

# Knee kinematics

## Validation of a re-orientation technique of knee axis.

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**Abstract**— This paper compares morphological and functional definitions of the flexion-extension axis using six dof electrogoniometry and bone Modelling.

**Keywords:** mean helical axis; knee; flexion-extension axis landmark.

### I. INTRODUCTION

In biomechanics, the kinematic "cross-talk" means that a component of rotation (e.g., flexion) can be interpreted as another (e.g., abduction) [1]. The misalignment or more exactly the wrong orientation of anatomical axes, defining the reference frames of observation, with the axes of movement would be the cause of a "cross-talk", the effect of which was mainly observed during knee analysis [2].

The question raised by the « kinematic cross talk » is also central for optoelectronic stereophotogrammetric methods. The use of external landmarks (quasi anatomical, manually or virtually palpated) to determine the orientation of the fixed coordinate system (the observational frame) is often considered as the most critical source of errors. Erroneous placement of knee landmarks or the thigh wand in the Helen Hayes model may induce large deviations in the computation of hip rotation and knee varus/valgus angles. The reproducibility of measurement is "landmark-dependant" for optical systems. The use of an exoskeletal "Knee alignment device" [KAD]) does not seem to solve the problem: the quality of the results is still dependent on suitable marker placement.

Functional approaches and more precise definition of reference bony landmarks could improve the minimization of the « cross talk » effect.

Two approaches are encountered in the literature. The first approach defines bony landmarks for the determination of an optimal flexion-extension axis [3,4,5,6]. The second approach calculates the average axis of the movement to re-orientate the axis of flexion-extension of the fixed reference frame [7,8,9].

*Approach 1.* Anatomical methods propose several definitions of an optimal axis like the transepicondylar line (LTE) or the axis of geometrical centre (AGC) of the posterior condyles. Questions relating to the curves of the condyles, the choice of the anatomical markers, the orientation of the axes of the movement with various ranges of flexion-extension or the values of antero-posterior displacements of the condyles are retrieved for this approach. The axes of the movement of the

knee would be quasi parallel in the range of 45 and 90° of knee flexion.

*Approach 2.* The functional method uses the mean helical axis as invariant. This axis is used like a kinematic descriptor making it possible to reorient the axis of flexion-extension [9]. The observation of the axode of the knee shows a cylinder of quasi-parallel axis between 40 and 80° of flexion [10]. Both reduction of inter specimen variability and inaccuracy in locating anatomical landmarks in vivo are the justifications most met to use this method.

This paper presented the results of a comparison between various definitions of the flexion-extension axis (anatomical and functional). We analysed the relative equivalence of both approaches when performed in vitro. Rigorous definition of anatomical reference frame was applied. The knee was chosen taking into account the important literature available, the importance of these definitions for the realization of gait protocols, and the functional concept of knee prostheses and their placement.

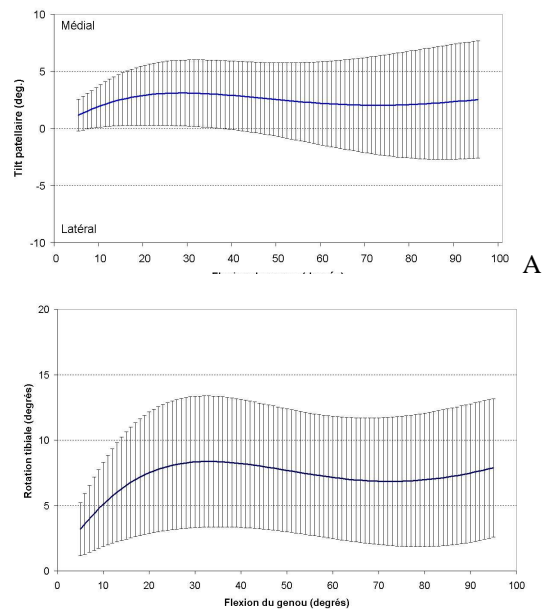


Figure 1 : Interspecimen variability (average curve and standard deviation of 7 specimens). A: Patellar tilt; B: Tibial Rotation. Note the quasi static level of internal rotation after 30° of knee flexion.

