Patellofemoral instability (PFI) is one of the most disabling conditions in the knee, often affecting young individuals. Despite its not uncommon presentation, the underlying biomechanical features leading to this entity are not entirely understood. The suitability of classic physical examination manoeuvres and imaging tests is a matter of discussion among treating surgeons, and so are the findings provided by these means. A potential cause for this lack of consensus is the fact that, classically, the diagnostic approach for PFI has relied on statically obtained data. Many authors advocate for the study of this entity in a dynamic scenario, closer to the actual situation in which the instability episodes occur. In this literature review, we have compiled the available data from the last decades regarding dynamic evaluation methods for PFI and related conditions. Several categories are presented, grouping the related techniques and devices: physical examination, imaging modalities (ultrasound (US), magnetic resonance imaging (MRI), computed tomography (CT) and combined methods), arthroscopic evaluation, and others. In conclusion, although a vast number of quality studies are presented, in which comprehensive data about the biomechanics of the patellofemoral joint (PFJ) are described, this evidence has not yet reached clinical practice universally. Most of the data still stays in the research field and is seldom employed to assist a better understanding of the PFI cases and their ideal treatment targets.

Key words: Patellofemoral joint; Patellar dislocation; Muscle contraction; Movement; Diagnostic techniques; Procedures

Introduction

The patellofemoral joint (PFJ), despite its apparent minor contribution to knee biomechanics, remains to be one of the less understood components in the lower limb. As several musculoskeletal conditions associated with the PFJ (e.g. arthritis, anterior knee pain syndrome) are troublesome in terms of diagnosis and successful treatment, there is a growing interest on patellofemoral instability (PFI)1. PFI is defined as an abnormal patellar tracking in relation to the femoral trochlea as the knee extends/flexes. Subtle cases present with discomfort during prolonged knee flexion or at certain sporting activities. In more severe situations, PFI can lead to recurrent patellar dislocation, a disabling condition. The list of predisposing factors recognized for PFI is vast, including (but not limited to): patella alta, trochlear dysplasia, increased Q-angle, muscular imbalance, increased femoral-tibial torsion, genu valgus, hyperlaxity, and traumatic rupture of stabilizers such as the medial patellofemoral ligament2-5.

Proper diagnosis of PFI requires a thorough physical examination with comprehensive imaging studies. However, there is still no consensus on appropriate techniques and measurements for PFI diagnosis based on previous literature. As a result, surgeons are often left with selecting diagnostic procedures according to personal preference, rather than utilizing evidence-based practice6. Furthermore, and perhaps more concerning, is that surgical correction is generally...
planned according to the data obtained from these equivocal investigations.

Patellar dislocation episodes typically occur during movement, in early degrees of flexion, when constraint provided by the femoral trochlea is less effective. Only in extreme cases can the patella dislocate while the patient is resting in a sitting or recumbent position, but fortunately this is not a common presentation. However, most currently applied physical examination manoeuvres and imaging tests are performed in this scenario: a supine patient in a resting attitude, rather than exploring the knee in more instability-prone conditions. Does this mean we may be building the whole diagnostic and therapeutic process from an incorrect starting point? Singularly, the widely employed classic patellar height ratios (Insall-Salvati, modified Insall-Salvati, Blackburne-Peel, Caton-Deschamps) change significantly if obtained during weight bearing (WB)\(^7\) (Fig. 1).

Many authors advocate for the study of the PFJ from a dynamic point of view. Presumably, reproducing the situations in which instability occurs should provide clinicians with a more relevant assessment of patellar mechanics. This trend is not recent, and several related diagnostic papers have been published in the last decades, as will be presented in this review. Moreover, additional papers have pointed out the utility of dynamic techniques in the postoperative evaluation of PFI surgical correction results. The objective of this review is to summarize the available evidence of the dynamic assessment of PFI; can it be considered a clinical tool, or does it remain a field in need of further research?

