



## Application guidelines for dynamic knee joint analysis with a dual fluoroscopic imaging system

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The widespread availability of mobile digital fluoroscopic systems with dynamic imaging capabilities places this type of motion analysis within reach of many research groups. With the addition of the second fluoroscope though, and the incorporation of a treadmill to analyze gait, the fluoroscopic analysis technique, which was once a rather straightforward method, has become more complex. Therefore, the purpose of the present manuscript was to provide a comprehensive review of the various processes that are associated with the dynamic knee joint motion analysis, including patient selection, construction of three-dimensional knee models, fluoroscopic scanning, and matching.

**Keywords :** fluoroscopy ; Magnetic Resonance (MR) ; kinematics ; joint biomechanics ; gait analysis.

### INTRODUCTION

Fluoroscopy has been used extensively for the analysis of *in vivo* knee joint and total knee arthroplasty (TKA) kinematics (2,13,22,23,25). The fluoroscopic images, taken by either one or two fluoroscopes, can be combined with three-dimensional (3D) anatomic models of the knee joint, created based on computerized tomography (CT) or magnetic resonance (MR) images. When analyzing

TKA kinematics, 3D computer-aided design (CAD) models of the TKA components (supplied by the manufacturer) are usually used. Both single- and double-plane fluoroscopic systems are utilized with excellent results. For the examination of tissue responses under *in vivo* loading conditions, single-plane fluoroscopy provides experimental flexibility and relatively large viewing volumes, besides the lower radiation and cost (18). Although 3D model matching could theoretically be achieved using a

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single image, certain studies have found that the use of only a single image may not result in the same accuracy in the out-of-plane degrees-of-freedom compared to the in-plane motion (13,17). For this reason, our laboratory has added the additional fluoroscope, thereby creating a dual fluoroscopic imaging system (DFIS) for the analysis of *in vivo* knee joint motion (17). In a recent validation study, we compared the reproduction of dynamic knee flexion by our combined MR-DFIS technique to the kinematics measured by a methodology similar to the highly accurate but invasive Roentgen Stereophotogrammetric Analysis (RSA) (16), and found an excellent agreement in all degrees-of-freedom that were determined by the two methods. Additionally, the feasibility of the DFIS for the application of *in vivo* knee joint kinematic analysis was demonstrated by measuring the six degrees-of-freedom (6DOF) knee joint motion of one living subject during a step ascent and treadmill gait.

With the addition of the second fluoroscope however, and the incorporation of a treadmill to analyze gait, the analysis technique has become more complex. Therefore, the purpose of the present manuscript was to provide a clear, illustrated, and comprehensive review of our experience to date with the DFIS technique (14,15).

## METHODOLOGY

### 1. Patient Selection

The first steps of the combined MR and DFIS technique are the inclusion, instruction, and protection of the patient. First, the treadmill gait of patients with a body mass index (BMI) greater than 30 is difficult to investigate, because the contralateral leg may obstruct the imaging of the studied knee joint and thus hamper the analysis of treadmill gait.

Second, during participation in the study, each patient's knee is MR scanned, which is necessary for the construction of a 3D anatomic knee model (see below). As with every MRI scanner, patients with metal implants (such as surgical clips, fixation screws and plates, and pacemakers) are excluded from the study.

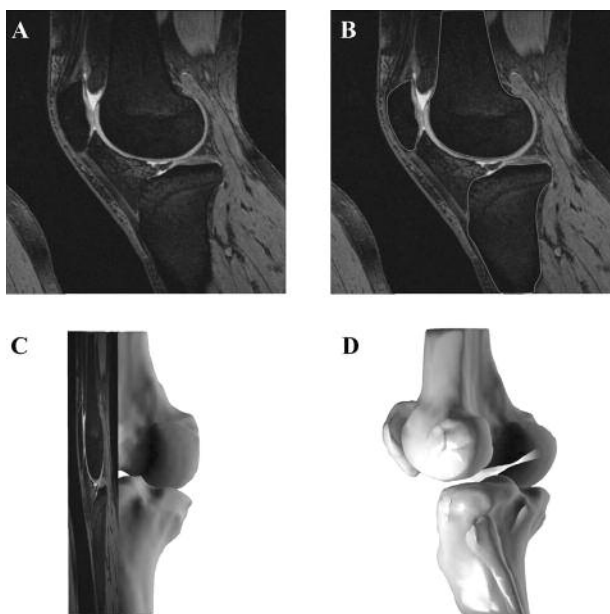
Finally, although low compared to traditional X-rays, a minimal amount of radiation exposure to the patient is intrinsic to the DFIS. The Radiation Safety Committee at our institute has calculated that the amount of radiation the patient is exposed to is 13 millirem during our dynamic imaging of the knee joint. For the protection against unnecessary radiation exposure, each patient is provided with a lead skirt and vest and a lead thyroid shield. Any woman of childbearing potential is questioned and urine or serum tested to determine whether she is possibly pregnant. If found pregnant, she is excluded from the study.

