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Sequential 3D analysis of patellofemoral kinematics from biplanar x-rays: In vitro validation protocol

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ABSTRACT

Background: Developing criteria for assessing patellofemoral kinematics is crucial to understand, evaluate, and monitor patellofemoral function. The objective of this study was to assess a sequential 3D analysis method based on biplanar radiographs, using an in vitro protocol.
Hypothesis: Biplanar radiography combined with novel 3D reconstruction methods provides a reliable evaluation of patellofemoral function, without previous imaging.
Material and methods: Eight cadaver specimens were studied during knee flexion cycles from 0° to 60° induced by an in vitro simulator. The protocol was validated by investigating sequential and continuous motion using an optoelectronic system, evaluating measurement accuracy and reproducibility using metallic beads embedded in the patella, and comparing the 3D patellar geometry to computed tomography (CT) images.
Results: The differences in position between the sequential and continuous kinematic analyses were less than 1 mm and 1°. The protocol proved reliable for tracking several components of knee movements, including patellar translations, flexion, and tilt. In this analysis, uncertainty was less than 2 mm for translations and less than 3° for rotations, except rotation in the coronal plane. For patellar tilt, uncertainty was 5°. Mean difference in geometry was 0.49 mm.
Discussion: Sequential analysis results are consistent with continuous kinematics. This analysis method provides patellar position parameters without requiring previous CT or magnetic resonance imaging. A clinical study may deserve consideration to identify patellofemoral kinematic profiles and position criteria in vivo.
Level of evidence: IV, experimental study.

1. Introduction

Patellofemoral kinematics is challenging to evaluate. Quantitative and qualitative characterisation of patellar tracking is not feasible in everyday practice yet would add useful information to the functional evaluation of patients with patellar instability or patellar pain syndromes. Furthermore, the lack of reliable and widely available investigative tools has prevented an accurate determination of potential associations between kinematic abnormalities and clinical patellofemoral disorders. Patellar kinematics and alignment differed between weight-bearing and non-weight-bearing conditions in patients with patellofemoral pain syndrome (PFPS) [1] and, in two other studies, were not significantly different between symptomatic and asymptomatic knees [2,3]. A recent literature review suggests that abnormal patellar kinematics and alignment may be mere risk factors and that studies are needed to accurately define normal patellar tracking [4]. We agree that identifying changes in patellar position is essential to the understanding, evaluation, and monitoring of patellofemoral function.

As a preliminary to the development of new in vivo investigation techniques, several groups have performed in vitro validation studies. Motion detected by skin sensors proved unreliable, due to movements of the skin over the bone [5]. Most published studies relied on optoelectronic systems [6–8], ultrasound [9], electromagnetic sensors [9–11], or fluoroscopy [12,13]. Most of these methods require preliminary computed tomography (CT) to collect reliable data on bone geometry for the kinematic analyses. Biplanar radiography is a recently developed method allowing low-radiation dose

Fig. 1. Automated in vitro knee flexion simulator.

imaging of the lower limbs in the standing position. It has been evaluated as a tool for knee kinematics studies [14,15], in combination with new modelling and 3D reconstruction techniques [16,17].

The objective of this work was to evaluate the accuracy and reproducibility of a sequential biplanar patellofemoral imaging protocol used to study cadaver knee flexion induced by an automated simulator. The working hypothesis was that patellofemoral kinematics could be reliably evaluated using a biplanar imaging system and new reconstruction techniques.

2. Material and methods

2.1. *Cadaver specimens*

Eight lower limbs from four fresh frozen (within the last 72 hours) cadavers were studied. There were 2 males and 2 females aged 65 to 78 years at death (mean, 74 years). The lower limbs were harvested after approval by the ethics committee of the Saints-Pères Pathology Laboratory (Institut d'Anatomie, UFR Biomédicale des Saints-Pères, Université René Descartes, Paris, France). Each limb was harvested by disarticulating the coxo-femoral and talocrural joints [14] then stored at −20 °C. Before the experiments, the specimens were allowed to thaw at room temperature for 12 hours.

The eight specimens were divided into two groups. Four limbs were equipped with tripods bearing passive infrared markers [14] for the sequential kinematics analysis. The remaining four limbs had metallic beads embedded in the patella (medial and lateral facets and apex) for the evaluation of accuracy and reproducibility.

