



## COMPUTED TOMOGRAPHY BASED REAL-TIME JOINT KINEMATICS DURING IN-VITRO TESTS

Matthias Verstraete PhD <sup>1,2,\*</sup>, Nele Arnout MD <sup>1</sup>, Thibeauc Vanouillie MSc <sup>1,3</sup>, Patrick De Baets PhD <sup>3</sup>, Jan Victor MD PhD <sup>1</sup>

<sup>1</sup> Department of Orthopaedic Surgery, Ghent University, Ghent, Belgium

<sup>2</sup> FWO Flanders, Brussels, Belgium

<sup>3</sup> Department of Mechanical Engineering, Ghent University, Ghent, Belgium

\* Matthias.Verstraete@UGent.be

### INTRODUCTION

To assess and compare the effect of new orthopedic surgical procedures, in vitro evaluation remains critical during the pre-clinical validation. Focusing on reconstruction

surgery, the ability to restore normal kinematics and stability is thereby of primary importance. Therefore, several simulators have been developed to study the kinematics and create controlled boundary conditions [1,2].

To simultaneously capture the kinematics in six degrees of freedom as outlined by Grood & Suntay [3], markers are often rigidly connected to the moving bone segments. The position of these markers can subsequently be tracked while their position relative

to the bones is determined using computed tomography (CT) of the test specimen with

the markers attached [4]. Although this method serves as golden standard, it clearly lacks real-time feedback. Therefore, this paper presents the validation of a newly developed real-time framework to assess knee kinematics at the time of testing.

## MATERIALS & METHODS

A total of five cadaveric fresh frozen lower limb specimens have been used to quantitatively assess the difference between the golden standard, CT based, method and the newly developed real-time method. A schematic of the data flow for both methods is shown in Figure 1.

Prior to testing, both methods require a CT scan of the full lower limb. During the tests, the proximal femur and distal tibia are necessarily resected to fit the knees in the test setup, thus also removing the anatomical landmarks needed to evaluate their mechanical axis. Subsequently, a set of three passive markers are rigidly attached to the femur and tibia, referred to as  $M_{3F}$  and  $M_{3T}$  respectively. For the CT based method, the marker positions are captured during the tests and a second CT scan is eventually performed to link the marker positions to the knee anatomy. Using in-house developed software, this allowed to offline evaluate the knee kinematics in six degrees of freedom by combining both CT datasets with the tracked marker positions.

For the newly developed real-time method, a calibration procedure is first performed. This calibration aims to link the position of the 3D reconstructed bone and landmarks with the attached markers. A set of bone surface points is therefore registered. These surface points are obtained by tracking the position of a pen while touching the bone surface. The pen's position is thereby tracked by three rigidly attached markers, denoted  $M_{3P}$ . The position of the pen tip is subsequently calculated from the known pen geometry. The iterative closest point (ICP) algorithm is then used to match the 3D reconstructed bone to the registered surface points. Two types of 3D reconstructions have therefore been considered. First, the original reconstructions were used, obtained from the CT data. Second, a modified reconstruction was used. This modification accounted for the finite radius ( $r = 1.0$  mm) of the registration pen, by shifting the surface nodes 1.0 mm along the direction of the outer surface normal. During the tests, the positions of the femur and tibia markers are tracked and streamed in real-time to an in-house developed, Matlab based software framework (MathWorks Inc., Natick, Massachusetts, USA). This software framework simultaneously calculates the bone positions and knee kinematics in six degrees of freedom, displaying this information to the surgeons and operators.

To assess the accuracy, all knee specimens have been subjected to passive flexion-extension movement ranging from 0 to 120 degrees of

flexion. For each degree of freedom, the average root mean square (RMS) difference between both measurement methods has been evaluated during this movement. In addition, the distribution of the registered surface points has been assessed along the principal directions of the uniformly meshed 3D reconstructions (average mesh size of 1.0 mm). Therefore, the relative variance  $\eta$  has been defined:

$$\eta_i = \sigma_{registered;i} / \sigma_{bone;i}$$

With:

$\sigma_{registered;i}$	variance of the registered surface points along principal axis $i$
$\sigma_{bone;i}$	variance of the bone stl points
$i$	principal axis (x, y or z)

## RESULTS

The root mean square difference between both measurements indicates a strong dependency on the variance of the registered points. This dependency is particularly pronounced when using the original 3D reconstructions in combination with the ICP algorithm, with an  $R^2 = 0.76$  and  $0.85$  for the translational and rotational degrees of freedom respectively (Figure 2 – blue triangles). When using the modified 3D reconstructions, which compensates for the finite radius of the marker tip, this dependency becomes negligible ( $R^2 = 0.10$  and  $0.05$ ; Figure 2 – yellow circles). Using this modified 3D reconstruction, the average difference between both measurements is also reduced to an average value of 1.20 degrees and 1.47 mm.