A detailed testing protocol is read and explained to the patient, and an Institutional Review Board approved consent form is signed by each patient before testing starts.

### 2. MRI scan and construction of 3D knee model

The next step following patient selection is the acquisition of MR images of the studied knee joint (8). When studying cartilage deformation, we ask the patient to refrain from all strenuous activity for at least four hours prior to their visit, and to remain non-weight bearing for one hour prior to the MR imaging of the knee (5). During scanning, each patient is asked to lay supine with the knee in a relaxed, extended position while sagittal and coronal plane images are acquired with a 3.0 Tesla MR scanner. Each knee scanning lasts approximately twelve minutes per plane.

The MR images are then imported into commercially available solid modeling software (Rhinoceros®, McNeel, Seattle, WA) to construct 3D surface mesh models of the tibia, fibula, femur and articulating cartilage. The 3D models are created by digitizing the contours of the tibia, fibula, femur and articulating cartilage within each MR image. Unfortunately, delineations between bone and soft tissue in MR images do not always lend themselves to unique contours. Numeric routines to locate "edges" (boundary regions based on the gradient in image intensity), combined with a human operator reviewing these contours to determine that faulty contours are not added to the model, have been developed (6). However, based on



**Fig. 1.** — Within each MR image of the knee (A), the contours of the tibia, fibula, femur and patella are digitized (B). Using the contour lines created in the individual MR images, meshes are assembled (C), resulting in a 3D model of the knee (D).

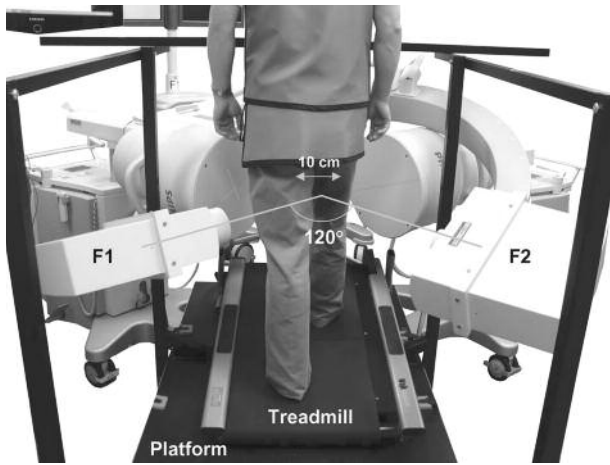
our experience, for the time being a trained researcher can accomplish the digitizing task most reliably manually. The digitized data ( $x$ ,  $y$ ,  $z$  coordinates) are then linked using B-Spline curves to reproduce the contours of the tibia, fibula, femur, and articulating cartilage. Meshes are assembled using the contour lines with a point density of 80 vertices/cm<sup>2</sup> and triangular facets with an average aspect ratio of 2, creating geometric bony models. A typical 3D knee joint model is shown in figure 1. Following one week of supervised training, the construction of one complete knee model requires on average eight hours.

### 3. Fluoroscopic Scanning

In order to capture simultaneous images of the knee at different flexion angles, two fluoroscopes (BV Pulsera®, Philips, Bothell, WA) are used. The fluoroscopes use a pulsed snapshot X-ray to capture images ( $1024 \times 1024$  pixels with voxel size  $0.28 \times 0.28$  mm). A snap shot in our system takes a pulse interval of 8 milliseconds (ms). Therefore, by

setting up 25.33 ms rest time between two X-ray pulses, we can obtain 30 snapshot images in one second. If we set up 58.67 ms between two X-ray pulses, we can obtain 15 snapshot images in one second (16). The fluoroscopes we use are commercially available and unmodified.

