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A single measure of patellar kinematics is an inadequate surrogate marker for patterns of three-dimensional kinematics in healthy knees

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ABSTRACT

Patellofemoral disorders, such as osteoarthritis and patellofemoral pain, are thought to be associated with abnormal patellar kinematics. However, assessments of three-dimensional patellar kinematics are time consuming and expensive. The aim of this study was to determine whether a single static measure of three-dimensional patellar kinematics provides a surrogate marker for three-dimensional patellar kinematics over a range of flexion angles. We assessed three-dimensional patellar kinematics (flexion, tilt and spin; lateral, anterior and proximal translation) at sequential static angles through approximately 45° of loaded knee flexion in 40 normal subjects using a validated, MRI-based method. The surrogate marker was defined as the static measure at 30° of knee flexion and the pattern of kinematics was defined as the slope of the linear best fit line of each subject's kinematic data. A regression model was used to examine the relationship between the surrogate marker and pattern of kinematics. The surrogate marker predicted 26% of the variance in pattern of patellar flexion ($p<0.001$), 27% of the variance in pattern of patellar spin ($p=0.003$), 11% of the variance in pattern of proximal translation ($p=0.037$) and 39% of the variance in pattern of anterior translation ($p<0.001$). No relationships were seen between the surrogate marker and tilt or lateral translation. The results suggest that a single measure of patellar parameters at 30° knee flexion is an inadequate surrogate marker of three-dimensional patellar kinematics; therefore, a complete assessment of patellar kinematics, over a range of knee flexion angles, is preferable to adequately assess patterns of patellar kinematics.

1. Introduction

Disorders of the patellofemoral joint are prevalent in the population, with the patellofemoral joint involved in half of all knee osteoarthritis cases [1] and patellofemoral pain syndrome affecting 25% of the population [2–4]. The patella moves continuously in three dimensions with knee flexion. Characterizing this motion is technically difficult and patterns of kinematics have been shown to vary considerably depending on the method of assessment employed [5]. Abnormal patellar kinematics is thought to contribute to the onset and progression of patellofemoral disorders. One possible reason for this is that abnormal kinematics disrupts the pattern of force transmission through the joint. Since patellar kinematics is difficult to measure, particularly *in vivo*, the relationship between patellar kinematics and disease onset and progression is not well understood.

Patellar position and orientation have been assessed in two dimensions (axial plane) at a single angle or sequential angles of knee flexion using radiographs, computed tomography (CT) or magnetic resonance imaging (MRI) both statically [6–9] and dynamically [10–13]. Parameters such as congruence angle [7], lateral displacement and lateral angle (tilt) [6] are the most common measures of patellar position in the axial plane. These parameters are often used in research studies to quantify malalignment in patients with patellofemoral disorders. For example, a recent study found that static patellar malalignment (displacement and tilt), measured radiographically at 30–40° of weightbearing flexion, was associated with radiographic patellofemoral osteoarthritis progression [14,15]. Another study, using a dynamic MRI-based assessment from 0° to 60° of flexion, found greater lateral patellar translation and greater lateral patellar tilt in subjects with patellofemoral pain as compared to controls [11]. The two-dimensional methods of analysis have been successful at describing malalignment in the patient population; however there are four other components of motion which cannot be described using these methods.

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In an effort to capture all components of patellar position, patellar kinematics has also been assessed in three dimensions using MRI-based methods [16–19]. Some groups have employed methods in which three-dimensional position and orientation of the patella are assessed in sequential static positions over a range of knee flexion angles [16,17]. During the assessment, the subjects simulate weightbearing by pressing against a plate with a prescribed load, requiring the activation of the quadriceps muscles (and to a lesser extent, the hamstring muscles) to maintain the load and stabilize the leg. These methods are limited because measurements are not made during continuous knee flexion/extension. Another approach is to assess patellar kinematics dynamically using cine phase contrast MRI [18,19]. The dynamic method has the advantage of assessing kinematics during continuous knee flexion/extension but is limited because the knee is loaded only by the weight of the shank, with the exception of one study in which extension was resisted by a 34 N weight [18]. Differences between three-dimensional loaded sequential static and dynamic methods have not been quantified, however differences were found between the unloaded sequential static and dynamic motions in two dimensions [10]. The three-dimensional methods have been used to study patients with patellofemoral disorders. Differences in three-dimensional kinematic parameters were found between subjects with varus and valgus tibiofemoral malalignment and knee osteoarthritis [20] and between patients with clinical signs of malalignment and patellofemoral pain and matched controls [21,22]. The results of studies to date suggest that additional, useful information is obtained by doing three-dimensional assessments, however these methods require substantially more imaging and analysis time than two-dimensional methods. As such, their application in large research studies or as diagnostic or treatment planning tools may not be feasible.

