

CINARTRO: Clinical Tool to Assess Knee Kinematics by Videofluoroscopy

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Abstract— A new software application has been added to CINARTRO, a clinical tool to study knee kinematics from videofluoroscopic images during extension. The user selects, for each image, a set of points located on the Tibial Plateau and Condyle projections to determine the value of the Tibiofemoral Contact Point and a proxy of the Quadriceps Ligament Moment Arm. The software generates reports in PDF, Excel and CDA formats. CDA (Clinical Document Architecture) reports are uploaded into an XDS repository, as part of the patient clinical record. To solve the problem of “pincushion” effect in images, a gray tone recognition algorithm and distortion correction algorithm were implemented. The software was used to analyze data of injured and healthy knees of 3 patients. Precision errors introduced during the location of the points were 0.235mm. The Tibiofemoral Contact Point shows an average displacement of 59% in terms of tibial plateau length for healthy knees and 49% for injured knees. The average Moment Arm proxy was 50mm for healthy and 45mm for injured knees. The reduction in Quadriceps Muscle strength after ACL injury is compensated by a 11% increase in the Quadriceps Moment Arm.

Keywords— *Knee Kinematics, Anterior Cruciate Ligament (ACL), Tibio-Femoral Contact Point (TFCP), Quadriceps Moment Arm, Computer Document Architecture (CDA).*

I. INTRODUCTION

The knee of a person is subject to continuous movements and exercises in everyday life. After a serious lesion such as the rupture of the Anterior Cruciate Ligament (ACL) the knee joint kinematics are altered [1]. Postoperatively, functional instabilities may develop which require careful and evidence-based rehabilitation.

One of the most common ways to check the state of a reconstructed knee is with the Lachman test [2]. This evaluation depends greatly upon the perception and experience of the physician. We have developed a way to enhance and supplement this test with quantitative methods [3]. The aim of CINARTRO (such is the name of our instrument) 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 [4]. The set of images obtained from a study by videofluoroscopy (VFC) is the source of input data to the software which interacts with the user to produce a relevant clinical report for the patient's medical record.

The procedure follows the theoretical methods by Baltzopoulos [5]. In particular, CINARTRO calculates the instantaneous position of the tibio-femoral contact point (TFCP) during extension movements [6]. Once the TFCP is known for every image, its posterior-anterior migration during extension is an indication of knee kinematics [4] and we add in the present paper the estimation of a proxy of the Moment Arm to further refine knee joint kinematics evaluation. This proxy is based on the TFCP rather than the instantaneous center of rotation, for simplicity.

II. DESIGN AND ARCHITECTURE

CINARTRO is a software application which includes usability, integration with external components and generation of medical reports based on the specifications of Table 1.

The design and architecture for CINARTRO is shown in Figure 1 to fulfill the following functions:

- Acquisition of VFC images
- Phantom image processing for distortion correction
- Decimation of VFC to 15 images for extension
- Management of patient/VFC/healthy-or-injured knee
- Interaction to select anatomical repères in each image
- Geometric calculations of TFCP and moment arm
- Report generation

Table 1 CINARTRO software specification

Characteristic	Description
Calculation	TFCP and Moment Arm for every VFC image
Platform	Multiplatform: Windows, MacOS, Linux
Internationalization	English, Spanish; easy adoption of other languages
Target user	Physicians, specially physiotherapist, exercise physiologist
External agents	EMPI [7], XDS [8], AGESIC [9], Salud.uy [10]
Output information	CDA [11] and PDF clinical reports. Excel spreadsheets containing raw data

