Reproducibility of an optical measurement system for the clinical evaluation of active knee rotation in weight-bearing, healthy subjects

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Summary

Introduction: A knee is typically evaluated passively by a clinician during an office visit, without using dedicated measurement tools. When the knee is evaluated with the patient standing and actively participating in the movement, the results will differ than when the knee is passively moved through its range-of-motion by the surgeon. If a precise measurement system was available, it could provide additional information to the clinician during this evaluation.

Hypothesis: The goal of this study was to verify the reproducibility of a fast, flexible optical measurement system to measure rotational knee laxity during weight-bearing.

Material and methods: Two passive reflective targets were placed on the legs of 11 subjects to monitor femur and tibia displacements in three dimensions. Subjects performed internal and external rotation movements with the knee extended or flexed 30°. During each movement, seven variables were measured: internal rotation, external rotation and overall laxity in extension and 30° flexion, along with neutral rotation value in 30° flexion. Measurement accuracy was also assessed and the right and left knees were compared. Reproducibility was assessed over two measurements sessions.

Results: The calculated intra-class correlation coefficient (ICC) for reproducibility was above 0.9 for five of the seven variables measured. The calculated ICC for the right/left comparison was above 0.75 for five of the seven variables measured.

Discussion: These results confirmed that the proposed system provides reproducible measurements. Our right/left comparison results were consistent with the published literature. This

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Introduction

A clinical knee evaluation is typically done through passive movements in a patient who is lying down. The evaluator performs standardized tests such as the Lachman and pivot shift tests. These tests are used to evaluate laxity during knee rotation in every plane: flexion-extension, varus-valgus, internal-external rotation [1,2]. Many studies have shown the advantage and accuracy of using measuring instruments such as the KT-1000, Genucom [3,4], GNRB [5] or even the Telos [3,6]. These instruments provide objective measurements of knee laxity in the anterior-posterior plane. A few studies have evaluated the reproducibility of electromagnetic methods to objectively measure movement during the pivot-shift test [7] and optical systems to measure knee rotation during walking [8]. The advantages of using an objective measurement system to analyse laxity during knee rotation was recently demonstrated [9].

In contrast to a clinical examination, active knee rotation can be measured during biomechanical studies, with the subject performing movements while standing and weight-bearing on the knee. Knee internal and external rotation has been shown to be different between weight-bearing and non-weight-bearing movements [10]. Lo et al. [11] performed an in vitro study simulating knee movements and found that it was preferable to work with a weight-bearing knee. Data captured by motion analysis systems are then processed to extract information about knee range-of-motion during flexion, varus-valgus movements, internal and external rotation that is useful to the clinician. The test protocol is often quite involved. It includes a lengthy calibration, palpation of anatomical landmarks, placing markers on the subject and then finally capturing the subject’s movements. The acquired data then have to be processed to extract joint range-of-motion information. For these reasons, these systems are mostly used in a research context. Use during clinical office visits is difficult to imagine.

And yet, measuring the rotation of the tibia relative to the femur has increasingly become important as we learn more about knee injuries. Multiple studies have been carried out recently on the recovery of rotation kinematics after anterior cruciate ligament (ACL) surgery as a function of the surgical technique (single or double-bundle) and type of rupture (complete or partial). These studies compared the kinematics of the injured knee before the surgery and rehabilitation with the kinematics of a healthy knee [12,13]. In knee replacement surgery, kinematics analysis is also essential to prosthesis design and the choice between fixed or mobile polyethylene tibial bearings. The degree to which a prosthesis allows rotation of the tibia relative to the femur must also be assessed so that normal knee kinematics can be reproduced as much as possible [14,15].

In this context, we wanted to develop a simple optical measurement system that can quickly and reproducibly evaluate knee laxity during internal and external rotation during weight-bearing under clinical conditions. The focus was on internal and external rotation of the tibia relative to the femur, as these are the most difficult for a clinician to evaluate. To validate this system, reproducibility tests were performed on 11 healthy subjects. We then compared measurements on the right leg with those of the left leg to evaluate the hypothesis that one knee can legitimately be compared to the contralateral knee for measurements of tibia internal and external rotation.