It is not clear whether the additional imaging and analysis time required to measure three-dimensional patellar kinematics over a range of knee flexion angles is essential to characterize the pattern of kinematics of any given subject. It is possible that one measurement of position and orientation at one angle of knee flexion provides an adequate surrogate marker of patellar kinematics through the range of knee flexion. Such a surrogate marker would be clinically very useful. In this study, we answered the question: Can a single static measure of three-dimensional patellar kinematics provide a surrogate marker for three-dimensional patellar kinematics over a range of flexion angles?

2. Methods

We selected 40 asymptomatic subjects from a database of participants with available three-dimensional patellar kinematic data. All subjects had undergone assessments of three-dimensional patellar kinematics using a sequential static position MRI-based method [16,23] while participating in previous studies conducted by our group [21,24,25]. The subjects had no history of knee injury, pathology or pain. Subjects who could not undergo MRI were excluded from their respective studies. Institutional ethical approval was obtained and all participants gave informed consent.

For each subject, one high-resolution and five low-resolution MR scans, required to assess three-dimensional patellar kinematics, were acquired using a 1.5 T scanner (Genesis-Signa, General Electric, Waukesha, USA) or a 3.0 T scanner (Intera, Phillips, Eindhoven, Netherlands). The high-resolution sagittal MR scan was acquired with the subject's leg in a relaxed position using a T1-weighted spin echo sequence (Table 1). Five fast, low-resolution sagittal MR scans were then acquired at sequential static positions of loaded knee flexion between full extension and 45°. For each of these scans, the participants loaded the knee by pushing against a foot plate on a custom-designed, MR compatible rig to a measured load of between 80 and 152 N while lying supine (Fig. 1). This load was chosen because it was the approximate maximum load that subjects with pathologies could tolerate and therefore normal subjects were tested at the same load for comparison purposes in other studies. The fast, low-resolution images were also acquired with a T1-weighted spin echo sequence (Table 1). There was a rest of approximately 5 min between each loaded, low-resolution scan. The time required for screening and image acquisition, including positioning and imaging time, was approximately 1 h per subject. The MRI data collection was carried in accordance with a standardized protocol by one of four trained experimenters (NM, EM, BM or KH).

Table 1
Magnetic resonance imaging parameters for the high-resolution and low-resolution images required to assess three-dimensional patellar kinematics.

Parameter	High-resolution	Low-resolution
In-plane resolution	0.625 × 0.625 mm	1.25 × 1.25 mm
Slice thickness	2 mm	2 mm
Slice spacing	2 mm	7 mm
Repetition time (TR)	750 ms	283 ms
Echo time (TE)	21 ms	13 ms
Flip angle	90°	90°
Field of view	320 mm	320 mm
Matrix size	512 × 512	256 × 256
Scan time	10 min 20 s	40 s

Three-dimensional patellar kinematics was determined from the acquired scans using our method, which has been described previously [16]. Briefly, the femur, tibia and patella were manually segmented from both the high- and low-resolution images in a slice-by-slice manner using Analyze software (Analyze Direct, Overland Park, USA). Geometric bone models were created from the segmented data obtained from the high-resolution MR image and an anatomical coordinate system was assigned to each bone (Table 2) [16]. Five sets of bone contours were extracted from the segmented data obtained from the fast, low-resolution MR images. The geometric models were then registered to each set of contours with an Iterative Closest Points algorithm [26] using custom software written in Matlab (The MathWorks, Natick, USA). The three-dimensional position and attitude of the patella relative to the femur was described using a modified Joint Coordinate System, which described rotations about an axis fixed in the femur, an axis fixed in the patella, and a floating axis [16,27]. The kinematic parameters assessed were patellar flexion, tilt, spin (adduction/abduction), proximal translation, lateral translation and anterior translation (Fig. 2). The data analysis was carried out in accordance with a standardized protocol by one of three trained experimenters (NM, EM or BM).