## DISCUSSION

The difference in kinematic parameters between both measurement techniques is an order of magnitude lower than the claimed accuracy of the motion tracking cameras [5]. However, the difference is in line with the inter- and intra- observer variability when identifying bony landmarks around the knee [6]. Since these landmarks are essential to calculate knee kinematics, it is understood that the proposed real-time system is sufficiently accurate to study these kinematics.

The link between the variance of the surface points and the difference in kinematic parameters indicates that using adjusted stl files is worth considering; thus compensating for the finite radius of the registration pen.

Doing so, the effect of the relative variance becomes negligible. This suggests that a correct estimation of the bone position relative to the rigidly attached markers can be obtained by only using a limited set of surface data points. In contrast to the current study, where large and widespread areas of the bone had been registered, future applications could thus focus on more localized and perhaps surgically representative, zones when registering the bone position.

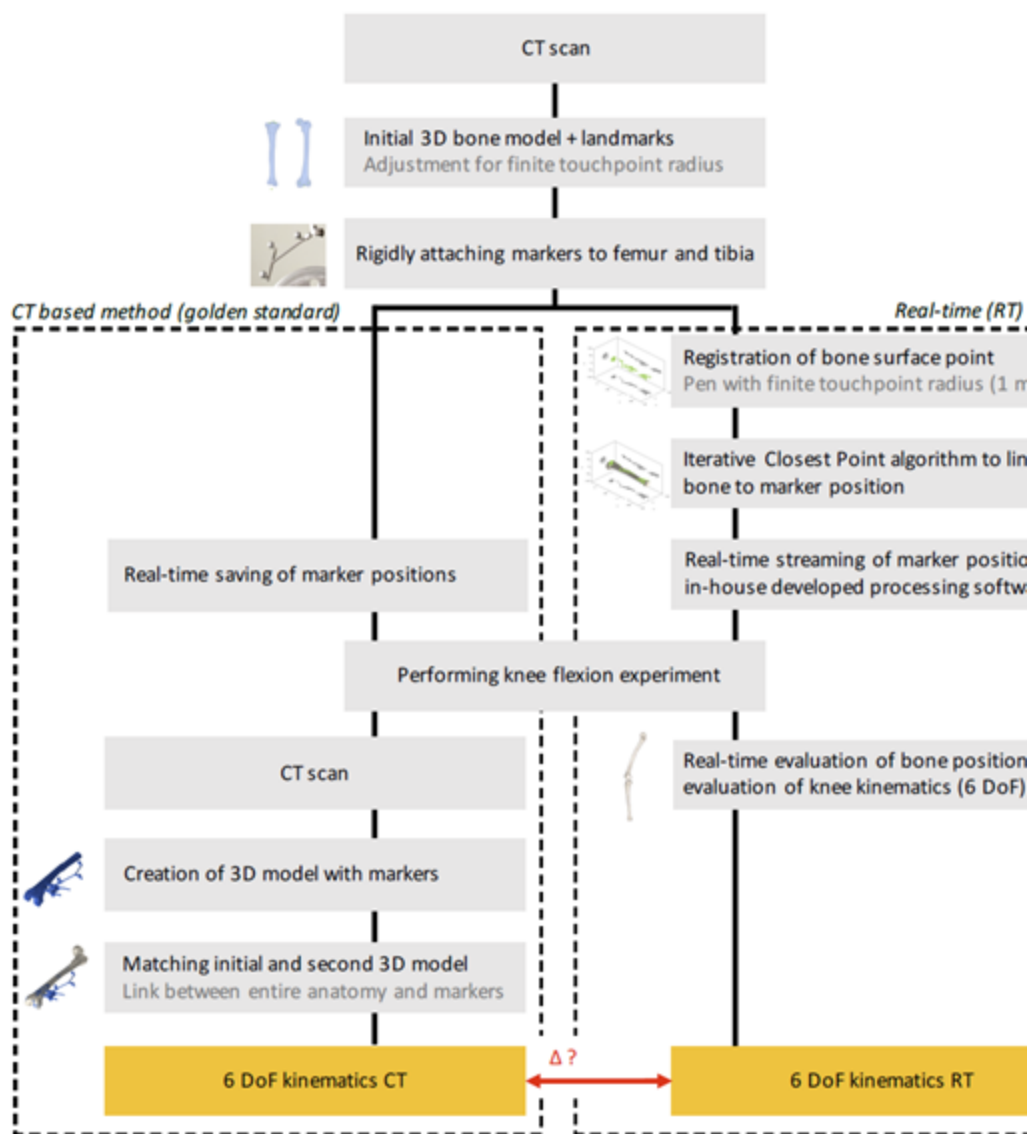


Figure 1 - Overview of test protocol for each cadaveric specimen indicating two parallel methods to evaluate knee kinematics in 6 degrees of freedom.

