

In vitro analysis of patellar kinematics: validation of an opto-electronic cinematic analysis protocol

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Abstract Opto-electronic cinematic analysis has already proven useful in the investigation of patients with a knee replacement; however, neither patellar tracking nor the various positional parameters relevant to instability such as patellar tilt and/or patellar shift have ever been specifically evaluated using this type of system. The aim of this research was to validate the relevance of this type of cinematic analysis in order to use it in the evaluation of the main factors underlying patellar instability. Six fresh-frozen anatomical specimens were studied. The data were acquired using the Motion Analysis[®] system. Statistical analysis reveals a good reproducibility of measurements. Our protocol based on an opto-electronic acquisition system has an accuracy of 0.23 mm for shift and of 0.4° for rotation, which is calculated by integrating the various

experimental parameters and instrumental features specific to the Motion Analysis[®] system. The results are consistent with published results which further attests to the validity and the efficacy of the protocol and encourages us that this protocol is suitable for the in vitro study of patellar kinematics.

Keywords Patellar tracking · Opto-electronic · Patellar instability · Patellar tilt

Introduction

Patellar tracking is an indispensable parameter when it comes to the assessment of femoro-patellar problems, and it is of particular importance in the pre- and post-operative evaluation of patellar instability. Various in vitro and in vivo systems have been described [1, 9, 14–17], but all have their own limitations leading to approximations in the analysis of patellar tracking, in terms of both accuracy and exhaustivity. Opto-electronic cinematic analysis of the knee joint has already proven useful in the investigation of patients with a knee replacement [11], although neither patellar tracking nor the various positional parameters relevant to instability, such as patellar tilt and/or patellar shift have ever been specifically evaluated using this type of system. In order to investigate the various factors involved in patellar stability, the authors developed an experimental set-up for the in vitro cinematic analysis of patellar tracking. The aim of this research was to validate the relevance of this type of cinematic analysis by reviewing its strong points and limitations and to demonstrate its place in the future evaluation of the main factors underlying patellar instability.

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Materials and methods

Experimental set-up

Six fresh-frozen anatomical specimens were studied. They had been taken from subjects with a median age of 72 [range 65–82] years. Each specimen included all the bones of the lower limb together with all associated tendons, muscles, fasciae and ligaments. None of the subjects had been physically injured, and none of the specimens showed signs of advanced degeneration. The specimens were thawed out at room temperature for 24 h.

The set-up for this experiment consisted of a femur/tibia/patella unit. The femur was fixed onto a rigid support by two screws through the bone which blocked any movement. The femoro-tibial joint was free and unconstrained, so the set-up allowed full amplitudes of movement at this joint from hyperextension to 90° of knee flexion. The quadriceps tendon was located and prepared by false spinning before a 10 Newton load was imposed in the direction of the femur's anatomical axis. All three bone segments were marked so that relative movements of the

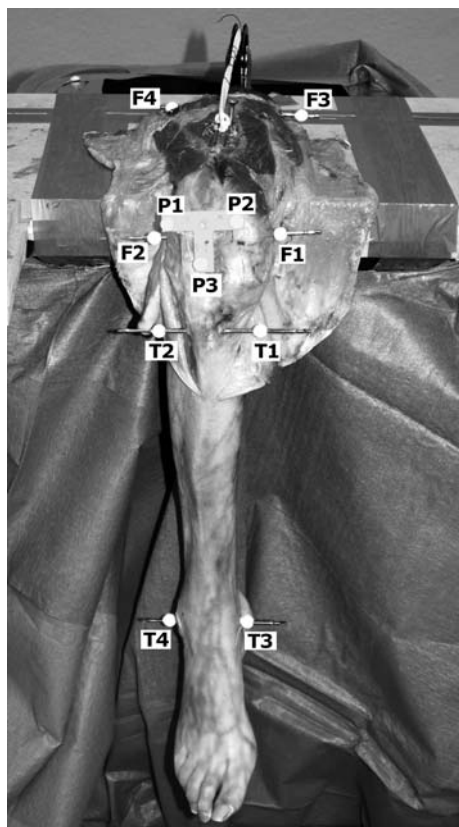


Fig. 1 All three bone segments were marked so that relative movements of the three segments could be monitored with respect to each other and in the six degrees of freedom

three segments could be monitored with respect to each other and in the six degrees of freedom (Fig. 1).