2.2. *Automated in vitro knee flexion simulator*

The knee flexion simulator rotated the tibia around the femur, which was fixed (Fig. 1). This device was previously validated at our laboratory during a preliminary feasibility study [14]. Two weights of 10 N each were applied to the distal tibia using a cord and pulley system. The point of weight application projected onto the centre of the femoral head, and the force vector produced by the weights was along the mechanical axis of the femur. Knee flexion-extension cycles were generated using an electric linear actuator (DSZY1, Drive-System Europe Ltd., Werther, Germany) applied to the quadricipital tendon using a steel cable secured by a metal clamp (traction speed, 12 mm/s for the continuous analysis).

2.3. *Biplanar radiograph acquisition protocol and 3D interpretation method*

The specimen attached to the simulator was positioned within the imaging system booth (EOS, EOS Imaging, Paris, France). For each specimen, sequential, simultaneous, biplanar, static, calibrated images were acquired in five positions, in the following order: 0°, 20°, 30°, 45°, and 60° of knee flexion. The 0° position (full knee extension, taken as the reference) allowed manual tracking of the femoral and patellar bone contours and of the infrared tripods or metallic beads. The templates thus obtained served to generate an individual model for each specimen, using a 3D reconstruction algorithm (Fig. 2). Image matching was then achieved by manually matching each 3D object to its contours on the following biplanar views. As the femur was fixed, no matching was required for the femoral images. Specific anatomical regions were defined and used to develop an anatomical coordinate system for each 3D object (Fig. 3), which then served to quantify the changes in position of each object from one sequential image to the next [14,17–19]. A personalised programme (MATLAB V5R20, Mathworks, Natick, MA, USA) was used to compute the position of the patella, infrared tripods, and metallic beads relative to the femur in each of the five knee flexion positions, from the linear and angular data provided by the coordinate systems. The angle sequence (Y, X', Z'') was selected to compute the angle matrix. The patellar 3D kinematic profile was expressed as six degrees of freedom, i.e., three translations and three rotations (Fig. 4).

2.4. *In vitro validation procedure*

2.4.1. *Analysis of continuous and sequential motion*

In the group of four limbs equipped with tripods bearing infrared markers, the initial 3D coordinates of each tripod were recorded using an optoelectronic motion capture system (POLARIS®, Spectra, NDI, Waterloo, Ontario, Canada) with two cameras (Fig. 5). The coordinates were recorded continuously from the fully extended position (0° of flexion) to 60° of flexion. To assess uniformity of the simulator cycles, continuous recordings were obtained for six consecutive flexion-extension cycles. The biplanar protocol was then executed with the four limbs equipped with tripods. The sequential tripod positions determined after manual image matching were then compared to the positions recorded continuously by the optoelectronic system.

2.4.2. *Biplanar reconstruction analysis of bone geometry*

The four limbs studied using metallic beads were first imaged using a 256-slice CT machine (iCT 256, Philips Healthcare, Best, The Netherlands), at the polyvalent radiology department of the Pitié-Salpêtrière Teaching Hospital, Paris, France. A reference model of the bone geometry of each patella was obtained by segmentation of each axial slice less than 1 mm in thickness, using dedicated software (Avizo® v7.1.0, VSG, FEI, Hillsboro, OR, USA). The two 3D patellar geometry models obtained using the biplanar reconstruction algorithm and CT segmentation, respectively, were superimposed and compared.

2.4.3. *Analysis of accuracy and reproducibility*

The biplanar protocol was executed on the four limbs equipped with metallic beads. Two operators with extensive experience in biplanar reconstruction (LD and BE) worked independently to produce three sequences of reconstruction and matching of the relative positions of the beads and patella, in order to evaluate the uncertainty for each degree of freedom (Fig. 6). The exact position of