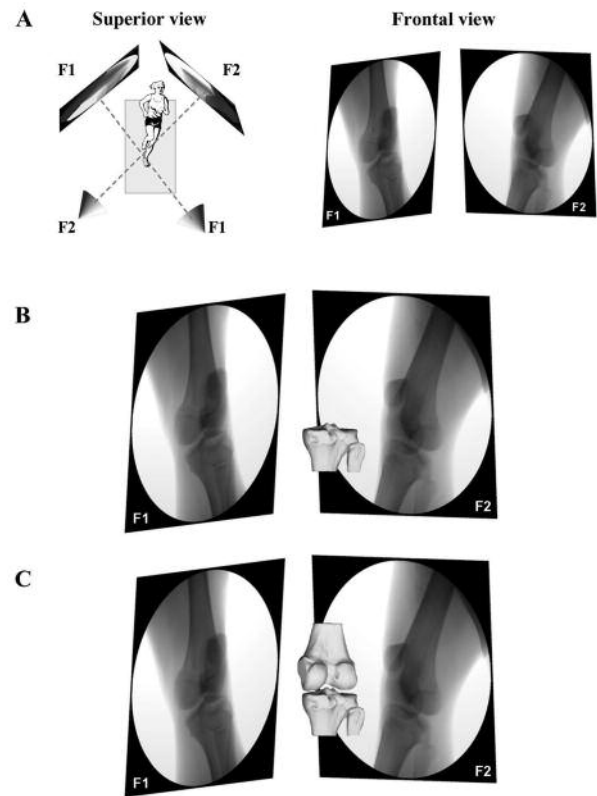
The fluoroscope has a clearance of approximately one meter between the X-ray source and the image intensifier, allowing the patient to be imaged by the fluoroscopes simultaneously as he or she performs dynamic weightbearing activities throughout the entire range of motion. A treadmill is incorporated within the DFIS to study the knee motion during walking. In theory, a force-plate instrumented treadmill could be used to capture the ground reaction forces in all three coordinates during walking (21). For the purpose of accurately differentiating the heel-strike and toe-off instances at a moderate cost though, we use two thin dynamic TekScan pressure sensors, fixed to the heel and the toe of the shoes. The treadmill is placed on a platform so that it can be easily centered between the fluoroscopes (fig 2). In general, the range of knee motion during the treadmill gait ( $\sim 350$  mm) is larger than the diameter of the image intensifier of the fluoroscopes ( $\sim 295$  mm). We therefore re-orientate the two fluoroscopes so that the knee motion can be captured within a field of view of  $\sim 450$  mm by both fluoroscopes during the gait. In our preliminary experience, the optimal fluoroscope setup for treadmill gait analysis is a  $120^\circ$  angle between the planes of the fluoroscopic intensifiers, spaced 10 cm apart, and with the radiation beams parallel to the ground (fig 2). Two laser-positioning devices, attached to the fluoroscopes, helped to align the target knee within the field of view of the fluoroscopes during the stance phase. In addition, a radioopaque marker taped to the skin of the studied knee facilitates the centering the studied joint during imaging on the display monitor. With this setup, we are capable of capturing the full gait cycle (16), and walking speeds up to 1.3 m/s could be analyzed without significant motion blur (15). The knee is then imaged during three consecutive strides. Our entire dynamic analysis of the knee joint, which includes treadmill gait, step ascent, chair rise, and lunge, takes less than 30 minutes.



**Fig. 2.** — Overview of fluoroscope setup for treadmill gait analysis. For capturing the entire gait cycle, the fluoroscopes (F1 and F2) are oriented with a 120° angle between the fluoroscopic intensifiers, spaced 10 cm apart (measured between the closest diameter point of the intensifiers), and with the radiation beams parallel to the ground. A metal frame is attached to the platform for patient safety.