Muhle et al. stated that ideal dynamic tests should be taken under WB conditions, while actively performing functional tasks such as walking, stepping, or squatting, in a short time, and with assumable costs (Table 1)\(^8\). Under the banner of dynamic evaluation, we have encountered a variety of concepts. Some reports refer to tests performed with active participation of the subject under WB, while others evaluate the PFJ under isometric quadriceps contraction. To avoid confusion, the term kinematic is often employed in publications involving active movement.

A first observation coming from the revised literature would be the fact that during the past decades, large amounts of research have been conducted in order to study the PFJ joint under dynamic conditions (Table 2). Nevertheless, despite several key findings, most research lines seem to run independently, without integrating previous data. This could be explained by the heterogeneity among publications: diversity of imaging devices, processing protocols, patient positioning, active or passive motion (among other factors). The amount of information is considerable but may be hard to integrate.

Another key point in this review is that, significantly, several authors question the validity of data obtained from static examinations. Routine findings obtained in a first contact with the patient such as an increased static Q angle or the presence of a positive j-sign may not be that relevant\(^2,29\). Still, conventional imaging measures, such as patellar tilt or sulcus angle, vary whether the images are obtained statically or not\(^10\) (Fig. 2). Some studies even observed that passive motion of the joint was not sufficient to reproduce the abnormal biomechanics of unstable joints\(^8\), and claim for the risk of obtaining false negative results with static magnetic resonance imaging (MRI) protocols\(^31\).

An additional interesting observation is that patellar tracking is a recurring item of discussion among the quoted references. The definition of a normal patellar tracking is inherently confusing, as the movement itself is complex, and the references to define it vary depending on the authors. Likewise, patellar tracking is often not assessed during WB, ignoring a crucial element in the physiological knee dynamics.

A common feature of the reported articles’ results is that most evidence comes from small cohorts, in certain cases implying just healthy volunteers. This limits the diagnostic utility of the results and could explain why very few publications report specific figures with practical use as cut-off points in clinical decision making.

### Methods

A literature review was conducted by the first author (SB). Search terms included patellar instability, patellar dislocation, dynamic, kinematic, active, assessment,
diagnostic, and imaging. PubMed was the primary search source, and side searches were conducted in private databases from associated universities and scientific organizations. No limit for publication date was set.

Publications were considered if they reported any sort of assessment method for patellar biomechanics in the setting of patellar instability with no-static conditions. Cadaveric, animal, or virtual/computerized models were also rejected. Papers in languages other than English or Spanish were also discarded.

Review Results

Physical Examination
A classical examination of a PFI patient takes place with the subject laying or sitting on the examination table, while the knee is passively explored. As an illustrative example of this we can cite "Comprehensive Physical Examination for Instability of the Knee," an instructive manuscript with 18 pages of manoeuvres where an only dynamic test is presented for PFI: evaluation of the j-sign (Fig. 3).

The diagnostic utility of the j-sign has even been questioned. In a cohort of PFI patients, Beckert et al. found poor correlation between j-sign and a centered position of the patella in relation to the trochlear groove. Another review on patellar tracking identified multiple limitations in defining specific movement patterns and questions its diagnostic suitability.

Sarkar et al. investigated the influence of quadriceps muscle activation on the Q angle, another classic examination item in PFJ assessment; observing a statistically significant difference of 4.65° ± 2.74° between relaxed and quads contracted (IQA) measurements. Therefore, they concluded that: "Measuring the change in the Q angle with IQA compared with the resting Q angle may enhance a clinician’s ability to predict which individual is at greater risk of developing patellar tracking and patellar dysfunction." Türkmen et al. calculated the average Q angle between different positions (standing, sitting, and supine) with and without quadriceps contraction, obtaining a ΔQ angle which was significantly lower in PF pain cases.

A recently published paper described the novel "reverse dynamic patellar apprehension test," in which the PFJ stability is explored under a medially applied force from deep flexion to extension, as opposed to the classic apprehension test where the exploration begins in full extension. Despite the term dynamic, the exploration is entirely passive, as the patient remains relaxed while the examiner manipulates his leg and applies the medial force.