## II. METHODS

### A. Preliminary Study

In a previous study on the effects of tibial tuberosity elevation on femoro-patellar kinematics [11], we used a technique of reorientation of the global reference frame from processing the mean helical axis (MHA) between 35° and 75° of knee flexion. This range avoided the screw home mechanism in the initial flexion and the posterior shift of the helical axis above 70°. This technique enabled reduction of the interspecimen variability of associated components of knee flexion, but also minimizing the variability of the patellar rotation and translation components. In this particular case, the quality of the reorientation could be assessed by the smallness of the standard deviations (Figure 1). However, the functional method did not enable to locate the position and orientation of this axis in the distal extremity of the femur. The combination of medical imaging and three-dimensional electrogoniometry used in this paper was intended to solve that limitation.

### B. Validation of the re-orientation method

Two fresh-frozen lower limbs (58 and 87 years) were used. The lower limb included a hemi-pelvis, thigh, shank and foot. The rectus femoris, vastus intermedius, vastus medialis and lateralis, biceps femoris, semitendinosus, semimembranosus, tensor fascia lata and gracilis muscles were dissected and loaded. The distal tendons of these muscles and joint capsule were preserved. Bony tunnels were drilled through the pelvic insertions of these muscles to ensure that their paths were kept close to the original anatomy.

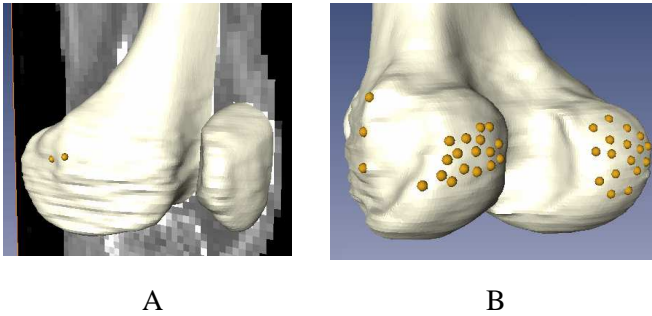


Figure 2. Virtual palpation of epicondyles, medial (A) et lateral (B).

### C. Measurement device

To describe tibiofemoral and patello-femoral kinematics [12], we used 2 custom-made six revolute joint instrumented spatial linkages (6R ISL) showing an accuracy of 0.6° rms in rotation and of 1.2 mm in translation, and a precision of 0.1° [13]. A 3D digitizer was used to register the kinematics on the bony models. To measure the excursion of quadriceps and hamstring tendons, four LVDT [Linear Variable Differential Transducers (Mach1 series; Solartron Inc.; USA)] were linked to the muscle tendons. Passive knee flexion/extension motion was then performed and kinematics data was collected by the 6R ISL's.

### D. 3D reconstruction and virtual palpation

After CT-imaging the lower limbs, bone segmentation and 3D reconstruction were processed using AMIRA (Germany, www.amiravis.com). On these bony models, a virtual palpation was performed to sample the co-ordinates of the chosen anatomical landmarks necessary to define the various axes of optimal flexion-extension.

Two virtual markers were identified on the medial epicondyle, or ME (Figure 2-A): one on the most medial ME point, another in the small depression posterior to ME (i.e., the medial sulcus). The latter point is used to define the surgical transepicondylar line (TEL). Three landmarks were located on the lateral epicondyle crest, or LE (Figure 2-B): superior aspect of the crest, middle aspect and inferior aspect of the crest. The TEL may be defined between these five points. In this paper, TEL is defined between the medial sulcus and the middle point of the lateral epicondylar crest [14]. To define the geometrical center of the posterior condyles, landmarks were virtually palpated on each condyle (Figure 2-B). By applying an iterative method, four different markers were selected at each iteration, allowing the calculation of the center and the radius of curvature of the sphere passing by these four points. The radii of curvatures permit to verify the good estimation of the curve center. The line joining both centers of the medial and lateral condyles was named AGC (axe of geometrical center).

### E. Re-orientation process

The parameters of the helical axis (HA) were first calculated from the 6R ISL's transformation matrices. The motion was described by a set of finite helical axes (FHA) computed at every 3° of helical rotation during knee flexion-extension. From all FHAs, we extracted 9 groups of FHA's each 20°-step of knee flexion or extension (0-20, 10-30, 20-40, 30-50, 40-60, 50-70, 60-80, 70-90, 80-100°) (similar to Wilson et al [15]). For each step, a mean helical axis (MHA) and its piercing points in parasagittal plans closed to the medial and lateral epicondyles were computed. MHA between 40 and 80° of knee flexion (AHM<sub>40-80</sub>) and MHA between 20 and 120° (AHM<sub>20-120</sub>) were also computed. All the transformations were expressed in the 6R ISL original frame. To express kinematics in an anatomical or functional reference frame, the matrices of displacements were pre-multiplied either by the matrix of transformation defined starting from the anatomical reference marks or by the matrix of defined starting from the orientation of the AHM<sub>40-80</sub> as

$$T = [\text{PRE}] * M2 * \text{MR}^{-1}$$

where MR is the reference matrix describing the pose of the tibia relative to the femur, M2 the matrix of the current pose during the movement and PRE the reorientation matrix.