**4. Matching**

The relative location and orientation of the X-ray sources and image intensifiers of the two fluoroscopes are reproduced as points in 3D space in the modeling software (Rhinoceros®, McNeel, Seattle, WA) (fig 3) (7). The fluoroscopic images are then corrected for distortion using the method of Gronenschild (10), imported in the solid modeling software and placed in the position of the intensifiers of the virtual DFIS. The bony contours of the femur, tibia, fibula, and patella are outlined on the fluoroscopic images. These curves representing the projections of the knee will aid in matching the 3D knee model to the fluoroscopic images (see below). Next, the 3D knee model is imported in the same modeling file, placed in the 3D space between the points that replicate the respective fluoroscopes, and viewed from the source points (by setting at origin of the view at the source point and directed at the intensifier point), effectively projecting the 3D model onto the fluoroscopic images (fig 3) (17). With the modeling file’s viewing screen set to multiple panes, the 3D model can be simultaneously



**Fig. 3.** — Illustration of the matching process. The fluoroscopic images are imported into the solid modeling software and placed in the planes based on the position of the respective fluoroscopes during the imaging of the patient (A, superior and frontal view of “virtual fluoroscopic system”, with illustrative person on treadmill for orientation). The 3D MR image-based knee models of tibia (B), femur (C), and patella are imported into the same software and independently manipulated in six degrees-of-freedom inside the software until the projections of the model matched the outlines of the fluoroscopic images.

translated and rotated in all degrees-of-freedom in a controlled manner in indefinitely small increments. Once the 3D model’s position in space approaches the bony contours of the fluoroscopic images though, the latter contours become difficult to detect, because the model blocks the viewing of the fluoroscopic images. To resolve this, we first outline the bony contours of the femur, tibia, fibula, and patella on the fluoroscopic images – these outlines can be highlighted and remain visible while the 3D model shifts over the bony contours on the fluoroscopic images. When the 3D model matches

the bony contours on both fluoroscopic images, a 'match' is made. This matching process is repeated for each desired instance of the dynamic activity. Manually matching the 3D model to the fluoroscopic images remains the gold standard at our laboratory, until automated algorithms have been further refined and validated (4). Following one week of supervised training, the entire matching process including image correction, virtual environment setup, and reproduction of the *in vivo* knee activities (treadmill gait, step ascent, chair rise, and lunge, totalling approximately 12 fluoroscopic image pairs per activity) requires on average eight hours.

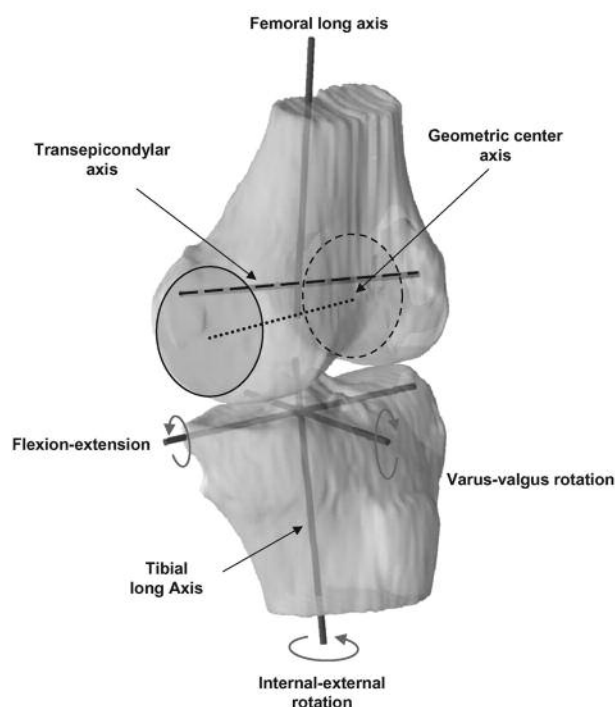
## 5. Measuring Kinematics

When describing knee kinematics, we typically use either a coordinate system based on the transepicondylar axis of the femur (9,20,24), or a coordinate system utilizing the geometric center axis of the femur (fig 4) in which the various tibial and femoral axes are drawn manually based on the bony geometry of the MR model (9).

The tibial coordinates are identical for both coordinate systems. The long axis of the tibial shaft is drawn first by creating a line parallel to the posterior wall of the tibial shaft in the sagittal plane. An anterior-posterior axis and a medial-lateral axis are then drawn perpendicular to the long axis of the tibia. The axes intersect at the center of the tibial plateau to form a Cartesian coordinate system.

In the coordinate system based on the transepicondylar axis of the femur, two axes are drawn on the femur : the long axis of the femur (parallel to the posterior wall of the femoral shaft in the sagittal plane) and the transepicondylar line (flexion axis). In the coordinate system based on the geometric center axis of the femur, the geometric center axis (flexion axis) is constructed by fitting circles to the medial and lateral condyles and by connecting the centers of these circles with a line (19). The middle point of the flexion axis is used as the origin of the femoral coordinate system.