The method has been rigorously validated for both accuracy and repeatability. The accuracy of the method, relative to a reference standard (Roentgen stereophotogrammetric analysis), is less than 1.02° for spin and tilt and less than 0.88 mm for translations [16]. The inter-subject repeatability of the method (expressed as the mean standard

Fig. 1. Subject loading the knee by pushing on the foot plate of the MR compatible loading rig.

Table 2
Anatomical coordinate systems origins and directions.

Coordinate system	Origin	Positive directions
Patella	Most posterior point on patellar mid-slice.	Proximal, lateral, anterior
Femur	Most proximal point of the trochlear notch.	Proximal, lateral, anterior
Tibia	Most superior point of the medial tibial eminence.	Proximal, lateral, anterior

deviation of spline fits assessed at 1° increments through knee flexion) is less than 1.04° for spin and tilt and less than 0.81 mm for translations (3 subjects, 4 trials each) [23]. The inter-experimenter repeatability of the method is less than 2.14° for spin and tilt and less than 0.68 mm for translations (3 experimenters, 1 randomly selected common dataset) although patterns were consistent between subjects [23]. Since only patterns were examined in the current study, the inter-experimenter repeatability is likely better than the quoted values.

We used the results from our kinematic analysis to determine whether a surrogate marker (patellar alignment at one position) could predict patterns of three-dimensional patellar kinematics. We defined the surrogate marker as the static measurement of three-dimensional patellar alignment at 30° of knee flexion. Therefore, there were six surrogate markers, one corresponding to each patellar parameter (Fig. 2). This knee flexion angle was chosen for the surrogate marker because it is commonly used to obtain skyline radiographs of the patella from which patellar alignment is measured [28], data were available at

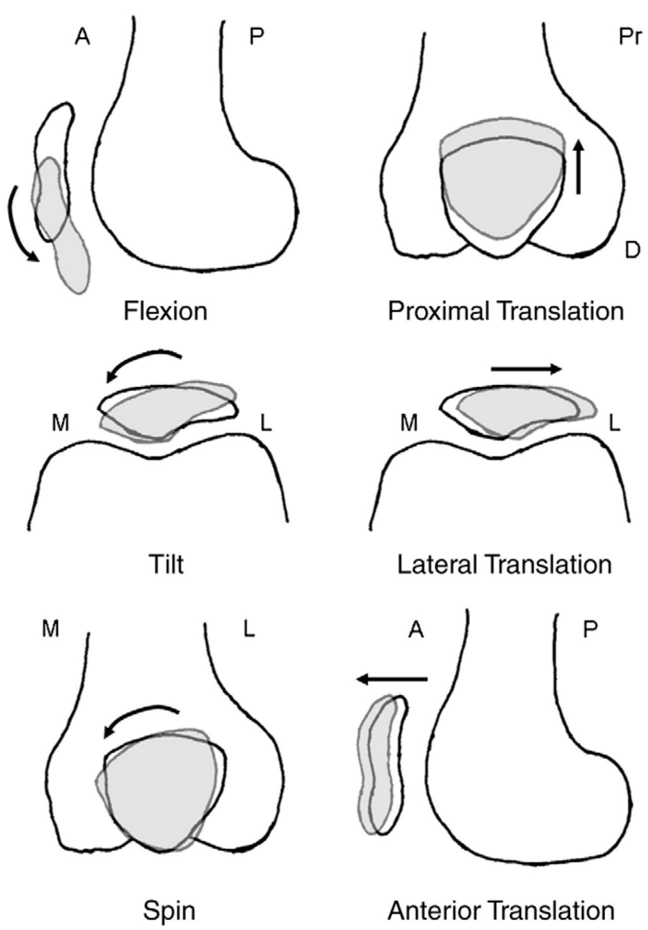

Fig. 2. Three-dimensional patellar kinematic parameters: three rotations (flexion, tilt and spin) and three translations (proximal, lateral and anterior). Arrowheads indicate the positive direction and M = medial, L = lateral, A = anterior, P = posterior, Pr = proximal, D = distal.