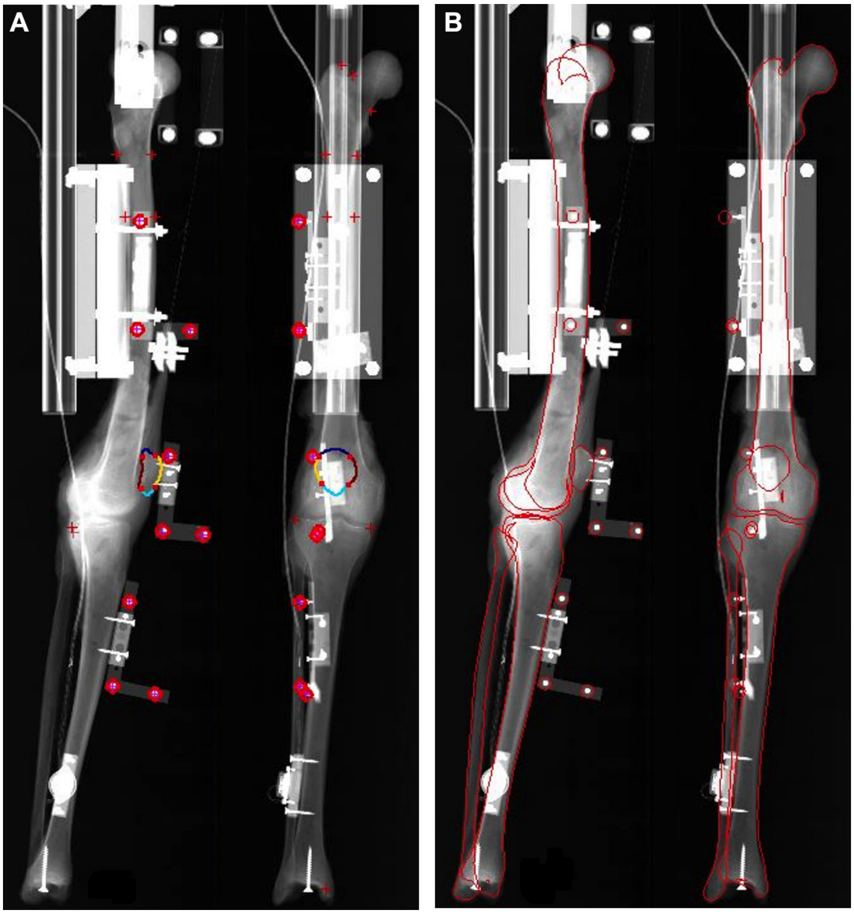

Fig. 2. 3D reconstruction in the reference position based on biplanar radiographs. A. Selection of femoral landmarks and identification of the patellar contours and tripods. B. Reconstruction using a 3D algorithm.

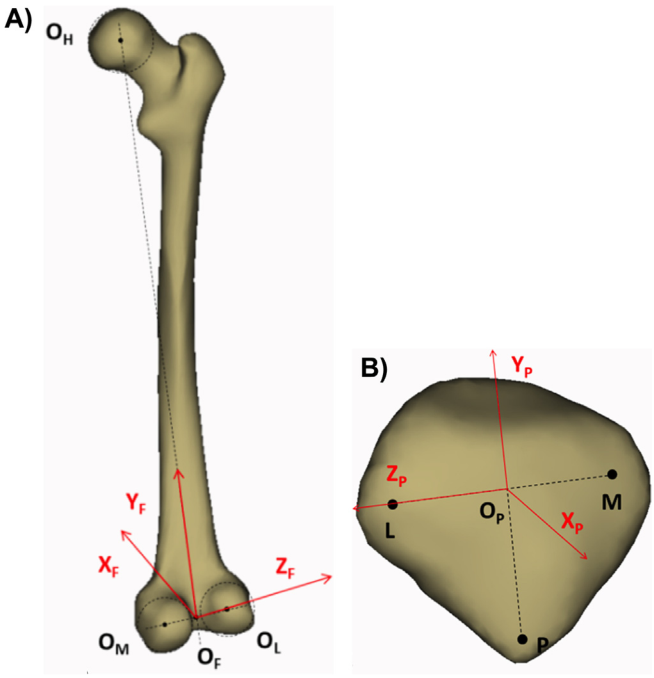

Fig. 3. Construction of the anatomical landmarks on the femur (A) and patella (B).

the patella was estimated using the mean bead position as the reference. Thus, accuracy was evaluated by comparing the bead positions to the matching patellar positions. Reproducibility was assessed based on differences in positions determined by the two operators.

2.5. Statistical analysis

The statistical analysis was performed using MATLAB® software (Mathworks, Natick, MA, USA). Differences and variations in relative positions were expressed for two standard deviations, corresponding to the 95% confidence interval (95% CI) and defining uncertainty. Reproducibility was assessed based on variations in patellar position matching for each degree of freedom (ISO norm 5725:2). Comparisons of 3D object bone geometry relied on the least-squares method and involved computing the mean and maximum errors with the 95% CIs of all point-to-surface distances for the two 3D objects.

3. Results

3.1. Comparison of continuous and sequential motion

For the six continuous flexion-extension cycles, variations in patellar shift and rotation were less than 0.5 mm and 0.5°, respectively (Fig. 7). In comparisons of sequential tripod positions versus continuous tripod position recordings, the differences were less than 1 mm for translations and 1° for rotations.