The skin was stripped from the anterior face of the knee in order to position three opto-electronic markers (P1, P2, P3) on the patella by fixation onto a rigid support continuous with the latter. The three markers defined the frontal plane of the patella. In the femur, a trans-epicondylar pin was inserted in the direction of the bicondylar axis, and an internal and an external marker were fixed onto this pin equidistant from the femoral corticals. A second pin was positioned in the bone at the level of the thigh, in the same direction as the first. An internal and an external marker (F3, F4) were fixed onto this second pin (also equidistant from the femoral corticals) to reconstruct a virtual marker (F5) equidistant from F3 and F4. F1, F2 and F5 defined the femur's frontal plane. The femur's anatomical axis was given by these markers.

A pin was inserted through the upper part of the tibia, parallel to this bone's frontal plane and also to the tibial plateau. An internal and an external marker (T1, T2) were positioned on this pin.

A second pin was positioned, colinear to the first, in the lower part of the tibia. Two markers, one internal and one external (T3, T4), were positioned on this. These two markers allowed the reconstruction of a virtual marker (T5) equidistant from T3 and T4. T1, T2 and T5 defined the frontal plane of the tibia. The tibia anatomical axis was given by these markers.

Definition of the reference and data acquisition landmarks

The data were acquired using the Motion Analysis[®] system, a cinematic analysis system with three-dimensional capture. Six cameras were placed and followed the movements of the reflective markers at 200 Hz. The work volume defined for the experiment was 1.8 m/0.8 m/1.2 m. The system was used by combining a restricted calibration volume, high Resolution cameras and markers interdependent from the bone. The calibration process is automatically performed in two stages: a static then a dynamic stage. At the end of the calibration process, the software gives the mean error for the position of a point in the defined work volume and for an angle delimited by three sensors. Therefore, the mean precision of the motion system was ± 0.23 mm and $\pm 0.4^\circ$ [3, 6]. The biomechanical landmarks used for each bone segment (which indicated the movements of each) respected biomechanical standards (Fig. 2) and thus fulfilled joint coordinate system (JCS) criteria as defined by Grood and Suntay [7].

For each knee, the movement during acquisition was identical; the starting point was the reference point of full extension of the joint, and the movement corresponded to

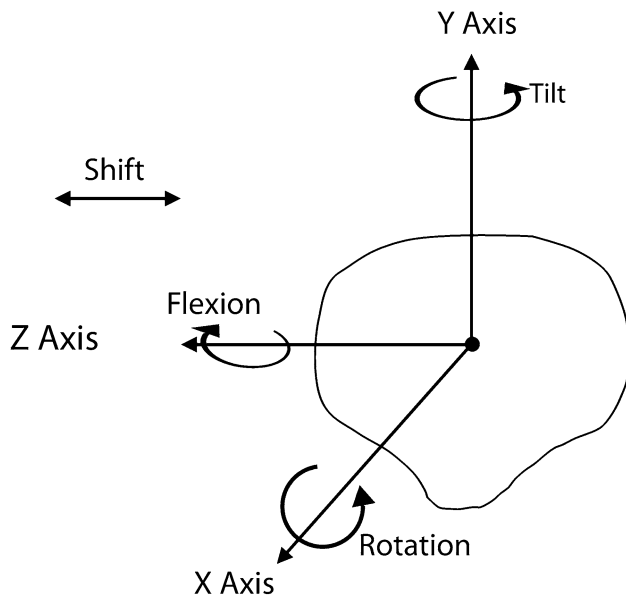


Fig. 2 Patella's six degrees of freedom

flexion to an amplitude of 90° . This non-automated movement was induced manually without constraint for about 1-s of flexion, with a 1-s return to the reference position. Each acquisition covered five full flexion/extension cycles.