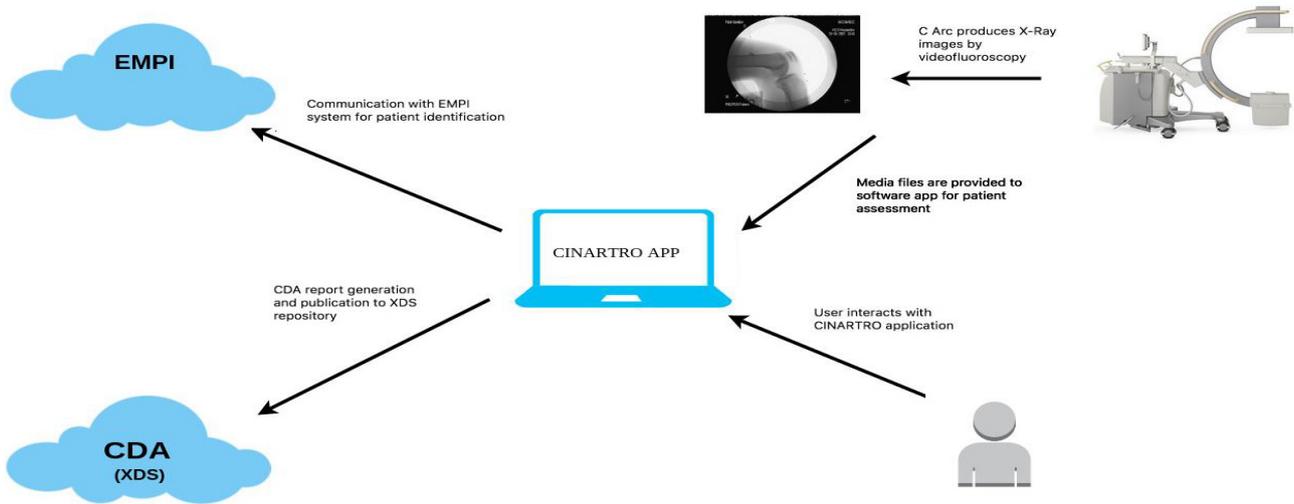


Fig. 1 General Architecture of CINARTRO. C arm sequence is analyzed to create a CDA report, with patient identified by EMPI web service.

Operation of CINARTRO begins when the user enters patient data, which is checked against a National Health Users EMPI (Enterprise Master Patient Index) index [6]. This ensures a reliable patient identification. Then the patient is subjected to X-ray with a C arm to obtain a VFC showing a knee extension movement. The media files of the VFC are presented to the user as individual frames and reduced to 15 images, at regular intervals during the leg extension movement.

The software guides the interactive identification of anatomical points following the method of Baltzopoulos [5], and our enhancements [4]. Once the process is completed, a report in Clinical Document Architecture (CDA) format [10] is created and published in an XDS repository [7] in the cloud for later use and access by Electronic Clinical Record (ECR) systems. Note that the Enterprise Master Patient Index (EMPI) is responsible for the identification of patients within either the Health institution or the Health Sector in case interoperability is available.

These two features (patients identified by an EMPI and CDA reports stored in XDS) give CINARTRO the ability to smoothly interact with any modern clinical record system. Additionally this feature is fully compatible with Uruguayan state standards under the SALUD.UY initiative [8][9].

III. WORKFLOW INSIDE THE APPLICATION

To obtain results from VFC images, the user must place a total of 11 points on each image as shown in Figure 2:

- Two points along the posterior Femur rim
- Two points along the posterior Tibia rim

- Three points along the internal Femur condyle
- Two extremities of the Tibial plateau
- Inferior Patella and anterior Tibial Tuberosity

CINARTRO calculates with these points the TFCP, a proxy of the Moment Arm and the bending angle, as also shown in Figure 2. Once processed, the user can see the fluctuation of these values in X-Y graphs where X is the frame number and Y the parameter such as TFCP position or Moment Arm proxy length. We call it “Proxy of Moment Arm” because the TFCP is not an instantaneous center of rotation.

Raw data may be output in Excel spreadsheets for further analysis. Since the CDA clinical reports (automatically uploaded to an XDS repository) are only readable by Electronic Clinical Record applications, CINARTRO also outputs regular PDF printable reports containing the same information. This information (both CDA and PDF) is of clinical value since it allows to compare different kinematics parameters (TFCP migration, MA proxy) of injured, contralateral and re-constructed knees.

Image distortion is corrected by using a phantom. To do this, the user must upload the rX image of the phantom, under the same conditions as the VFC, and select the visible parts of the grid points, as seen in Figure 3, so that the software identifies the matrix points to implement the corrections explained by Baltzopoulos [5]

IV. IMPLEMENTATION

Table 2 summarizes the programming elements used for a compact implementation of CINARTRO. We selected libraries to solve several programming issues. Java was the basic

coding language following the paradigm of Object Orientation. JavaFX framework was chosen to operate the graphics application. The Singleton design pattern was used to maintain a single instance of classes. Other modules were dedicated to generate reports with external agents.

Pin cushion distortion error using the phantom was 0.235mm for 40% utilization of phantom points, which is close to 0.246mm, obtained by Baltzopoulos.

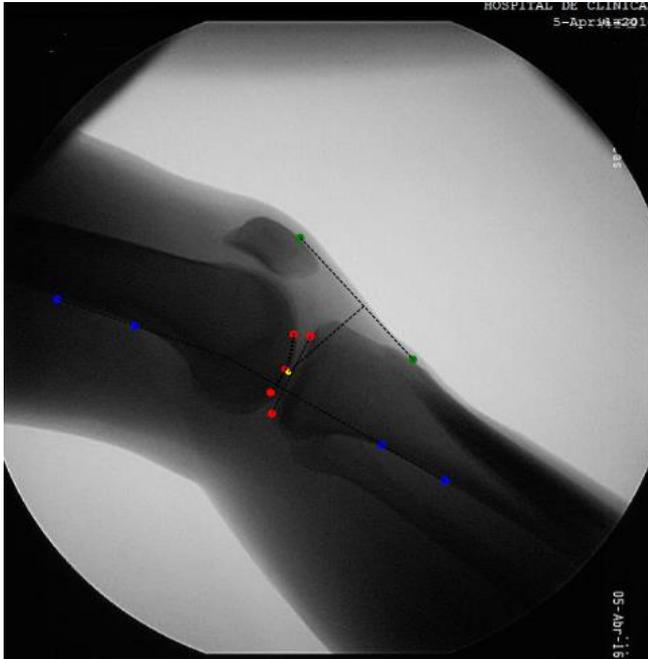


Fig. 2 Anatomical points marked by the user with CINARTRO. The line between patella and anterior tuberosity represent quadriceps ligament.