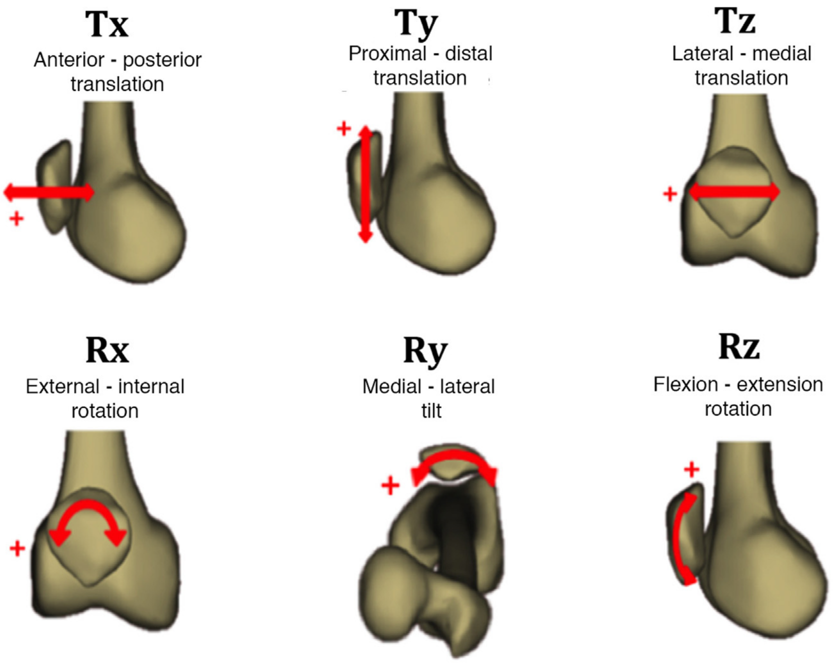

Fig. 4. Description of the six degrees of freedom of the patella. Lateral shift is designated with a plus sign and external tilt with a minus sign.

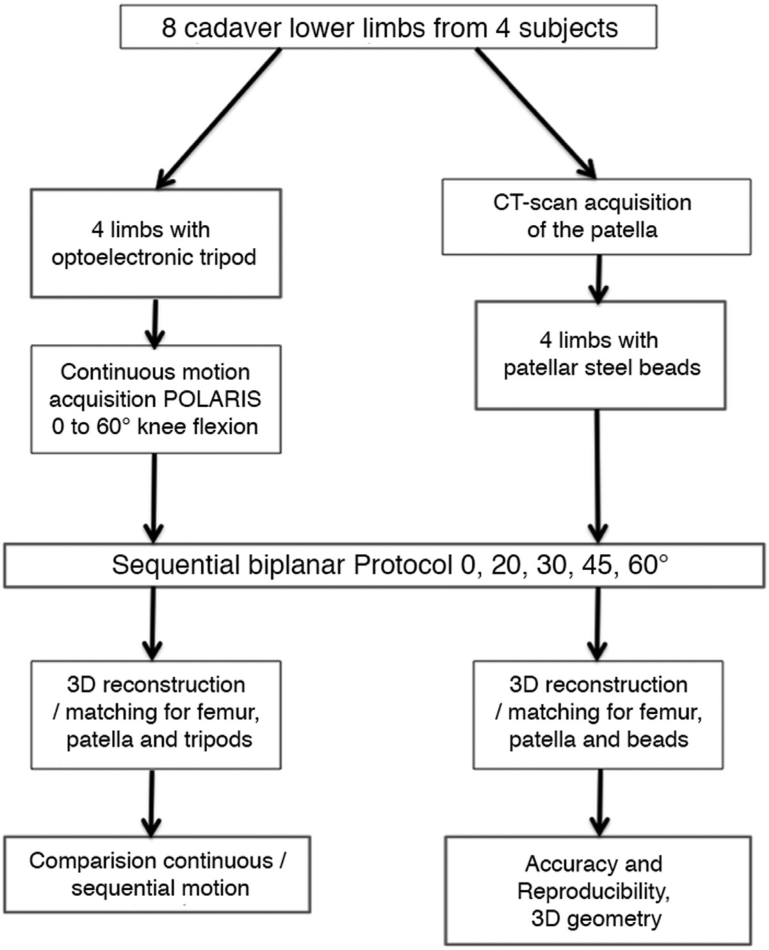

Fig. 5. In vitro validation protocol.