The raw data were processed by Motion Analysis[®] with 12 Hz Butterworth filtering to remove background noise. Then, using Skeleton Builder[®], data were extracted, and the bone segments could be reconstructed with the previously defined reference axes. The data were delateralised so that right- and left-hand sides could be compared, and then these data were sub-sampled for each degree of knee flexion. The sampling unit was, therefore, 1° of flexion of the knee.

All these measurements were recorded, but the analysis focused on the patella's six degrees of freedom (Fig. 2):

- The patella's external/internal tilt (defined as the patellar rotation around the Y_p axis).
- The patella's external/internal shift (defined as the patellar shift according to the Z_p axis).
- Patellar rotation (patellar varus/valgus) (defined as the patellar rotation around the X_p axis).
- Anterior/posterior patellar translation (defined as the patellar shift according to the X_p axis).
- Patellar flexion (defined as the patellar rotation around the Z_p axis).
- Proximal/distal patellar translation (defined as the patellar shift according to the Y_p axis).

In order to make interpretation easier and facilitate comparison with published findings, all these parameters were assigned the value 0 at 0° of flexion of the knee, i.e. full extension.

Statistical analysis

The statistical analysis focused on the reproducibility of measurements during acquisition (five cycles) by one-factor analysis of variance (ANOVA with repeated measurements). When the analysis of variance detected a significant difference, post hoc Duncan, Bonferroni and Tukey tests (SPSS software; SPSS, Chicago, Ill) were used to identify non-homogenous cycles. The P value for statistical significance was set to ≤ 0.05 . Homogenous cycles were averaged to generate a standard cycle for each knee. Intraclass correlation coefficients (ICC) [13] with 95% confidence intervals were calculated to assess intraobserver agreement.

Results

Reproducibility

For each knee, five successive acquisition cycles were recorded. Reproducibility was statistically analysed as described above using analysis of variance, post hoc tests and calculating ICC. Of the six knees analysed, the various post hoc tests showed that there is a maximum of one non-homogenous cycle out of the five recorded on each knee. This non-homogenous cycle was always the first or the last of the acquired series. Thus, the mean standard cycle for each knee was defined by either four or five selected cycles. The ICC for the 6 knees and for each of six degrees of freedom were always ≥ 0.98 . Figure 3 illustrate this reproducibility in measurements across the five acquisitions (five cycles) for each knee.

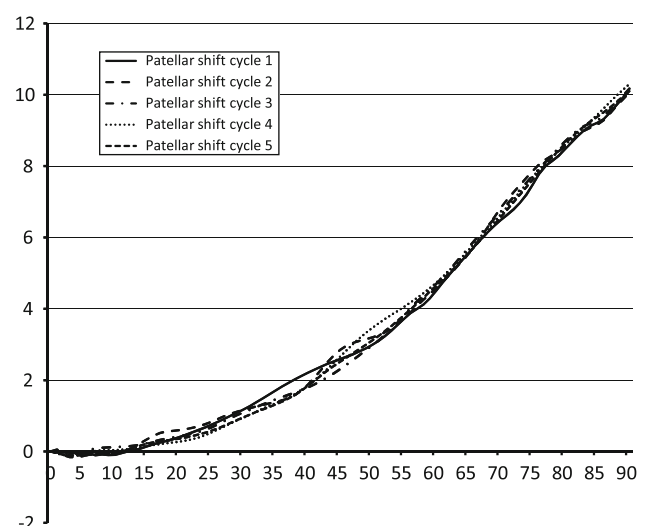


Fig. 3 Example illustrating the reproducibility of measurements in the course of five acquisitions on knee no. 4 for patellar shift (according to the Z_p axis)

Kinematics of the healthy knee

Patellar tilt was almost zero through the first 45° of knee flexion. From 45° on, the patella underwent external tilting which became accentuated towards 90° flexion, reaching a maximum of $-3.7 \pm 8.9^\circ$ with respect to the reference position (Fig. 4).

