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The Femoral Epicondylar Frame to track femoral rotation in optoelectronic gait analysis.
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ABSTRACT

Background: Relative movement of skin markers to underlying bone limits a valid interpretation of axial femorotibial rotation in noninvasive optoelectronic gait analysis. A distal femoral clamp is a practical solution for thigh marker placement, however, existing devices are still susceptible to measurement errors at increased angles of knee flexion. We developed the Femoral Epicondylar Frame (FEF), which should result in less femoral rotational measurement error due to its anatomic fitting and controlled pressure adjustment.

Methods: Seven subjects with a total knee replacement in situ, mean age 71 years, mean body mass index 28, were equipped with the frame mounted with a set of tantalum markers. Fluoroscopic data was collected during a step-up motion. A three-dimensional model fitting technique was used to compare the in vivo position and orientation of the frame and the femoral prosthesis component of the prosthesis.

Results: The frame rotational measurement error appeared to be linearly dependent on the knee flexion angle. When considering knee flexion angles lower than 40 degrees of flexion, the highest measurement error was 3.3 degrees on average, with an absolute extreme of 6.2 degrees.

Conclusions: It is concluded that the accuracy of the FEF is sufficient to evaluate axial knee rotation with optoelectronic gait analysis at group level in clinical studies.
INTRODUCTION

Model based fluoroscopic analysis is a highly accurate technique to study axial rotation in total knee arthroplasty (TKA), but is limited to relatively simple tasks that can be performed within the small measurement volume of the fluoroscope. Optoelectronic gait analysis does not suffer from this limitation and is technically equally accurate. However, the relative movement of skin-based markers to underlying bone might impede the accurate noninvasive tracking of bone kinematics. Especially for the thigh this soft-tissue artefact is expected to be considerable. Garling et al. found a maximal axial rotational error of 7 degrees for strap-mounted shank markers, while the maximal thigh markers error was as high as 12 degrees during a step-up motion.

Recently, we designed the Femoral Epicondylar Frame (FEF), inspired by the external marker device presented by Houck et al. The FEF should improve noninvasive optoelectronic measurement of axial knee rotation by achieving near rigid fixation of the device, through increased clamping pressure and custom made epicondylar attachment. The objective of this study was to assess the precision and accuracy of the FEF as femoral tracking device, using model based fluoroscopy as gold standard.
METHODS

Subjects
Seven patients, six women and one man, mean age 71 years (range 54-77) and mean body mass index 28 (range 24-30), participated. All subjects had received a TKA (NexGen LPS mobile, Zimmer Inc., Warsaw, USA) three to four years prior to the study. Informed consent and approval by a local ethical committee was given.

FEF
The FEF consists of a stiff lightweight aluminum arch and a compression screw housed in a Delrin block (Fig. 2.1A). The frame is positioned anteriorly to the knee and attaches to individually molded thermoplastic shells (padded with neoprene) covering the medial and lateral femoral epicondyles. The attachment is tightened using the screw similar to a pair of glue tongs. A torque wrench was used to control for the amount of torque applied (10-15 cNm). The frame is originally mounted with a cluster set of optoelectronic markers (Fig. 2.1B); for the purpose of this study a cluster set of three tantalum markers was used.

Experimental setup
The patients were asked to perform a step-up motion, with the knee centered between the image intensifier and focus of a fluoroscope (15 frames/second; 1024 x 1024 image matrix; pulse width of 1 millisecond). Prior to measurements, an image run of 3 seconds of a specially designed calibration box (BAAT Engineering B.V., Hengelo, The Netherlands) was made to
calibrate the fluoroscopic system (Super Digital Fluoroscopy (SDF) system, Toshiba Infinix-NB: Toshiba, Zoetermeer, the Netherlands). A three-dimensional model fitting technique (Model-based RSA, Medis specials bv, The Netherlands) was used to reconstruct the in vivo position and orientation of the frame marker set and the prosthesis components (Fig. 2.2). Knee kinematics (flexion-extension, axial rotation) were determined from the three-dimensional pose of the prosthesis components, the coordinate systems based
on their design, compatible to the ISB recommendations. Cardan angle decomposition was used to describe orientation. A reference scene with the knee in full extension determined the reference alignment, i.e., zero angles.

Parameters and analysis
The femoral rotational measurement error, defined as the difference between axial rotation of femoral component and frame marker set, was calculated for each time frame of a fluoroscopic run. Accuracy, or systematic error, was defined as the mean measurement error; precision, or random error, was defined by the root mean square of the measurement error. Values were calculated for each 10 degrees of knee flexion, for each run. Results were averaged over three runs and all patients. A paired student T test was used to evaluate systematic differences. A Pearson correlation coefficient was used to analyze interactions between variables.