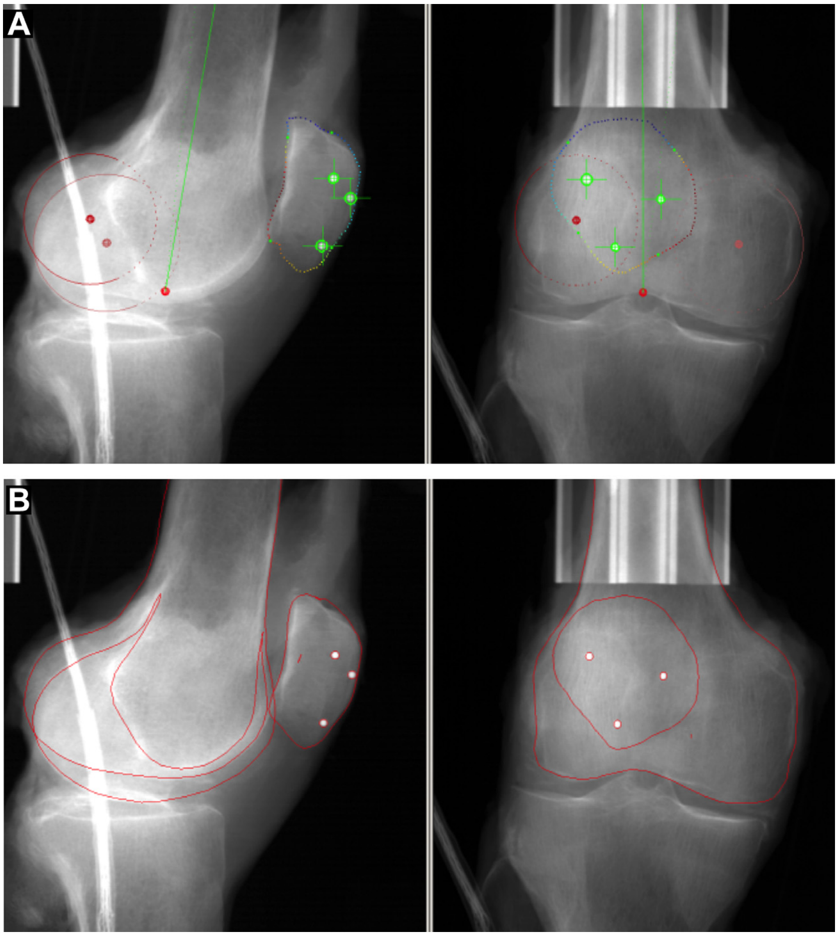

Fig. 6. A. Selection of the femoral landmarks and of the contours of the patella and metallic beads. B. Reconstruction with visualisation of the contours of the 3D objects.

3.2. *Validation of the reference standard based on metallic bead position measurements*

Table 1 reports the reproducibility of the recording of the three metallic beads. For all degrees of freedom, 95% CI values were about 0.1 mm and 0.5°. These results validate the use of our position measurement method as the reference standard.

3.3. *Accuracy and reproducibility of patellar position relative to the femur*

Reproducibility and accuracy were assessed by having two operators each performs three reconstructions of each of four lower limbs (yielding 24 reconstructions of the femur and patella in all) and patellar image matching at each of the four additional degrees of flexion (yielding 24 matches in all). Table 1 reports the 95% CIs for each patellar degree of freedom. Table 2 shows an example of a comparison between the image matching variations and the position of the beads taken as the reference standard.

3.4. *Analysis of patellar geometry using the reconstruction method*

The analysis of point-to-surface distances obtained using the geometric model produced by 3D reconstruction and using CT image segmentation showed a mean error of 0.49 mm with a 95% CI of 1.32 mm (maximum, 2.78 mm).

4. Discussion

Two approaches were used to validate the kinematic analysis method, namely, comparisons of continuous versus sequential motion and quantification of the accuracy and reproducibility of patellar position measurements, including the accuracy of 3D patellar geometry. The validation process relied on two reference standards: one was an evaluation using infrared tripods coupled to an optoelectronic system, and the other monitored the position of metallic beads. Our choice of an optoelectronic system as the reference standard for analysing continuous motion was based on the previously reported reliability of this technique [6,7,14]. However, overlap between the infrared tripods (which fails to closely replicate in vivo conditions) was an obstacle to contour acquisition and patellar image matching. The use of metallic beads not only eliminated problems related to bulky material with tripod overlap, but also proved reliable (reproducibility of about 0.1 mm and 0.5° in this study). The metallic bead method was therefore chosen as the reference for determining patellar position.

