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The quality of bone surfaces may govern the use of model based fluoroscopy in the determination of joint laxity

P. Moewis[a], N. Wolterbeek[b], G. Diederichs[a], E. Valstar[b], M.O. Heller[a], W.R. Taylor[a,*]

[a] Julius Wolff Institut, Charité – Universitätsmedizin Berlin, Germany
[b] Leiden University Medical Center, P.O. Box 9600, 2300 RC Leiden, The Netherlands

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ABSTRACT

The assessment of knee joint laxity is clinically important but its quantification remains elusive. Calibrated, low dosage fluoroscopy, combined with registered surfaces and controlled external loading may offer possible solutions for quantifying relative tibio-femoral motion without soft tissue artefact, even in native joints. The aim of this study was to determine the accuracy of registration using CT and MRI derived 3D bone models, as well as metallic implants, to 2D single-plane fluoroscopic datasets, to assess their suitability for examining knee joint laxity.

Four cadaveric knees and one knee implant were positioned using a micromanipulator. After fluoroscopy, the accuracy of registering each surface to the 2D fluoroscopic images was determined by comparison against known translations from the micromanipulator measurements. Dynamic measurements were also performed to assess the relative tibio-femoral error. For CT and MRI derived 3D femur and tibia models during static testing, the in-plane error was 0.4 mm and 0.9 mm, and out-of-plane error 2.6 mm and 9.3 mm respectively. For metallic implants, the in-plane error was 0.2 mm and out-of-plane error 1.5 mm. The relative tibio-femoral error during dynamic measurements was 0.9 mm, 1.2 mm and 0.7 mm in-plane, and 3.9 mm, 10.4 mm and 2.5 mm out-of-plane for CT and MRI based models and metallic implants respectively. The rotational errors ranged from 0.5° to 1.9° for CT, 0.5–4.3° for MRI and 0.1–0.8° for metallic implants.

The results of this study indicate that single-plane fluoroscopic analysis can provide accurate information in the investigation of knee joint laxity, but should be limited to static or quasi-static evaluations when assessing native bones, where possible. With this knowledge of registration accuracy, targeted approaches for the determination of tibio-femoral laxity could now determine objective *in vivo* measures for the identification of ligament reconstruction candidates as well as improve our understanding of the consequences of knee joint instability in TKA.

1. Introduction

The *in vivo* quantification of knee joint laxity is gaining clinical importance due to joint instability related problems, joint pain and arthritic degeneration [1], as well as revision surgery after total knee arthroplasty (TKA). A reliable quantification of tibio-femoral laxity *in vivo* could provide a measure for assessing the degree of ligament damage or deficiency [2], and may contribute significantly to decision making regarding surgical or conservative treatment.

Clinical examination of the knee is often limited by pain after recent trauma and is dependent upon the examiner's skill and experience [3,4]. Some medical devices and measurement techniques have been established to aid clinical decision making and assess joint motion quantitatively [5]. Arthrometers have been developed to assess the range of antero-posterior (AP) knee translation, but low inter-tester reliability and overestimation of the results has been observed [6]. Furthermore, a measure of rotational laxity is not possible using these devices as the motion is restricted to the AP plane. In order to measure the tibio-femoral laxity in more than the A-P plane, studies have assessed the use of electromagnetic sensors attached to the thigh and shank of patients to measure the rotation between the femur and the tibia [3,4,7], but the outcome is sensitive to soft tissue artefact. By providing a more direct measure of skeletal position, the use of imaging techniques can overcome many of these problems. Here, planar stress radiography uses a series of X-rays in the sagittal plane to compare the displacement

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* Corresponding author at: Julius Wolff Institut, Charite – Universitätsmedizin Berlin, Centrum für Sportwissenschaft und Sportmedizin Berlin (CSSB), Philippstr. 13, Haus 11, D-10099 Berlin, Germany. Tel.: +49 030 2093 46016; fax: +49 030 2093 46001.
E-mail address: Bill.Taylor@charite.de (W.R. Taylor).

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of the tibia relative to the femur [8], but is limited to measurements in only a single plane. MRI techniques, on the other hand, allow imaging of the entire joint in a non-invasive manner, and good quality images can be achieved with a close bore MRI, but this limits the range of joint motion that can be tested [1]. As an alternative, roentgen stereophotogrammetric analysis (RSA) allows the measurement of relative motion in three dimensions [9]. While this technique can be performed using 3D surfaces of bones and metallic implants, translational and rotational accuracies of 10–250 μm and 0.03–0.6° can only be reached with the use of previously implanted tantalum beads [9,10], which limits its applicability in different subject cohorts. Moreover, the use of two fluoroscopic units limits the freedom of movement during measurement.

One solution may be the use of fluoroscopy in combination with cross-sectional imaging such as magnetic resonance imaging (MRI) or computed tomography (CT). Fluoroscopy offers high resolution imaging with low radiation exposure [11], while also allowing relative freedom of movement. The high sampling rate of this procedure additionally offers the ability to assess dynamic activities *in vivo* [12,13]. Furthermore, the high image quality allows the registration of 3D surfaces to the 2D fluoroscopy images, providing access to *e.g.* tibio-femoral kinematics during functional activities [12]. While the assessment of implanted component motion has long been established using model based fluoroscopy [13–15], the investigation of intact joint kinematics is still limited due to the less sharp edge contours of skeletal shadows, as well as the requirement for accurate bone surfaces for image registration.