Material and methods

Study population

The study was performed on a continuous series of 11 subjects, 10 men and one woman, having an average age of 27 years and 9 months (min 21, max 37) and an average mass of 77 kg (min 54, max 110). Subjects did not have a history of injury or trauma to the legs. Both knees were evaluated in each subject, which provided data for a continuous series of 22 healthy knees.

Measurement system

We used a portable three-dimensional optical measurement system (Polaris, Northern Digital Inc., Waterloo, ON, Canada). This system is typically used during computer-assisted surgery. Two interdependent, calibrated cameras with light emitting diodes are used to detect marker movements. Each target consisted of three passive reflective markers at a known distance from each other. The measurement system recognizes these targets directly. Their position in the working space is sent via a serial port to a computer. This system can operate at defined frequencies of 20, 30 or 60 Hz. We used a 30 Hz frequency in this study. The precision determined by the manufacturer (0.5 mm and 0.5°) has been independently evaluated and confirmed [16–18].

Software was developed in our department using LabView® (National Instruments Corporation, Austin, Texas, USA) to acquire and process the Polaris data. This software had multiple functions:

- data entry to identify the patient (civil status, type of test);
- initialization of the test when the subject was in the reference position defined below (to define the reference axis);
- real-time calculation and display of tibia rotation relative to the femur based on the three axes of rotation in
Reproducibility of method to measure rotation in a weight-bearing knee

The “Joint Coordinate System” (JCS) defined by Grood and Suntay [19], restated in the International Society for Biomechanics recommendations [20] and known to be valid for the study of knee movements [21];

- recording of instantaneous values acquired by a potential second system;
- display and recording of maximum and minimum values obtained during the movement;
- resetting of maximum and minimum values after each movement.

The measurement system was always run by the same person, who was experienced and well trained with the tool.

Test protocol

The subject stood in bare feet, wearing underwear or shorts to only show the legs. Two targets were placed on the subject: one on the lateral side of the thigh, about 10 cm above the lateral condyle, and one on the antero-lateral side of the lower leg, about 10 cm below the head of the fibula. These targets were developed specifically for lower limb studies. The targets were rectangular in shape and consisted of a 7 mm thick rigid melanine plate on the side visible to the camera (outside) and shaped, high-density EVA foam on the inside surface to optimize contact with the limb. The targets were attached to the segments using a compressive Velcro® strap. Because of the foam’s roughness, the target did not move once it was attached to the leg. Once the targets were placed on the subject, he/she performed a few simple movements to ensure that the targets did not move.

The use of large targets with three reflective markers reduces potential measurement errors due to soft tissue placement. The target itself does not deform when one area moves relative to another. Also, to reduce known artefacts related to soft tissue movement, these tests were performed without impact. The feet were required to stay in the same position during the entire test, and the movements were performed slowly.

The subject stood with feet 20 cm apart. Two parallel reference lines, 20 cm apart were placed on the ground so that each line passed under the subject’s foot, from the middle of the heel to the middle of the big toe (Fig. 1). A vertical reference target was attached to a stand (Fig. 2a). This stand was placed so that the reference target was parallel to the reference lines. This target was used to define the reference axis when the measurement system was initialized.

Since we specifically wanted to measure rotation of the tibia relative to the femur, the exact position of the targets did not matter. The target had to be solidly attached to the segment, so any change in its orientation corresponded directly to a change in the position of underlying bone. The relative rotation of two markers in space is independent of the original position of the markers; only the orientation of the markers themselves is important. To ensure that the orientation of the markers on our targets provided useable data, a reference position was used to transform the tracking markers attached to the bone segments so that these markers were aligned with the markers on the reference target. This allowed the transformation matrix of the tracking marker relative to the reference marker to be calculated.

![Figure 1 Position of feet on the ground during the test.](image)

This matrix was valid for the entire measurement session as long as the subject did not move his/her feet relative to the ground.

Initial position in extension

At the start of the test, the subject stood in a neutral position with feet on the reference lines. The knees were fully extended. The subject was directed to look straight ahead to a point on the horizon (Fig. 2a).