When studying kinematics, the knee flexion simulator must produce uniform flexion-extension cycles, to ensure that the analysis of continuous motion is relevant and closely replicates in vivo findings. The concepts underlying the simulator used in our study, described by Azmy et al. [14], simulate reliable and reproducible cycles: the femur is fixed and the tibia free, the tibio-fibular ligaments and inter-osseous membrane are preserved, and force is applied to the quadricipital tendon in a single direction identical to that of the mechanical femoral axis. Choosing this simulator minimised the risk of experimental errors due to approximation

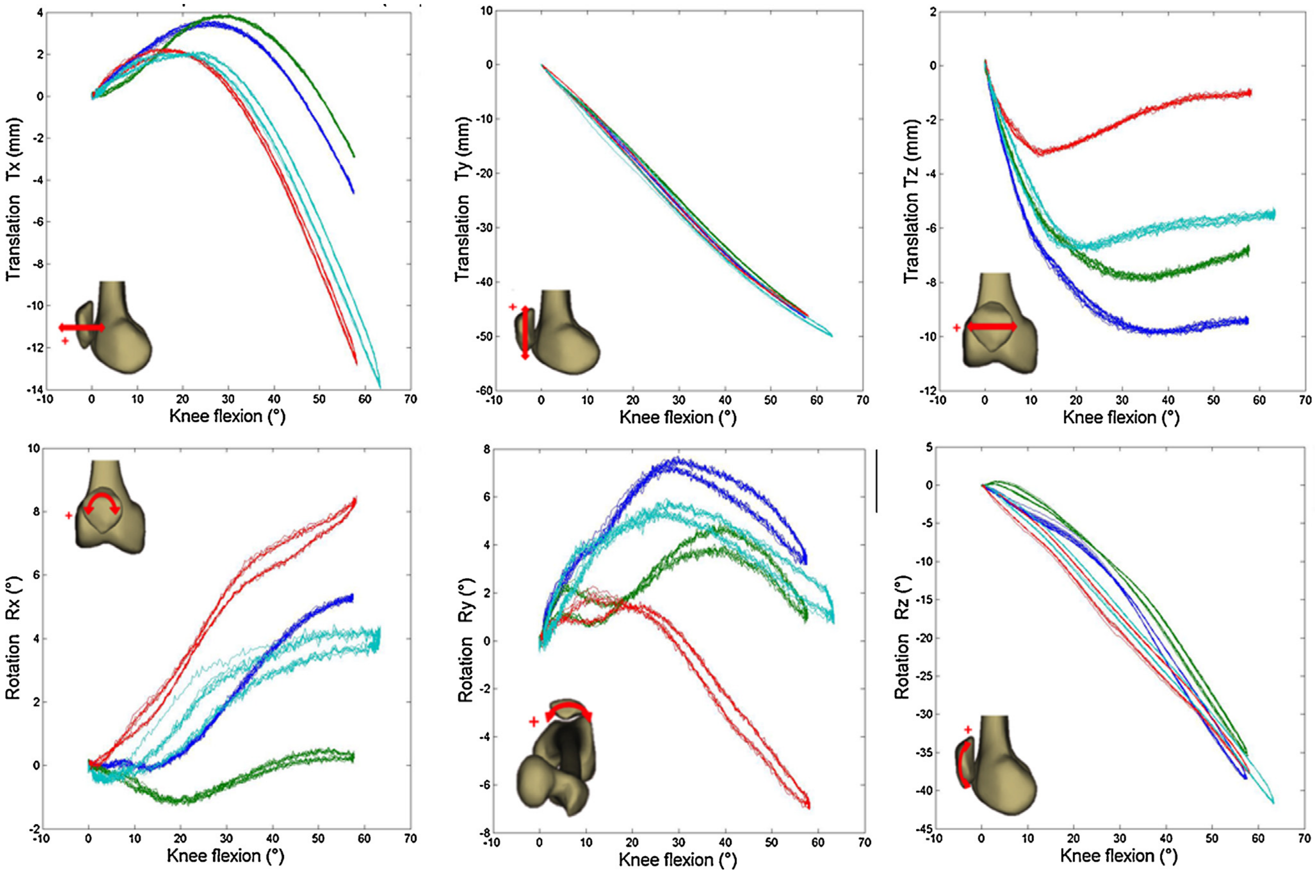

Fig. 7. Continuous kinematics of 3D patellar position relative to the femur, as assessed using an optoelectronic system, for each degree of freedom.