this angle in all subjects and it was in the mid-range of the flexion angles assessed. To define the pattern of three-dimensional patellar kinematics, we fit a linear least-squares line to the graph of kinematic parameter versus knee flexion for each subject. This yielded 6 lines per subject corresponding to the 6 patellar kinematic parameters. Kinematic pattern was defined as the slope of the least-squares fit line, which described the rate and direction of change of the kinematic parameter with knee flexion. We determined whether the surrogate marker could predict patterns of three-dimensional patellar kinematic parameters using a regression model. Quadratic terms were included in the model when significant. To assess the fit of these models we used the coefficient of determination. All statistical analysis was carried out using Stata (StataCorp LP, College Station, TX, USA).

3. Results

Forty subjects (29 male, 11 female, mean age 28.6 years (SD 8.7 years)) were selected from the database. Thirty subjects were originally recruited from a military population [21,24] and ten were originally recruited from a university community [25]. The mean knee flexion angle for the surrogate marker was 28.7° (SD 3.2°).

Using regression models, we found statistically significant relationships of the single measure at 30° knee flexion (surrogate marker) with the patellar pattern from full extension to 45° knee flexion for four of the six parameters measured, including patellar flexion, proximal translation, spin and anterior translation. We found no statistically significant relationship of the surrogate marker with the patellar pattern for patellar tilt or lateral translation.

3.1. Patellar flexion

A linear regression model showed that patellar flexion at 30° knee flexion predicted 26% of the variance in the pattern of patellar flexion from full extension to 45° of knee flexion ($p<0.001$). The model showed that when the patellae were in a greater angle of flexion at 30° of knee flexion, they flexed at a greater rate over the range of knee flexion (Fig. 3).

3.2. Patellar tilt

There was no relationship between the patellar tilt at 30° of knee flexion and pattern of patellar tilt over the range of knee flexion ($R^2=0.00$, $p=0.867$) (Fig. 3).

3.3. Patellar spin

Using a quadratic regression model, we found that patellar spin at 30° of knee flexion predicted 27% of the variance in the pattern of patellar spin over the range of knee flexion ($p=0.003$). The model for patellar spin showed that when the surrogate marker was less than 2° of internal spin, the patellae spun internally at a relatively constant rate of 0.1° per degree of knee flexion, but when the surrogate marker was greater than 2° of internal spin, the rate of internal spin with knee flexion increased (Fig. 3).

3.4. Proximal translation

A linear regression model showed that proximal patellar translation at 30° knee flexion predicted 11% of the variance in the pattern of proximal patellar translation over the range of knee flexion ($p=0.037$). The model showed that when the patellae were in a more proximal position at 30° of knee flexion, they translated distally at a greater rate over the range of knee flexion (Fig. 4).

3.5. Lateral translation

There was no relationship between lateral translation at 30° of knee flexion and pattern of lateral translation over the range of knee flexion ($R^2=0.00$, $p=0.698$) (Fig. 4).

3.6. Anterior translation

Using a quadratic regression model, we found that anterior translation at 30° of knee flexion predicted 39% of the variance in the pattern of anterior translation over the range of knee flexion ($p<0.001$). The model for anterior translation showed that when the surrogate marker was in a more anterior position, the patellae translated posteriorly at a lesser rate (Fig. 4).

4. Discussion

We have shown that the surrogate markers of patellar measurements at 30° knee flexion described less than 39% of the variance in patterns of patellar flexion, spin, proximal translation and anterior