The origin of the reorientation frame was placed either on the middle of TEL, or on the middle of ACG or at the pivot estimated between 20 to 120° of flexion. For the AHM<sub>40-80</sub>, the piercing point of this axis in the sagittal plan was used due to the inaccuracy of the estimation of X component of the pivot in this range of knee flexion, the helical axes being quasi parallel.

## F. Experimentation

Femoro-tibial kinematics was described in terms of flexion-extension, abduction-adduction, tibial rotation, medio-lateral, anterior-posterior and proximo-distal shift. Femoro-patellar kinematics was described in terms of patellar flexion, patellar and patellar tilt. The angles between LTE and ACG, LTE and AHM<sub>40-80</sub>, ACG and AHM<sub>40-80</sub> were also processed.

## III. RESULTS AND DISCUSSION

The angle between TEL<sub>surgical</sub> and AGC, between MHA and TEL<sub>surgical</sub>, and between MHA and ACG were 2.3°, 1.1° and 6.7°, respectively. We previously mentioned the importance of the choice of the reference frame for the representation of kinematics data. A comparison of 3D poses of different definitions of flexion-extension axis for the specimen 1 is shown in figure 3.

This is of importance for reproducibility and communication of results in anatomical terms. To our knowledge, this paper showed for the first time, a comparison between the morphological and functional approaches on the same specimens by using registration techniques (Van Sint Jan *et al.*, 2002)

Both the choice of anatomical landmarks and the precision of location are prone to error. Errors from 13 to 25 mm were reported during *in vivo* palpation of anatomical landmarks (Della-Croce *et al.*, 1999). To solve this lack of reproducibility, many authors tried to get rid of anatomical landmarks by developing numerical methods to determine the centers and axes of rotation of a joint in an optimal way (Besier *et al.*, 2003)

However, numerical methods raise interrogations. Where is this axis located in the joint? Over which motion range one must estimate the center or the optimal axis of the movement? Can one use the pivot of the movement to locate the origin of the reference frame of observation? What is the sensitivity of this invariant of movement (the helical axis) to the load conditions of the joint? Our results suggest a relative agreement between the MHA and some above-described anatomical landmarks.

In short, if the optimal axes (TEL, ACG) are close to parallel, rotations will be equivalent. However, translations seem more dependent on the definition of the optimal axes and seem minimized if related to the posterior bicondylar axis (AGC). The position of the MHA seems to be also closer to this posterior axis.

Some limitations must be underlined. The reference frame related to the tibia was not morphologically defined permitting to define its mechanical axis. We regarded the fixed and mobile reference frames as coincident at the reference position. Nevertheless, this approach limits the number of palpated landmarks.

In patients presenting bony deformations, separating the relative experimental bias of the deformation itself (true knee misalignment) from the error arising from the real cross talk is

not easy. The results of this paper should be first validated *in vivo* prior to clinical implementation.

The effect of load is a significant parameter if this method is applied in the operating room. The first observations show little effect on rotations. On the other hand, the translations should be affected by the loading conditions. Experimental protocols focused on this parameter should be continued to inform or confirm this observation.

The sensitivity of the components associated with the principal movement was shown and reinforces our conviction in the use of reorientation techniques of the movement axis. These techniques are not reserved for the knee joint, and could be used for other joints where similar cross-talk problems are also described (elbow, wrist).

In conclusion, this paper tackled the issue of knee axis reorientation. Such work is of importance for a reproducible analysis of experimental protocols. The agreement between both functional and morphological methods reinforced our decision to insert it in our clinical protocols.