The patella progressively shifted externally to reach, at 90° flexion, a maximum shift of 3.18 ± 9.67 mm with respect to the reference position (Fig. 5).

Through the first 30° of knee flexion, the patella showed medial rotation, reaching a maximum amplitude of $0.8 \pm 4.6^\circ$ at 15° of flexion; there was then a switch to lateral rotation, reaching a maximum of $1.45 \pm 6.5^\circ$ at 90° flexion (Fig. 6).

Concerning the findings for antero-posterior patellar translation (patellar shift according to the Xp axis), patellar flexion (patellar rotation around the Zp axis) and proximodistal patellar translation (patellar shift according to the Yp axis), their values rise progressively out to 90° knee flexion. They correlated strongly with both each other and the degree of knee flexion ($R = 0.98$).

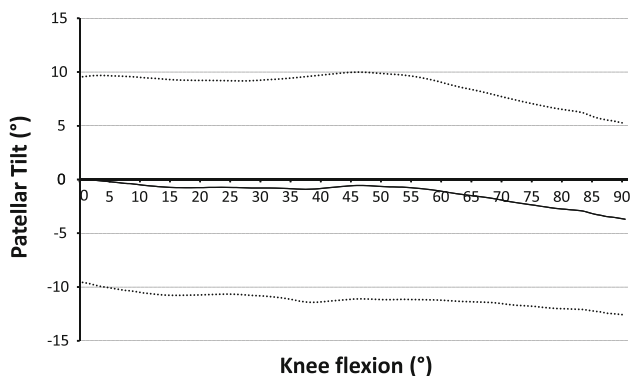


Fig. 4 Changes in patellar tilt during knee flexion (mean of six knees)

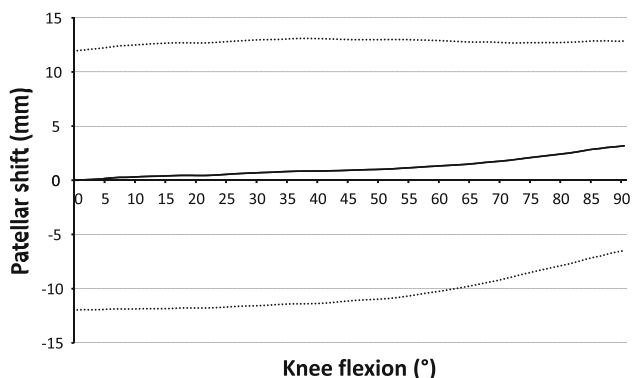


Fig. 5 Changes in patellar shift during knee flexion (mean of six knees)

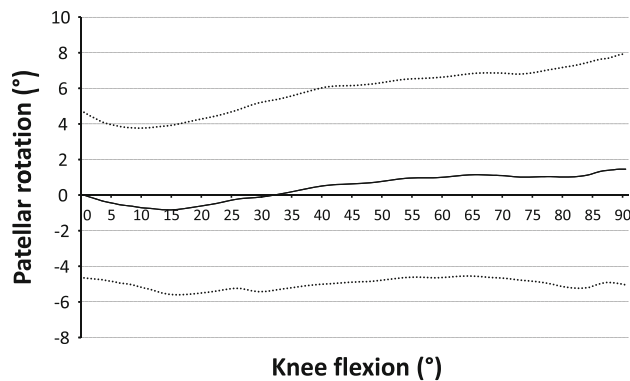


Fig. 6 Changes in patellar rotation during knee flexion (mean of six knees)

Discussion

The most important findings of the present protocol were first, the reproducibility of the measurements; and secondly, the remarkable accuracy of the experimental system. Statistical analysis of the reproducibility of measurements between different cycles on a single knee reveals a maximum of no more than one non-homogenous cycle in five. This proves that the acquisition system is reliable, especially given that the same reproducibility was revealed in the statistical analyses for all the knees tested. This idea of reproducible measurement is only rarely reported in the literature [12], which is regrettable because it is a fundamental parameter in any cinematic protocol designed to address patellar kinematics.