The reconstruction of 3D bone surfaces can be achieved using MRI or CT datasets assessed in one additional scan of the patients [11,16]. CT offers rapid acquisition of high resolution images, providing sharp contours of the bone surfaces due to density related contrast differences, but subjects are exposed to ionizing radiation and legislation is strict in cases that are not clinically indicated. On the other hand, surface reconstruction from the lower bone contrast offered by MRI images might result in reduced accuracy during registration to fluoroscopic data [17–19]. Using a synthetic fluoroscopic image creation process, Fregly et al. [20] reported the theoretical accuracy of model-based shape matching using CT based models with results for tibiofemoral poses within 2 mm for sagittal plane translations and 1.5° for all rotations. The most rigorous assessment of the use of CT and MRI derived bone models for the purpose of shape registration-based motion assessment was reported by Moro-oka et al. [21]. Although no absolute accuracy for CT or MRI based models was reported, the accuracies calculated from synthetic images generated by ray tracing processes were 0.74 mm and 0.53 mm for sagittal translations, 2.0 mm and 1.6 mm for medio-lateral translations and 1.4° and 0.54° for all rotations for MRI and CT data derived models respectively.

In order to use novel techniques for the quantification of tibiofemoral instability in a clinical setting, the assessment technique must be of sufficient accuracy to provide a clinical perspective. Based on the results of previous *in vitro* robotic studies [22,23] in which anterior–posterior tibio-femoral translation of between 3.5 and 12.9 mm, and between 2.5° and 5° axial rotation were detected, a registration accuracy of within approximately 1 mm and 0.5° would be required in order to detect significant differences in knee joint laxity between patients. Within such confines, it is therefore imperative to know the accuracy of surface reconstruction and understand its influence on the accuracy of spatial registration to 2D images. Under the postulation that the accuracy of such registration is dependent upon the quality of the surfaces used, the aim of this study was to assess the absolute and relative accuracy of surface reconstruction and registration of 3D bone models derived from CT or MRI, compared to 3D models of metallic implants, to 2D single-plane fluoroscopic datasets.

2. Materials and methods

Four human cadaveric knees, including surrounding soft tissues, were used in this *in vitro* study. Each knee was scanned over the region approximately 15 cm above and below the joint line of the knee using CT (Siemens Sensation 64, 512 × 512 image matrix, resolution 0.4 mm × 0.4 mm, slice thickness 1 mm) and MRI (Siemens Magnetom Avanto, 1.5 T, T1 weighted, 512 × 512 image matrix, resolution 0.35 mm × 0.35 mm, slice thickness 3 mm) (Fig. 1). Here, two polarised radio-frequency knee coils were used in to guarantee a similar scan length of the knees to that acquired using CT. Segmentation of the exterior cortical bone edges was performed using commercial software (Amira, Visage Imaging, Berlin, Germany), for generation of triangulated polygonal surface models of each femur and tibia (approximately 80,000 triangles each). In an initial assessment of the surface quality, each MRI surface was registered to its CT counterpart and the distance between each vertex was computed.

In order to assess the relative accuracy of registration of metallic knee implants, the components of a PFC-Sigma knee prosthesis were implanted into femur and tibia sawbones. The components were fixed together to ensure that no relative motion between the components could occur. Prior to the experiments, the fluoroscopic system was calibrated to correct for image distortion by performing an image acquisition using a specially designed Perspex calibration

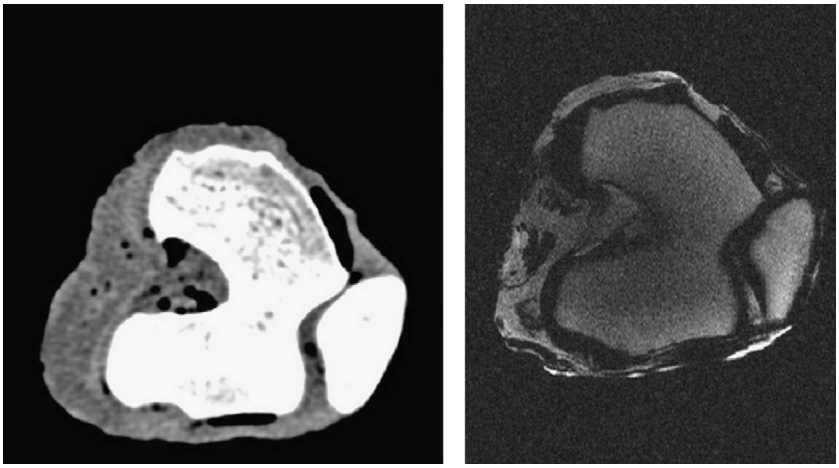

Fig. 1. CT (left) and MRI (right) axial images of one exemplary knee. A clear differentiation between the tissues is possible in both scan procedures.