of the participation of the vastus medialis, vastus lateralis, vastus intermedius, and rectus femoris muscles. The direction and magnitude of the forces developed by these muscles have little influence on patellar kinematics under experimental conditions [11,20]. The knee flexion simulator used for this study generated highly reproducible flexion-extension cycles for a given limb specimen, an essential prerequisite for comparisons of continuous and sequential kinematics. Furthermore, in our study, the differences in patellar position between continuous and sequential motion were small (about 1° and 1 mm). These differences are probably smaller in vitro than in vivo, given the effects of weight bearing and muscle strength. The patellofemoral kinematics of the various cycles investigated using the optoelectronic system is similar to results obtained previously in vivo, with the degree of knee flexion influencing some parameters (Tx, Ty, and Rz) but not others (Tz, Rx, and Ry) [7]. In this study, during patellar tracking, slight medial shift and medial tilt were detected during the first few degrees of flexion, in keeping with previous descriptions of patellofemoral kinematics [7,10,21]. Thus, the kinematic profiles documented in our study are consistent with those obtained using other in vitro preparation and analysis protocols. We elected to describe sequential patellar kinematics relative to the femur not only because the testing rig required fixing the femur, but also because this method was used in most previous studies [22,23]. When performing in vivo analyses, the movements of the femur and patella must be taken into account independently from each other, before determining the overall patellofemoral kinematics profile.

The accuracy of patellar translations measurements in this study varied from 0.7 to 1.7 mm. Measurements of rotation in the sagittal plane (Rz) and axial plane (Ry) also showed good precision (2.5° and 1°, respectively). Accuracy was poorer for rotation in the coronal plane (about 6°), due to difficulties in delineating the patellar contours in this plane and to the absence of identifiable morphological criteria. These precision values should be taken into account for in vivo analyses of patellar tracking in patients with disorders of the knee [15]. Studies of knee kinematics analysed using

Table 1
Estimation of the 95% confidence intervals for reproducibility and accuracy for each of the six degrees of freedom of the patella.

95% CI	Translations (mm)			Rotations (°)		
	Tx	Ty	Tz	Rx	Ry	Rz
Reproducibility of metallic bead recording	0.1	0.1	0.1	0.5	0.6	0.5
Accuracy of patellar position relative to the femur	0.8	0.7	1.7	6.5	2.5	1
Reproducibility of patellar position relative to the femur	1.1	1	2.2	5.8	5	2

95% CI: 95% confidence interval; Tx: translation in the coronal plane; Ty: translation in the axial plane; Tz: translation in the sagittal plane; Rx: rotation in the coronal plane; Ry: rotation in the axial plane; Rz: rotation in the sagittal plane.

Table 2
Analysis of accuracy and reproducibility of measurements on the PA13020D specimen. Variability in positions of manual image matching (median and range) compared to the bead position means (reference standard) for each degree of freedom and each degree of flexion.

	Tx (mm)	Ty (mm)	Tz (mm)	Rx (°)	Ry (°)	Rz (°)
0°						
Image matching	50.6	18.4	8.5	8.2	−7.3	−0.5
	[50,51]	[18,20]	[7,10]	[5,12]	[−6, −8]	[0,−2]
Beads	50.6	18.4	8.5	8.2	−7.3	−0.5
20°						
Image matching	52.3	4.6	8.6	6.4	−7.5	−9.5
	[52,53]	[4,6]	[6,9]	[1,8]	[−6, −13]	[−8, −11]
Beads	52.5	4.4	7.7	7.6	−5.9	−8.4
30°						
Image matching	50.8	−2.1	8	6.4	−5.9	−14.4
	[50,51]	[−1, −3]	[6,9]	[4,11]	[−4, −12]	[−14, −16]
Beads	50.9	−2.2	6.9	8.6	−4.4	−13.7
45°						
Image matching	45.7	−11.7	6.6	6.1	−4.9	−23.6
	[45,46]	[−11, −12]	[5,8]	[3,12]	[−4, −9]	[−22, −25]
Beads	45.9	−11.9	4.9	8.4	−4.9	−23.7
60°						
Image matching	38.6	−19	6.5	4.1	−7.1	−37.7
	[38,39]	[−18, −20]	[5,7]	[2,9]	[−4, −11]	[−36, −40]
Beads	38.9	−18.9	4.5	7.6	−7	−37.6

Tx: translation in the coronal plane; Ty: translation in the axial plane; Tz: translation in the sagittal plane; Rx: rotation in the coronal plane; Ry: rotation in the axial plane; Rz: rotation in the sagittal plane.

