletal kinematics from sequences of biplane radiographs: application to knee kinematics.," *IEEE Trans. Med. Imaging*, vol. 20, no. 6, pp. 514–525, Jun. 2001.

[3] V. Baltzopoulos, "A videofluoroscopy method for optical distortion correction and measurement of knee-joint kinematics.," *Clin. Biomech. (Bristol, Avon)*, vol. 10, no. 2, pp. 85–92, Mar. 1995.

[4] R. Nandra, G. S. Matharu, K. Porter, T. Ashraf, and I. Greaves, "A review of anterior cruciate ligament injuries and reconstructive techniques . Part 2 : Treatment," *Trauma*, vol. 15, no. 2, pp. 116–127, 2013.

[5] F. Simini and D. Santos, "Anterior Cruciate Ligament reconstruction follow-up instrumentation based on Centre of

This work was done under the auspices of ANII, Agencia Nacional de Investigación e Innovación, Uruguay, as part of the "level II" Researcher Contract with FS.