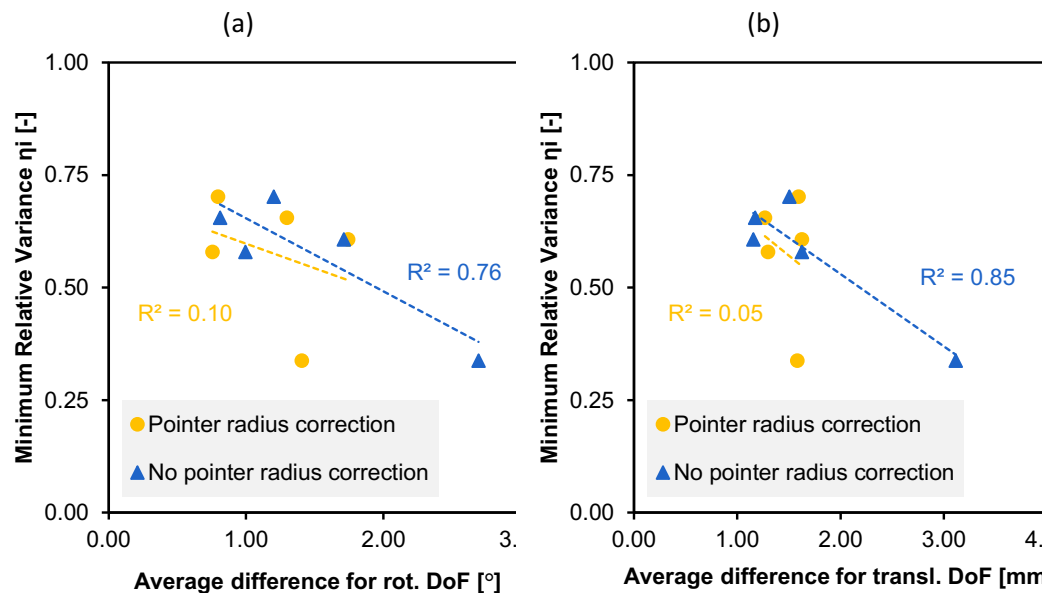


Figure 2 – Evaluation of accuracy for the rotational (a) and translational (b) degrees of freedom for all tests indicating a strong correlation between the obtained accuracy and the minimum relative variance before accounting for the radius correction.

## REFERENCES

- [1] Verstraete, Matthias, and Jan Victor. 2015. "Possibilities and Limitations of Novel In-vitro Knee Simulator." *Journal of Biomechanics* 48 (12): 3377–3382.
- [2] Victor, Jan, Pius Wong, Erik Witvrouw, Jos Vander Sloten, and Johan Bellemans. 2009. "How Isometric Are the Medial Patellofemoral, Superficial Medial Collateral, and Lateral Collateral Ligaments of the Knee?" *American Journal of Sports Medicine* 37 (10): 2028–2036.
- [3] Grood ES and Suntay WJ. 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *Journal of Biomechanical Engineering* 105: 136-44.
- [4] Gutierrez Delgado, Guivey, Matthieu De Beule, Dolgis R. Ortega Cardentey, Patrick Segers, Arsenio M. Iznaga Benítez, Tania Rodríguez Moliner, Benedict Verheghe, Tanneke Palmans, Tom Van Hoof, and Alexander Van Tongel. 2017. "Procedure to Describe Clavicular Motion." *Journal of Shoulder and Elbow Surgery*.

[5] Schmidt Jill, Devin R. Berg, H-L. Ploeg. 2009. "Precision, repeatability and accuracy of Optotrak optical motion tracking systems." *International Journal of Experimental and Computational Biomechanics*, Vol. 1, No. 1.

[6] Victor, Jan, D Van Doninck, L Labey, B Innocenti, PM Parizel, and Johan Bellemans. 2009. "How Precise Can Bony Landmarks Be Determined on a CT Scan of the Knee?" *Knee* 16 (5): 358–365.

### **ACKNOWLEDGEMENTS AND DISCLOSURES**

The first author acknowledges the financial support of the Research Foundation – Flanders (FWO) through grant number 12N5117N.