Arthroscopic Evaluation
Before the routine implementation of high definition imaging devices such as the MRI, arthroscopy was considered the gold standard for intraarticular evaluation. In terms of dynamic evaluation, arthroscopy allows the surgeon to directly visualize the relations in PFJ while it moves passively or actively; in the latter, the procedure should be performed under local anaesthetic to permit active collaboration. It has also been studied that quadriceps activation by means of electrical stimulation significantly affects the relations in the PFJ observed during arthroscopy in PFI patients (Fig. 4).

Brossman proposed a 3-tier malalignment classification according to arthroscopic findings, achieving good correlation with cine-MRI findings. This classification may be useful as a qualitative grading system during an arthroscopic evaluation, but the fact that it correlates well with the nowadays widely accessible MRI examination may raise a reasonable doubt about its current convenience as an isolated diagnostic gesture.

Recently, in 2019, an Australian group published the utility of arthroscopic evaluation in PFI assessment. They estimated the knee flexion angle (KFA) at which the patella engages with the central portion of the trochlea and found a significantly higher angle in unstable joints: a recommendation to consider a tibial tubercle distal transfer is made when a KFA >40° is found.


| Author          | Year | Category | Participants | Findings and comments                                                                 |
|-----------------|------|----------|--------------|---------------------------------------------------------------------------------------|
| Beckert et al.  | 2016 | PE       | 10 PFI patients | MRI more accurate than clinical J-sign for patellar position                          |
|                 |      |          |              | Suggests lateral patella edge as a better target than static                            |
|                 |      |          |              | TTTG for surgical correction                                                          |
| Sarkar et al.   | 2009 | PE       | 23 healthy women | Relevant changes in Q angle with quads contraction                                    |
| Shih et al.     | 2004 | US       | 10 healthy controls | Significant changes in patellar tilt between sitting, squatting and stepping          |
| Shellock et al. | 1988 | MRI      | 1 PFI patient  | Sequential static MRI slices at different degrees of flexion to produce a kinematic sequence |
| Grossman et al. | 1993 | MRI      | 13 maltracking cases | First motion-triggered report                                                        |
|                 |      |          | 15 healthy controls |                                                                                      |
| Sheehan et al.  | 1999 | MRI      | 18 healthy knees | First published cine-phase study                                                     |
| Witonski and Góraj | 1999 | MRI      | 12 AKP cases   | Different values for most parameters in the PFJ if obtained under relaxed conditions vs. quads activation |
| McNally et al.  | 2000 | MRI      | 474 AKP cases  | First ultrafast MRI article                                                          |
| Draper et al.   | 2009 | MRI      | 13 AKP women   | Assessment of bracing effect on patellar tilt and subluxation                       |
| Carlson et al.  | 2017 | MRI      | 32 AKP cases   | Static TTTG does not correlate with lateral tracking at full extension               |
| Burke et al.    | 2018 | MRI      | 20 PFI cases   | First use of real time gradient echo imaging in peripheral skeleton                  |
|                 |      |          | 10 healthy controls | Suggests patellar subluxation greater than 3 mm as highly specific for PFI            |
| Barroso et al.  | 2018 | MRI      | 9 PFI cases    | Dynamic assessment method of patellar height                                         |
|                 |      |          | 68 controls    |                                                                                      |
| Dupuy et al.    | 1997 | CT       | 20 AKP knees   | First report on spiral CT                                                            |
|                 |      |          |               | Higher sensitivity than static sequences                                            |
| Elias et al.    | 2014 | CT       | 6 PFI          | Dynamic assessment after surgical stabilization                                       |
| Tanaka et al.   | 2016 | CT       | 67 PFI knees   | Maltracking grading system                                                           |
| Nha et al.      | 2008 | Misc     | Eight healthy controls | Validated method combining static MRI + 2D fluoroscopy during weight bearing (WB) |
| Liu et al.      | 2017 | Misc     | 30 PFI cases   | List of normal values for several PFJ features                                       |
|                 |      |          | 30 controls    | Diffusor tensor imaging as an early detector of potential PFI cases                   |
| Wilson et al.   | 2009 | Misc     | 10 PFI patients | Thermoplastic patellar clamp and optoelectronic motion capture                      |
| Suganuma et al. | 2014 | Misc     | 24 PFI knees   | Arthroscopically observed that quads activation significantly alters the relations in the PFJ |
|                 |      |          | 49 controls    |                                                                                      |

CT, computed tomography; PE, physical examination; PFI, patellofemoral instability; Misc, miscellaneous; MRI, magnetic resonance imaging; US, ultrasound.