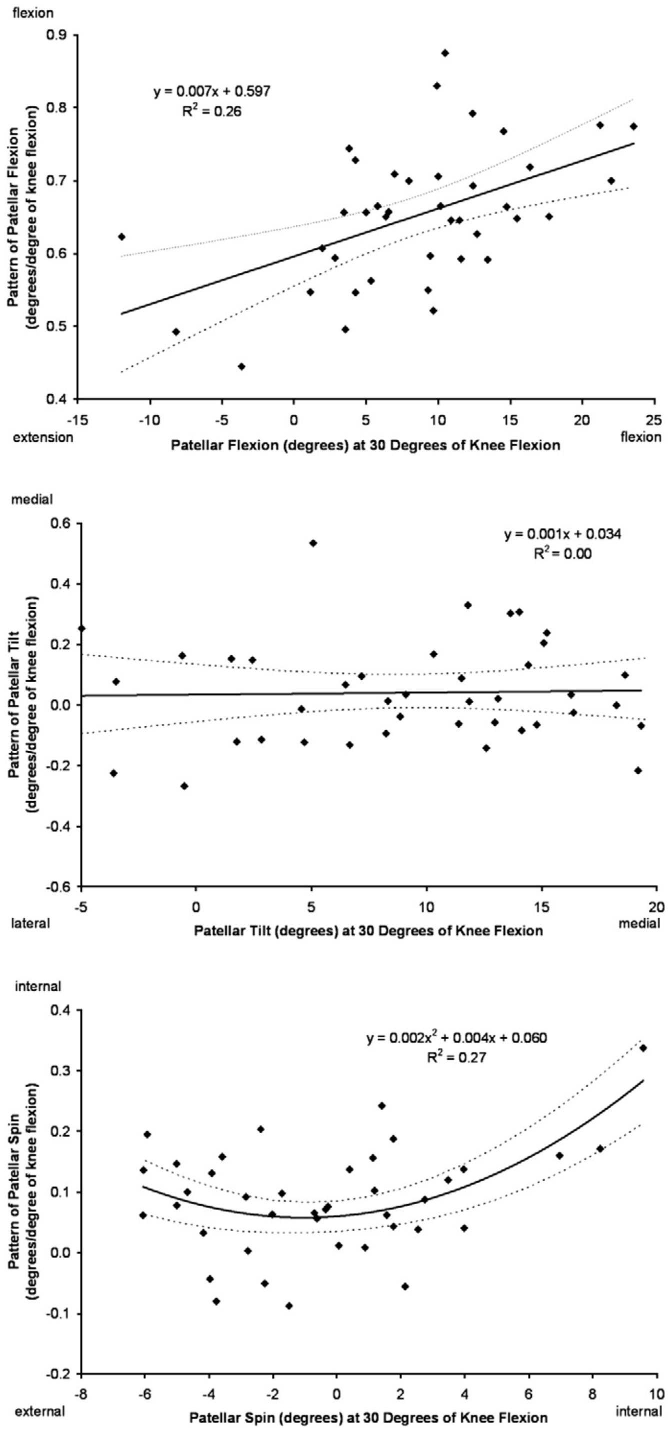

Fig. 3. Regression line fits describing the relationship between the surrogate marker and pattern of rotation (flexion, spin and tilt). The surrogate marker is the measurement of the patellar rotation at 30° of knee flexion for each individual. The pattern of patellar rotation is the slope of the linear least-squares fit line for each individual's values of patellar rotation versus knee flexion. A positive pattern indicates patellar flexion, internal spin or medial tilt and a negative pattern indicates patellar extension, external spin or lateral tilt. Dashed lines indicate the 95% confidence intervals.