Translation is defined as the motion of the midpoint of the femoral flexion axis relative to the tibial coordinate system (19). Femoral translations are then converted to tibial translations (antero-



**Fig. 4.** — Coordinate systems used to define knee joint motion. [Reproduced from : Kozanek M *et al.* Am J Sports Med 2008 Nov ; 36 (11) : 2151-7. Reprinted with permission].

posterior, mediolateral, and proximodistal) so the data can be reported in a manner consistent with previous studies. The rotation of the knee is measured in a fashion similar to that described by Grood and Suntay (11). Flexion is defined as the angle between the long axes of the femur and tibia, projected onto the sagittal plane of the tibia. Internal-external rotation is defined as the rotation of the femoral flexion axis in the transverse plane of the tibia (perpendicular to the long axis of the tibia). Varus-valgus rotation is defined as the angle between the long axis of the tibia and the femoral flexion axis projected onto the coronal plane of the tibia. Each knee position along the *in vivo* activity path is recorded using these six variables. Following one instruction session, the kinematics measurement of the *in vivo* knee activities (treadmill gait, step ascent, chair rise, and lunge) requires on average four hours.

## VALIDATION

A thorough understanding of the capabilities and limitations of the analysis system is necessary to investigate the dynamic knee joint motion with the technique (16). When comparing the results of the DFIS technique with the 'gold standard' in joint kinematics analysis, namely the highly accurate but invasive RSA technique, we found an excellent agreement in all degrees-of-freedom that were determined by the two methods. The difference in reproduction of tibiofemoral kinematics during dynamic flexion-extension between the DFIS technique and the RSA method was  $0.1 \pm 0.65^\circ/\text{second}$  in flexion speed ;  $0.24 \pm 0.16$  mm in posterior femoral translation ; and  $0.16 \pm 0.61^\circ$  in internal-external tibial rotation (16). When measuring the tibiofemoral kinematics of a living subject during the stance phase of gait and subsequently reproducing the positions of the tibia and femur five times using the matching procedure, excellent intra-observer repeatability was found (15).

## CONCLUDING REMARKS

When asked about the accuracy of the current non-invasive technologies to measure joint kinematics, it is important to always take into account the balance between 'accuracy of measurement' and 'accuracy of reproduction of natural activity'. Fluoroscopy has a sub-millimeter accuracy to measure joint translations (16). However, natural, unrestricted motion is difficult to perform within the constraints of the fluoroscopes. On the other hand, the kinematics of virtually all daily activities could be assessed using gait laboratory technology (1), unfortunately at the expense of a certain degree of accuracy (rotational errors up to  $4.4^\circ$  and translational errors of up to 13.0 mm for walking have been reported) (3). Knee kinematics are greatly activity dependent, and should therefore be interpreted in the context of the test modality (12,14,18). For instance, we noted that motion of the medial femoral condyle in the transverse plane measured with the DFIS was greater than that of the lateral femoral condyle during the stance phase of gait – a trend opposite to what has been observed during

non- weightbearing flexion or single-leg lunge in previous studies (14).

The dynamic knee joint analysis using the DFIS with current technology is time- consuming and laborious, and therefore not yet applicable in the routine clinical practice. Significant advances in the development and validation of automated algorithms of the processes are therefore needed, so that the cost of manual labour could be reduced and the size of study samples increased. Ultimately, the DFIS could then be employed in routine clinical practice, assessing the impact of joint diseases and the efficacy of its various treatments. At this point, we believe that the increased accuracy of the DFIS already outweighs the time-cost associated with the technique when performing the analysis of the cartilage biomechanics following cruciate ligament deficiency, where the smallest errors in measurement are required to detect the often-subtle changes. The main advantage though of the dual fluoroscopic technique is that, in addition to its high accuracy, relatively low radiation, and non-invasive nature, it places the *in vivo* analysis of the various musculoskeletal joints, such as the knee, ankle, wrist, hip, and shoulder, as well as the human spine, within reach of virtually every researcher working in a routine clinical setting : an MR scanner, two fluoroscopes, and a group of keen (pre-) medical students with computers suffice.

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