With the subject in position and all the targets visible to the measurement system, the operator initialized the reference position. Values for rotation in flexion-extension (FE), internal and external rotation (IR, ER) and varus-valgus (Var-Val) were set to 0 in the system.

Calculation of the Joint Coordinate System (JCS)

Once the initial position in extension was captured, the system calculated the reference position. Given that the subject was standing in full extension, with the feet 20 cm apart, parallel to each other and in line with the reference target, the vertical axis (Y) of the reference target corresponded to the vertical axis of the femur and the vertical axis of the tibia in the reference position. Similarly, the anterior-posterior axis (X) and the medial-lateral axis (Z) for the reference target corresponded to the X and Z axes for the femur and tibia in the reference position. The JCS was then used to interpret the rotation during the entire movement phase. Rotation of the tibial marker was decomposed relative to the femur marker in the order Z, X, Y. The Z-axis was the femur mediolateral axis, the Y-axis was the tibia vertical axis and the X-axis was the “floating axis”, which means that at any point in time, it was orthogonal to the other two axes.
Internal and external rotation movements in extension

Once the initial position was recorded, the subject was asked to slowly rotate the head and shoulders to one side by 90° (Fig. 2b) while maintaining the knees extended and the feet glued to the ground. The operator made sure that the subject followed instructions during the movement. Once the rotation was performed, the subject returned to the neutral starting position and stopped for 1 or 2 s to make sure that momentum was not carried over to the next movement. The subject then performed the same slow 90° rotation movement to the other side (Fig. 2c) and returned to the neutral starting position. If the movement was performed correctly, the values were recorded. The maximum value (positive) corresponded to internal rotation and the minimum value (negative) corresponded to external rotation. The entire internal-external rotation movement took about 10 s. It was performed slowly enough to be sure that no confounding skin movement occurred due to momentum. The entire movement was repeated five times. The testing period was about 1 min long.

Rotation movements in 30° flexion

The subject was then asked flex his/her knees by 30°. Real-time feedback on the computer screen was provided to the subject to attain 30° of flexion. Once the required flexion was achieved, the subject performed the same internal and external rotation movements as those performed during extension. The operator made sure that the subject maintained 30° of flexion during the movement and that the subject regained the appropriate flexion angle when returning to the neutral starting position. A variation of ± 3° flexion was acceptable. The neutral rotation position at 30° flexion was automatically recorded at the start of every test repetition and was compared to the neutral rotation position while in full extension.

The subject’s two lower limbs were measured one after the other. The order in which the lower limbs were tested was randomized.

Reproducibility

To evaluate the reproducibility of the system and method, each subject performed the testing twice, at least one day apart; the median time between both tests was 1 day (min: 1 day, max: 30 days).

Calculation of results

During each test period, each knee had two test conditions: extension (labelled: Flexion0) and 30° flexion (labelled: Flexion30). The magnitude of the total rotation ($R_{Total} = R_{Internal} - R_{External}$) was calculated for each complete movement involving internal rotation ($R_{Internal}$) and external rotation ($R_{External}$). An average was taken of the five repeats for each test condition (Flexion0 and Flexion30). An average was also taken of the five repeats for the neutral rotation at 30° flexion ($R_{Neutral}$).

For each knee during each test, values for $R_{Internal}$, $R_{External}$ and $R_{Total}$ at Flexion0 and Flexion30 were obtained, along with the $R_{Neutral}$ value for Flexion30, thus seven measured variables in all.

Statistical analysis

Average and standard deviation values were used to describe the calculated values during the two test phases (Test1 and Test2) for the seven variables on the 22 knees.

The intra-class correlation coefficient (ICC) is typically used to assess the reproducibility of consecutive
measurements \cite{22,23}. The ICC is considered good if the ICC > 0.7 and very good if the ICC is > 0.8 \cite{24}. Independent tests for neutral rotation (R_Neutral) at 30° flexion, internal rotation (R_Internal), external rotation (R_External) and full rotation (R_Total) were performed. Statistical tests were performed for the two conditions: Flexion0 and Flexion30.

We also evaluated the reproducibility of the measurements (Test1) between the two knees (right and left) for each subject using the same statistical method.