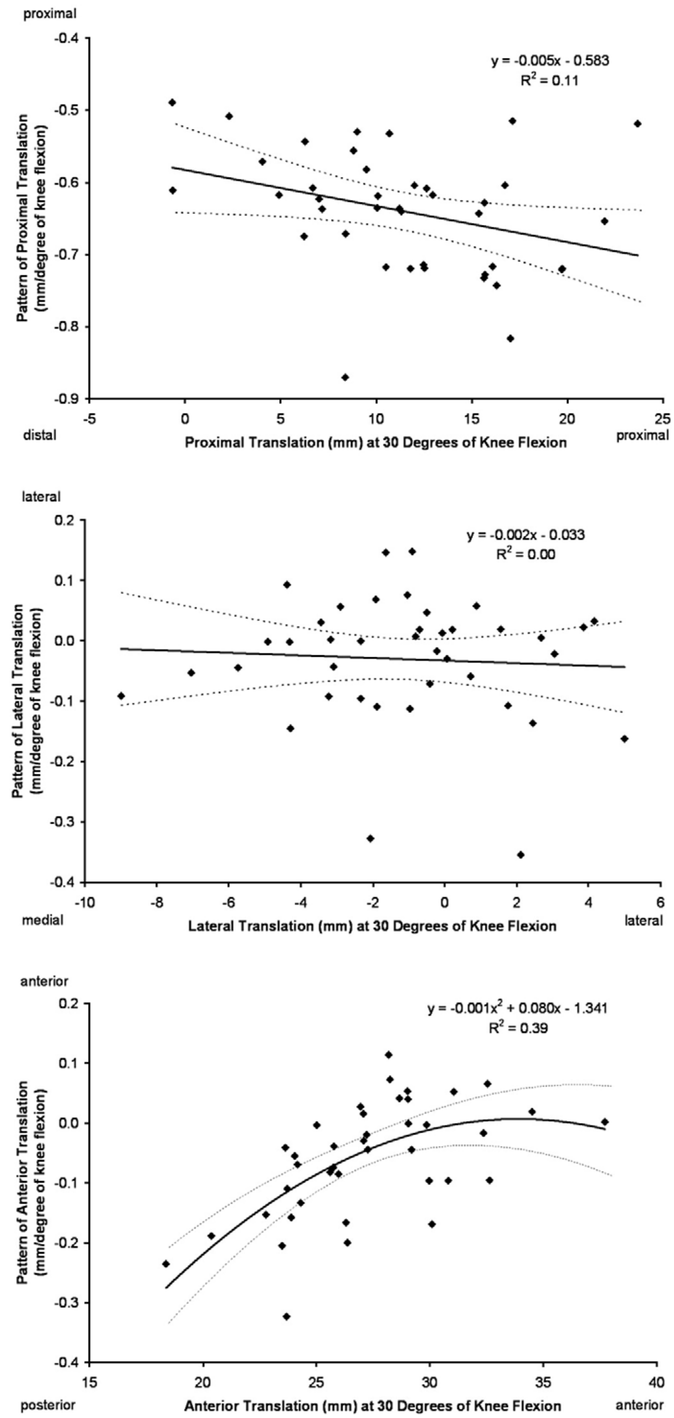

Fig. 4. Regression line fits describing the relationship between the surrogate marker and pattern of translation (proximal, lateral and anterior). The surrogate marker is the measurement of the translation at 30° of knee flexion for each individual. The pattern of translation is the slope of the linear least-squares fit line for each individual's values of translation versus knee flexion. A positive pattern indicates a proximal, lateral or anterior translation and a negative pattern indicates a distal, medial or posterior translation. Dashed lines indicate the 95% confidence intervals.

translation and did not describe patterns of patellar tilt or lateral translation. Since patterns of patellar tilt and lateral translation could not be adequately described by the surrogate markers and only a portion of the variance was described for other parameters, three-dimensional patellar kinematics should be optimally assessed over a range of knee flexion angles.

It is possible that the surrogate marker did not predict kinematic parameters because of the inter-individual differences inherent in three-dimensional patellar kinematic data, the particular angle chosen for the surrogate marker and the dependent variables used in the regression model. Large inter-individual differences, described as the standard deviation of the average slope (pattern), of up to 0.17° and 0.10 mm per degree of knee flexion were observed in this study and this is consistent with differences found previously in normal subjects using a dynamic method [29]. Even for parameters where a portion of the variance was predicted by the surrogate marker, many subjects did not follow the prevailing patterns. For example, in two subjects with an anterior patellar position of 24 mm at 30° of knee flexion (surrogate marker angle), the rate of anterior translation was −0.3 mm per degree of knee flexion in one subject, while it was −0.05 mm per degree of knee flexion in the other. Measuring patellar alignment at a different knee flexion angle may yield a more predictive surrogate marker, however, the angle chosen is consistent with clinical assessments of patellar malalignment made in two dimensions from a skyline radiograph. Our regression model assumed that patterns of three-dimensional patellar kinematics were dependent on only one measure of patellar position. In reality, kinematics is likely affected by soft tissue properties, bone geometry and muscle pull and attachment. A surrogate marker that includes these measures may be better at predicting patterns of patellar kinematics.