RESULTS AND DISCUSSION
The femoral rotational measurement error of the FEF ranged from 6.2 degrees external to 4.7 degrees internal rotation less than 40 degrees of knee flexion, the average precision being 3.3 degrees (Table 2.1).
Houck et al. also validated the use of an epicondylar clamping device, based on a spring instead of a screw mechanism. In a validation study against bone-pins in two healthy young men, they found an error of 0.5 degrees and 3.2 degrees, respectively, for knee flexion angles less than 20 degrees.
(reported as: limited to the first 85 percent of stance in walking). In late stance, when knee flexion is expected to increase to 40 degrees, an error of more than 5 degrees was shown. Our study, based on a group of typical subjects after TKA and with higher BMI’s, showed more precision: less than 2 degrees error for knee flexion angles less than 20 degrees and less than 4 degrees for knee flexion angles less than 40 degrees. None of the patients experienced any discomfort of the FEF, like pain, limping or hinder due to opposite knee contact.

The higher knee flexion angles were not always achieved or tracked within the measurement volume of the fluoroscope (Table 2.1). Like Südhoff et al., we found a positive correlation between increased knee flexion and the RMS measurement error.

**TABLE 2.1.** Axial knee rotation: fluoroscopic data and FEF measurement error (all values in degrees, tibial internal rotation is positive).

<table>
<thead>
<tr>
<th>Knee Flexion</th>
<th>Knee Rotation (Femur – Tibia)</th>
<th>FEF Measurement Error (FEF – Femur)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Nr</td>
</tr>
<tr>
<td>0°-10°</td>
<td>21</td>
<td>-3.23</td>
</tr>
<tr>
<td>10°-20°</td>
<td>21</td>
<td>-2.83</td>
</tr>
<tr>
<td>20°-30°</td>
<td>21</td>
<td>-1.67</td>
</tr>
<tr>
<td>30°-40°</td>
<td>18</td>
<td>-2.89</td>
</tr>
<tr>
<td>40°-50°</td>
<td>13</td>
<td>-5.35</td>
</tr>
<tr>
<td>50°-60°</td>
<td>5</td>
<td>-5.75</td>
</tr>
</tbody>
</table>

*RMS* root mean square;  
*SD* standard deviation;  
*Nr* number of runs with a maximum of three per subject (N=7).
error (Pearson r = 0.99). In the range of 0-40 degrees knee flexion no systematic error was seen. At higher knee flexion angles a systematic error appeared, however still not significant. This systematic error may be due to hinder of the medial vastus muscle at the medial frame attachment or sliding of the iliotibial tract under the lateral frame attachment. The amount of subcutaneous tissue is likely to be a factor, for which BMI could act as an indicator. However, in the small group with a small BMI range (26-30), no relationship was found between the precision of the FEF and the BMI.

Considering that the extreme values of the rotational measurement errors are in the same range as the actual axial femorotibial rotation, optoelectronic analysis is not suitable to assess axial knee rotation in an individual subject. In addition to this lack of precision of the FEF to measure femoral rotation, one must also take in account an amount of tibial measurement error. Manal et al. found an average rotational error for the tibia of 2 degrees, using bone-pins as reference, provided the optimal marker set was used.\textsuperscript{11} When axial knee rotation needs to be evaluated in group studies, however, optoelectronic analysis and the FEF have several advantages over fluoroscopy. It is far more convenient, noninvasive and less limiting for functional tasks than fluoroscopy. An additional advantage of optoelectronics is that it allows a more comprehensive assessment using force plates, inverse dynamics and surface electromyography.

The long and successful track record of the LCS\textsuperscript{©} knee prosthesis stimulated the orthopaedic industry to widely adopt the concept of mobile-bearing TKA.\textsuperscript{12} This concept should minimize implant wear by providing freedom of axial rotation
to the polyethylene bearing in combination with increased conformity of the bearing surfaces. Few kinematic studies demonstrated indeed a greater range of axial rotation in mobile-bearing than in fixed-bearing TKA during knee bends.\textsuperscript{13-14} Awaiting the long-term clinical results comparing both designs, further kinematic comparison studies seem warranted. These may include more complex tasks than knee bends, necessitating improved measurement techniques such as the FEF in optoelectronic gait analysis.

It is concluded that the use of the FEF is a major improvement to conventional skin marker placement in optoelectronic gait analysis. Its accuracy allows studying axial knee rotation in patients and healthy subjects at a group level.

**CONFLICT OF INTEREST STATEMENT**

The authors have no conflicts of interest to disclose.

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REFERENCES