biplanar radiography have been published [15,24–26]. However, our method is original in that it relies solely on geometric data obtained by contouring (limb-specific 3D models) and thus requires no preliminary imaging. The CT images obtained in this protocol served only for the geometric evaluation. Bey et al. [15] reported excellent accuracy, with less than 0.5 mm and 1° of error, but their acquisition method requires a high-resolution volumetric analysis of the femur and patella using CT combined with a reconstruction phase. Sharma et al. [25] obtained similar results using preliminary CT imaging and a calibration frame. To be suitable for use in everyday clinical practice, however, a protocol must be as simple and widely available as possible, require no preliminary imaging, and involve the smallest possible number of image- and data-processing steps.

Few published data are available on the reproducibility of measurement protocols [7,22]. Reproducibility is a crucial consideration when data are acquired manually (contour delineation, image matching). With the protocol described here, intra-operator variability was small for measurements of patellar translations and sagittal rotation (Rz). Greater intra-operator variability occurred for coronal and axial rotation, a finding ascribable to challenges in delineating the patellar contours and in achieving image matching at 45° and 60° of flexion, related to overlap of the femur and to difficulties in identifying the apex of the patella. The difficulty of image matching for coronal rotation on the antero-posterior view increases with the degree of patellar flexion, and this variability influences the reproducibility associated with the other rotations. On the lateral view also, the absence of identifiable landmarks is a hindrance. Analyses of patellar tracking in vivo should therefore be limited to the beginning of knee flexion (0°–45°), as uncertainty may increase with further flexion. In patients with patellofemoral disorders, the kinematic abnormalities occur in the 0°–30° range of flexion and may exhibit relative differences (about 5° of tilt on average in PFPS) [4,27].

Using biplanar contours with no preliminary imaging creates methodological challenges related to the small size of the patella and absence of reliable patellar landmarks. Mean error in 3D geometry was less than 1 mm for the four patellae studied. This 3D geometry is of the utmost importance, as it governs the description of the reference patellar model involving determination of the regions of interest (medial facet, lateral facet, and apex). It also influences the accuracy and reproducibility of the protocol [9]: as the reliability of the 3D geometry decreases, the uncertainties regarding its sequential position increase. In patients with marked morphological abnormalities (chiefly dysplasia), the effect of patellar geometry on the system of coordinates should be taken into account. In this study, none of the specimens exhibited patellar dysplasia. In addition, the errors in geometry were greatest at the lateral edge, whereas hypoplasia affects the medial side of the patella. Thus, a more specific study is needed to assess uncertainties related to patellar dysplasia.

This in vitro validation protocol has several limitations. The first is the small number of specimens studied with each validation approach, with the use of both limbs of each of 4 individuals. The variability in sequential profiles may be ascribable to variability across specimens related to differences in morphology or kinematics. The two limbs from the same individual tend to be anatomically similar [28], and morphological variations of the distal femur chiefly involve the anterior part of the femoral condyles and the trochlear contours [14,22]. We therefore used posterior condyle morphology as the reference for constructing the femoral anatomical landmark. Regarding patellar sources of variability, bilateral evaluations suggest that patellar kinematics and geometry may not be symmetrical [29]. The largest differences between the right and left sides were 2.14° for rotation, 0.46° for tilt, and 1.30 mm for shift, and none of the differences was statistically significant [2]. The second limitation is the use of an in vitro model. Only passive knee flexion can be replicated with such a model, which therefore provides only a rough approximation of the in vivo dynamic effects of active patellar stabilisers [22,30].

However, we developed a new sequential approach to the in vitro assessment of patellofemoral tracking, based on innovative 3D reconstruction methods and on an imaging system that is proving useful in an ever-increasing range of situations. Furthermore, the absence of preliminary imaging (CT or magnetic resonance imaging) and the low-radiation exposure support the feasibility of this protocol in vivo. A detailed description of the reconstruction and image matching steps should allow any clinician or technician trained in biplanar reconstruction to carry out this protocol, as is already the case for other functional evaluations and for EOS measurements. Finally, this protocol may find many clinical applications, including defining patellofemoral kinematics of the asymptomatic knee, evaluating differences in position in a patient with patellofemoral instability, and quantitating the post-operative effect of surgery done to correct patellar kinematics during weight bearing.

Disclosure of interest

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The authors P.T, B.E and F.C declare that they have no competing interest.

WS: grant awarded by the Fondation ParisTech during the conduct of the study; co-inventor of the EOS system, with no personal financial benefits.

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