Statistical software was used to perform the descriptive statistics and assess the ICC (SPSS 18, IBM Corp New York, USA).

**Results**

The time required for an entire test (both of the subject’s legs) was about 5 min. If the time to explain the study to the subject, put the markers on the subject and remove them is included, the operator spent less than 10 min on the entire procedure.

Raw data for the 22 knees are provided in Table 1. Average and standard deviation values are provided in Table 2 (columns 1 to 4). The neutral rotation in Flexion30 averaged 4.77° during the first test and 4.75° during the second test (internal rotation relative to the extension reference position). Internal and external rotation was less while in flexion than in full extension for both testing sessions.

The ICC between Test1 and Test2 is given in the last column of Table 2. The ICC was below 0.90 only for internal rotation in full extension (0.73) and neutral rotation at 30° flexion (0.75).

Table 3 provides a comparison between the right and left knee. Neutral rotation was positive in Flexion30 in both the right and left knee. Internal and external rotation was less in flexion than in extension. The ICCs were between 0.74 and 0.86.

**Discussion**

Knee internal and external rotation is typically measured passively using a heavy object \cite{22,25,26}. We believe that the lower limb should be tested under real-life conditions, which means during active, weight-bearing movements.

Our results in full extension are consistent with an in vitro study performed by two evaluators \cite{26}. However, only four knees were tested in the cited study, and the choice of markers used to measure rotation was not well described, which makes it impossible to directly compare our flexion
results. We also found less internal and external rotation in Flexion30 in comparison to the above study. This can be attributed to our test protocol comprising active, weight-bearing movements. The knee is more stable during weight bearing [27]. Because of their shape, the menisci link the two segments together and reduce laxity [28–30]. Since the muscles are active during the test, they also participate in knee coaptation [31].

The tibia was internally rotated when the subject was at the neutral starting position in 30° flexion (4.77° during Test1 and 4.75° during Test2). This physiological rotation was noted by Kanisawa et al. [32] in a post-ACL reconstruction study with weight-bearing subjects. When going up and down a 25 cm high stair, the average internal rotation while in 30° flexion was 12°. Our measured internal rotation was lower, probably because the subject always loaded both legs and did not perform dynamic movements.

This slight neutral rotation in 30° flexion could also be explained by the skin movements that often plague studies using optical systems [33–35]. However, our targets are non-deformable tripods. This negated the relative movement between markers, which usually needs to be corrected [36,37]. In addition, very slow movements without impact were performed to reduce the errors that are known to occur during walking, landing or abrupt directional changes [34]. But it is impossible to be totally free of muscle contraction-related effects that could lead to unwanted marker movement when using a non-invasive protocol [38].

The ICC between Test1 and Test2 was considered good for a test with active subject participation. The ICCs were almost always above 0.90, which suggests that this system and method have good reproducibility [39]. The ICC was below 0.75 for internal rotation in full extension. This specific ICC can easily be improved. In a post hoc analysis of the raw data for the three combined rotation planes (flexion-extension, internal-external rotation and varus-valgus), we detected that a small flexion movement was combined with internal rotation in certain subjects, but this was not systematic. This easy-to-perform active test could be done on patients at any stage of treatment: before surgery, after rehabilitation and after 2 years, which is the typical follow-up date for ACL reconstruction and prosthetic surgery in our department. Test results could be correlated to static data from radiographs, assessments performed by the clinician during office visits and subjective quality of life questionnaires.

The reliability results for the left-right comparison were good. However they were not as good as results on the

### Table 2  Mean internal rotation, external rotation and full rotation values for all the knees for both tests and the intra-class correlation coefficient between Test1 and Test2.