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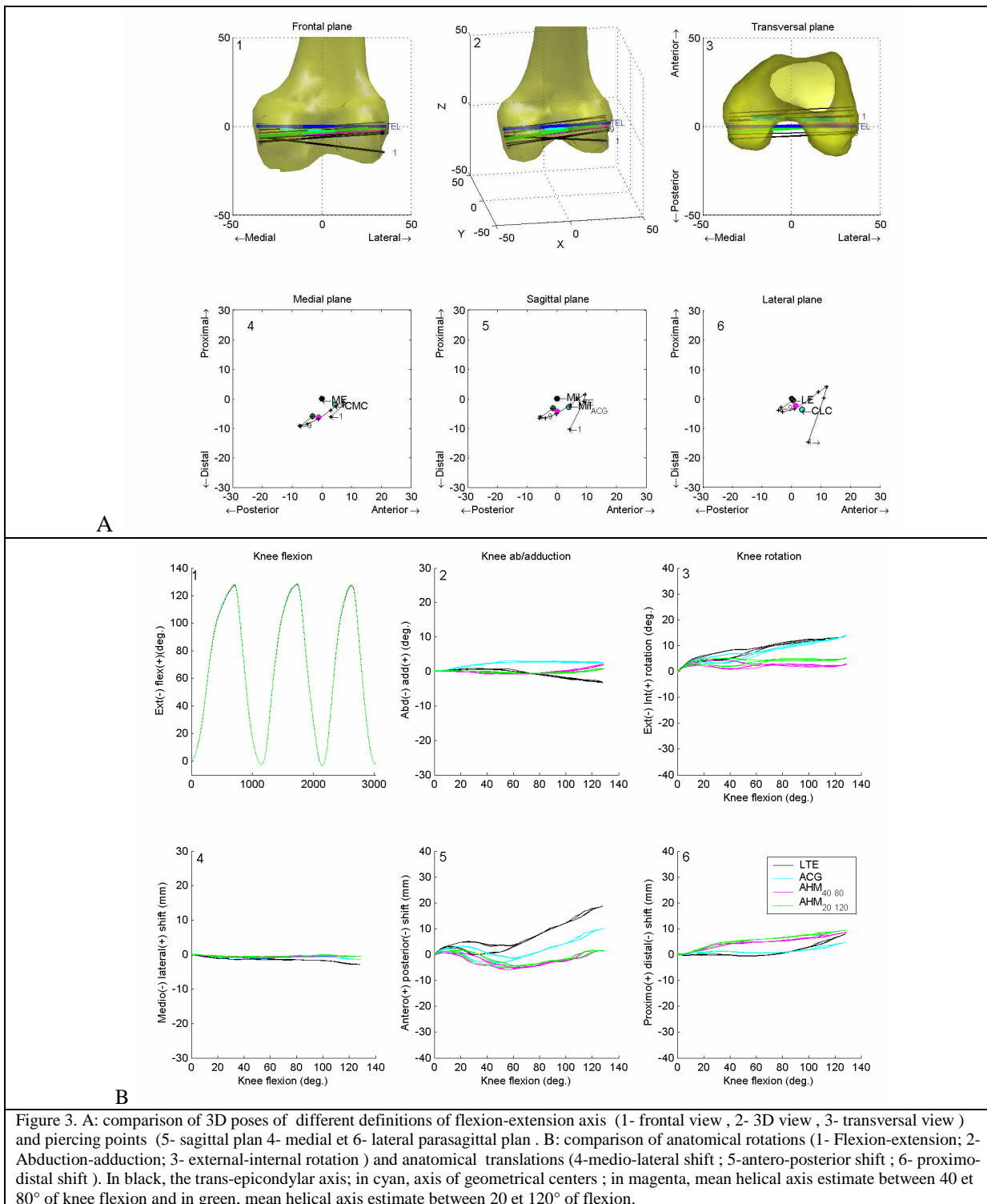


Figure 3. A: comparison of 3D poses of different definitions of flexion-extension axis (1- frontal view , 2- 3D view , 3- transversal view ) and piercing points (5- sagittal plan 4- medial et 6- lateral parasagittal plan . B: comparison of anatomical rotations (1- Flexion-extension; 2- Abduction-adduction; 3- external-internal rotation ) and anatomical translations (4-medio-lateral shift ; 5- antero-posterior shift ; 6- proximo-distal shift ). In black, the trans-epicondylar axis; in cyan, axis of geometrical centers ; in magenta, mean helical axis estimate between 40 et 80° of knee flexion and in green, mean helical axis estimate between 20 et 120° of flexion.