Interestingly, the surrogate marker did not predict patterns of patellar tilt or lateral translation, which are the parameters commonly studied in two-dimensional analyses in the axial plane. This finding may explain why alignment differences in patellar tilt and lateral translation were not observed between subjects with patellofemoral pain syndrome and normal subjects in radiographic studies at one angle of knee flexion in the axial plane [30]. However, it should also be noted that when these same groups and parameters were studied, using both a dynamic kinematic method in the axial plane [11] and a sequential static kinematic method in three dimensions [21], differences were observed between patients and normals. These contrasting findings suggest that it is important to assess kinematics over a range of knee flexion angles and that there may be differences in kinematics between the static and dynamic measures. Further, the findings of the current study are not surprising from a biomechanical point of view. Patterns of patellar tilt and lateral translation are influenced by muscle lines of action and soft tissue properties, in particular before the patella engages the trochlear groove (between 20 and 30° of knee flexion), and by bony geometry, after the patella engages the trochlear groove. Therefore, it is not unexpected that the surrogate marker did not adequately predict patterns over a range of flexion angles.

The overall patterns of three-dimensional patellar kinematics in normal subjects are similar to those reported by other groups using both sequential static [17] and dynamic [29] methods. Comparisons to the other sequential static method are most suitable in this case [17]. In that study, kinematics was assessed in 10 normal subjects between approximately −10° and 60° of knee flexion using random effects models. Patellar spin and anterior translation were modeled linearly with slope or pattern values of 0.07891° per degree of knee flexion and 0.05180 mm per degree of knee flexion, respectively, which are comparable to the mean patterns (slope) of kinematics found in our study. Patellar tilt, proximal translation and lateral translation were modeled quadratically. One possible reason for the difference in the model between this study and the present study (all linear at the subject level) was that most of the curvature was seen above 35°, in particular for tilt and lateral translation, and therefore may not have been captured by the data of the present study. Comparisons to measurements of kinematics made using the dynamic method are also useful [29] and in that study knee flexion angles from 1° to 44° were assessed and patterns were described as the mean value of the parameter for each knee flexion angle at 1° increments. By qualitative comparison, patterns of patellar flexion, spin, proximal translation and anterior translation are similar to those in the current study, while patterns of tilt and lateral translation are different.

The strengths of this study lie in the fact that our measurement method allows three-dimensional patellar kinematics to be characterized accurately and precisely [16,23]. Both the variability between subjects observed in this population and the changes in parameters through the range of flexion are large relative to the uncertainty in the measurements (accuracy and repeatability). To our knowledge, we are the first group to study the necessity for studying three-dimensional patellar kinematics over a range of flexion angles, which is important since the data collection and analysis procedure is time consuming and expensive. A limitation of this study is that it employed a sequential static method of assessing three-dimensional patellar kinematics, therefore the results may not necessarily be extended to assessments of three-dimensional patellar kinematics using dynamic methods. Another limitation is that we chose to describe patterns of kinematics with a linear fit because the physical interpretation of the slope and intercept of the linear model is easily comprehensible. Initially, quadratic models were also fit to each subject's kinematic data however no relationships were seen between the surrogate marker and pattern of slope or pattern of the quadratic coefficient for any parameter and therefore this analysis was not presented in the current study. The lack of relationship with the quadratic model may be due to the small number of data points being fit (five) and the lack of an existence of a clear quadratic pattern in the data. Finally, this study is an assessment of asymptomatic subjects and therefore the results cannot necessarily be extended to subjects with patellofemoral disorders.

We found that patellar measurements at 30° knee flexion described a portion of the variance in patterns of patellar flexion, spin, proximal translation and anterior translation but not in patterns of patellar tilt or lateral translation measured from full extension to 45° of knee flexion. Therefore, the surrogate marker does not capture the full pattern of three-dimensional patellar kinematics in asymptomatic adults. As a result, three-dimensional assessments of patellar kinematics over a range of knee flexion angles are preferable to evaluate patellar malalignment.

Conflict of interest statement

The authors have no conflicts to declare.

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