Katchburian et al. [12] emphasises the need for high resolution in any system used to analyse patellar kinematics, especially if the focus is on pathologic situations (clinical or experimental instability). During data recording, different sources of error affected the accuracy of the coordinate of the sensors. Two types of error were detected: experimental errors in one hand and instrumental errors in the other hand. The value of the experimental error is the only one that can be controlled during protocol initiation. It depends on the size of the work volume, sensors positioning in this volume, the type of sensors fixation on the subject and cameras configuration. Therefore, by working on a volume restricted to the maximum (1.8 m/0.8 m/1.2 m), by choosing a bone fixation for the sensors and using 6 HD cameras, it was possible to markedly reduce the incidence of systematic experimental error [3, 6]. The various articles in the literature of this field [1, 9, 15, 17] report an accuracy of 0.05–1.5 mm for shift and of 0.03–2° for rotation; this protocol based on an opto-electronic acquisition system has an accuracy of 0.23 mm for shift and of 0.4° for rotation, i.e. it is highly accurate.

Many protocols for the analysis of patellar tracking in vitro and in vivo such as those based on radiologic acquisition systems [2] or fluoroscopy [8] do not allow genuine dynamic analysis but merely yield sequential statistical analyses at a specific amplitude of knee flexion. Brossmann et al. [4] explains that, because of slippage of the patella in the trochlea and its spontaneous tendency to recentre itself in the base of the trochlea, a sequential statistical analysis cannot accurately elucidate this dynamic phenomenon. Dynamic evaluation in vitro, as is made possible by our opto-electronic acquisition system, is therefore closer to reality.

To validate this protocol, all of the patella's six degrees of freedom were studied, this being indispensable for validation of the reproducibility and accuracy of measurements. Three parameters (patellar tilt, patellar shift, patellar rotation) are independent of the degree of knee flexion and are qualified as major; the other three parameters (patellar flexion, anterior patellar shift, distal patellar shift) correlate strongly with the degree of knee flexion and are qualified as minor. The results obtained using this in vitro system for the investigation into patellar kinematics are perfectly consistent with published in vitro results [1, 5, 9, 14, 16, 17], which further attests to the validity of the protocol and the efficacy of this type of acquisition system.

It was used an unique quadriceps load of 10 Newtons orientated in the direction of the axis of the femur, thereby reproducing the action of the rectus femoris, although this does not perfectly mimic the dynamic effect of the femoral quadriceps in vivo [15], and it was the main limitation of the procedure. In order to reproduce the specific action of the four assemblies of the femoral quadriceps in vivo, some experts use four separate loads [16]; however, this still represents a gross approximation since, in vivo, the force exerted by each of the four quadriceps assemblies varies through the amplitude of knee flexion, and particularly depends on the type of contraction (concentric, eccentric, isometric). There is, therefore, no real consensus about quadriceps load and its orientation [5], and some experts [9, 10] recommend using a single, unidirectional load which is easier to set up and which may cut down the risk of error in manipulations and analysis.

Numerous clinical implications are reported. In vitro, this protocol enables a thorough study of patellar kinematic under physiological conditions or under stress, prior to or after section of anatomic elements (MPFL for instance), prior to or after medialization of the anterior tibial tubercle, and allows the study and classification of the different factors of patellar instability. In vivo, this protocol enables the study of patellar tilt and medial patellar shift correction during the surgical management of patellar instability.

Conclusion

The main aim of this set of experiments was to validate a method for the investigation into patellar kinematics. The protocol used is reproducible and gives extremely accurate results. Although all are not in agreement about using a single, unidirectional load, the concordance of these results with those in the literature encourages us that this protocol is suitable for the in vitro study of patellar kinematics in experimental situations (experimental instability for instance). Moreover, as described above, this protocol, when performed intraoperatively during patellar instability surgery (such as the reconstruction of the medial femoropatellar ligament) allows good control of the different patellar parameters, such as patellar tilt, patellar shift, which contribute to patellar instability.

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