<table>
<thead>
<tr>
<th>Flexion0</th>
<th>Test1 Average</th>
<th>Test1 Standard deviation</th>
<th>Test2 Average</th>
<th>Test2 Standard deviation</th>
<th>ICC Test1/Test2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal R</td>
<td>8.85</td>
<td>2.32</td>
<td>7.91</td>
<td>2.33</td>
<td>0.73</td>
</tr>
<tr>
<td>External R</td>
<td>-14.37</td>
<td>3.88</td>
<td>-13.40</td>
<td>4.65</td>
<td>0.95</td>
</tr>
<tr>
<td>Total R</td>
<td>23.22</td>
<td>5.26</td>
<td>21.32</td>
<td>6.31</td>
<td>0.90</td>
</tr>
<tr>
<td>Flexion30</td>
<td>Neutral R</td>
<td>4.77</td>
<td>3.51</td>
<td>4.75</td>
<td>3.03</td>
</tr>
<tr>
<td>Internal R</td>
<td>7.51</td>
<td>2.54</td>
<td>6.70</td>
<td>2.79</td>
<td>0.90</td>
</tr>
<tr>
<td>External R</td>
<td>-11.36</td>
<td>5.47</td>
<td>-10.78</td>
<td>5.70</td>
<td>0.90</td>
</tr>
<tr>
<td>Total R</td>
<td>18.87</td>
<td>7.50</td>
<td>17.48</td>
<td>7.80</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Bold = ICC > 0.75 (good to very good for the authors).

### Table 3  Average internal rotation, external rotation and full rotation values for Test1 with a left-right comparison. Intra-class correlation coefficient (ICC) between right and left.

<table>
<thead>
<tr>
<th>Flexion0</th>
<th>Right Average</th>
<th>Right Standard deviation</th>
<th>Left Average</th>
<th>Left Standard deviation</th>
<th>ICC right/left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal R</td>
<td>8.22</td>
<td>1.59</td>
<td>9.47</td>
<td>2.82</td>
<td>0.74</td>
</tr>
<tr>
<td>External R</td>
<td>-13.27</td>
<td>3.44</td>
<td>-15.47</td>
<td>4.14</td>
<td>0.79</td>
</tr>
<tr>
<td>Total R</td>
<td>21.49</td>
<td>3.97</td>
<td>24.95</td>
<td>5.99</td>
<td>0.82</td>
</tr>
<tr>
<td>Flexion30</td>
<td>Neutral R</td>
<td>4.08</td>
<td>2.85</td>
<td>5.46</td>
<td>4.09</td>
</tr>
<tr>
<td>Internal R</td>
<td>7.50</td>
<td>2.15</td>
<td>7.52</td>
<td>3.00</td>
<td>0.79</td>
</tr>
<tr>
<td>External R</td>
<td>-10.25</td>
<td>4.68</td>
<td>-12.47</td>
<td>6.18</td>
<td>0.80</td>
</tr>
<tr>
<td>Total R</td>
<td>17.75</td>
<td>6.07</td>
<td>19.99</td>
<td>8.85</td>
<td>0.86</td>
</tr>
</tbody>
</table>
reproducibility between Test1 and Test2. But they are limited because of being performed on 11 knees instead of 22 knees. However, they confirm that for healthy subjects, if no other data is available, the healthy contralateral limb is a good comparator for the injured limb [39,40]. This would allow results to be analysed right away by comparing data from the two knees. Nevertheless, we can hypothesize that for pre/post-surgery studies, it would be preferable to evaluate a knee relative to itself instead of relative to the contralateral knee.

This system does not provide the same precision as existing clinical research instruments because flexibility and speed are the highest priority [26]. Because of the simple method used to attach the targets, they could have moved during the test movements. But this did not seem to be the case for the rotation movements that we tested, because the measurement system and test method had good reproducibility. The flexibility of this measurement system makes it possible to look at other simple movements in a reduced field of vision: flexion-extension, varus-valgus, combination movements such as going up a stair or rising from a chair. Thus, the reproducibility of these tests with these other measurements should be evaluated.

**Conclusion**

The system that was validated in this study allows an experienced operator to reproducibly measure a patient’s knee rotation in about 10 min. With active patient participation, the test could be performed before the surgeon’s clinical examination, with the results being available for the office visit. Since this system consists of an acquisition module on a movable stand and a portable computer, it can be easily moved and quickly installed. We are putting together a database with injured patients. By performing preoperative, postoperative and postrehabilitation tests, the device will allow us to quantify the objective improvement seen in the clinical setting after ligament surgery or arthroplasty.

**Disclosure of interest**

The authors declare that they have no conflicts of interest concerning this article.

**References**