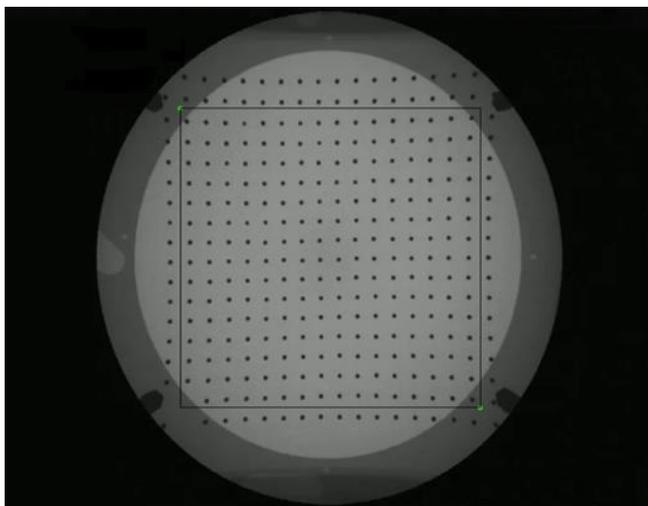


Fig.3 Equidistant lead sphere regular pattern seen by C-arm & CINARTRO. Note the pin cushion effect distorting shapes.

Table 2 CINARTRO Software Implementation

Feature	CINARTRO
Installation	Standalone (Desktop)
Programming Language	Java [12]
Graphic interface	JavaFX [13]
Graphic design tool	Scene Builder
Patient identification	EMPI (OpenEmpi) [7]
Studies output format	CDA (XML)
Math library	Apache Commons Math [14]
Data output / reports	Excel, PDF
PDF library	iText PDF [15]
Excel library	No, String CSV
XML management library	JAXB [16]
Video manipulation library	Xuggler [17]
HTTP messages exchange	HTTP Client (Java Core)
Architecture patterns	POO, Singleton

V. TESTS AND RESULTS

The software obtained fulfills the goal set in the specifications: we obtained a clinical tool to process VFC of injured, healthy and reconstructed knees during extension, with direct ECR documentation. We tested CINARTRO with VFC images obtained from 3 patients. The tests correspond to healthy knee and ACL injured knee for each patient.

Table 3 shows the results of TFCP with an average of 59% displacement for healthy knee and an average of 49% for injured knee. Additionally the Moment Arm proxy was 50 mm in average for healthy knees and 45 mm for injured knees.

Table 3 Moment Arm from TFCP to Quadriceps Ligament

Patient	Hanging 100° -110°		(135° - 145°)		Extended 170°-180°		Average Moment Arm (mm)	
	H	I	H	I	H	I	H	I
1	43	43	47	51	44	46	45 ± 2	48 ± 4
2	43	46	51	57	41	54	47 ± 5	52 ± 5
3	44	47	45	54	43	49	44 ± 1	51 ± 4
mean	43	45	48	54	43	50	45 ± 3	50 ± 4

Table 4 Tibio-Femoral Contact Point Migration

Patient	Hanging 100° -110°		(135° - 145°)		Extended 170°-180°		Average migra- tion % TFCP	
	H	I	H	I	H	I	H	I
1	57	48	63	46	60	58	60 ± 3	50 ± 6
2	52	55	54	45	67	51	57 ± 8	50 ± 5
3	54	46	68	46	65	51	62 ± 7	47 ± 2
mean	54	49	61	45	64	53	60 ± 3	49 ± 2

VII. DISCUSSION AND CONCLUSION

For the first time we could easily process VFC images to obtain a quantitative evaluation of the kinematics of the knee. This follows the pioneering works of Baltzopoulos who defined parameters in the research setting, which we are now extending to potential routine clinical assessments with the new CINARTRO instrument [6]. Using the TFCP as a proxy for an equally migrating instantaneous center of rotation, we have defined a proxy of the Moment Arm seen by the quadriceps ligament during knee extension movement.

The measurement of a proxy of the Quadriceps Moment Arm (QMA) during extension is valuable to assess the load of the quadriceps during rehabilitation [3]. We found in this paper that after ACL injury, the QMA increases with respect to the pre-injury knee, as measured in the contralateral joint. Additionally, clinical practice [18] observes that quadriceps muscle strength (QMS) decreases after ACL injury. We may therefore be in a position to describe a natural compensation mechanism by which the product of QMS x QMA (Moment) is kept as constant as possible after ACL injury, MS decreasing approximately 30% [18] compensated by 11% increase in QMA.

This new finding needs further research to be confirmed by careful protocols and patient follow-up with CINARTRO.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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