**Imaging Techniques**

**Computed Tomography (CT) Studies**

CT scans have been extensively used in the field of dynamic study of PFJ biomechanics. Early works in 1983–1986 accomplished dynamic sequences by obtaining static images with quadriceps contraction at several flexion angles, as motion capture techniques were not entirely available. In 1988, the utility of electron-beam CT for dynamic PFJ evaluation was reported; however, the high costs limited its availability. In 1994, a study by Pinar, in which static images at different flexion angles were obtained, concluded: "A regular pattern could not be observed. Further research is needed in this area" and "Kinematic CT scanning may reveal useful data on the pathogenesis of […] PFI" (Fig. 5). Also in 1994, Guzzanti et al. observed that quadriceps activation during CT examination could displace the patella proximally up to 1 cm, potentially altering patellar height values, already suggesting that diagnostic and preoperative evaluations for PFI patients should not rely only on static imaging.

Most succeeding efforts focused on dynamic kinematic CT scanning (DKCT). A first mention of a kinematic study of the PFJ by means of spiral CT dates back to 1997; the authors reported the feasibility of the technique and its clinical utility for PFI and anterior knee pain cases. In recent years, we have witnessed a number of papers reporting on DKCT, both as a diagnostic tool and as an assessment method for surgical interventions for PFI. In 2014, Elias studied the biomechanical effects of surgical corrections in six PFI cases (medializing osteotomies and MPFL reconstruction) by means of kinematic CT. Williams compared the results of dynamic CT scans from PFI knees to those of healthy contralaterals. The study was performed under no WB and described statistically significant differences in most parameters. The same group also demonstrated how DKCT can differentiate specific patterns of patellar maltracking.
establishing a grading system of 10 categories with high correlation with the severity of symptoms; only one of them was labelled as normal tracking. This variability was also highlighted in a specific review on patellar tracking, concluding that “there may be no normal pattern”.

Also, in 2016, Forsberg et al. reported another DKCT study assessing the results of isolated MPFL reconstructions, evaluating various methods to reference and compute anatomical landmarks (Fig. 6); another publication presented a similar design with the same purpose.

**Dynamic MRI**

Several non-static MRI protocols and devices have been employed in the analysis of PFJ (Table 3). The almost universal availability of this equipment, lack of radiation, and the progress in image definition and acquisition protocols...
have turned MRI into the preferred imaging option for knee clinicians.

A pathfinder paper, the first of a vast series, was published by Shellock in the late 1980s; he studied several aspects of PFJ biomechanics by means of “kinematic MRI,” obtaining cine-sequences by combining static images acquired in increasing flexion angles. The first publication of a motion-trigger MRI study for PFJ dynamics appeared in 1993, reporting differences among normal and maltracking knees under active extension but not if passively extended. A first cine-phase MRI report appeared in 1999, obtaining 3D motion studies from a healthy cohort under no-WB; an error of up to 2°/C14 is noted. The same year Witonski and Goraj published a clinical work employing dynamic MRI; in an anterior-knee-pain cohort they obtained conventional MRI sequences under isometric quadriceps contraction, in different degrees of knee flexion, and evaluated sulcus angle, congruence angle and patellar tilt, observing a significant difference to static images. To our knowledge, the first study employing an ultrafast MRI protocol on PFI patients is the one from McNally et al. in 2000; they found that a sulcus depth of less than 4 mm or with an angle flatter than 150° is highly specific (98%) for maltracking, providing clinically useful references.

In addition, Burke et al. reported a continuous, real-time radial gradient echo imaging for the first time in peripheral skeleton, obtaining high detail images and videos in moving knees from 0° to 30° of flexion, with a study time of 3–7 min. They suggest a lateral subluxation beyond 3 mm could be considered as a PFI threshold, as no control subjects exceeded this value.

In 2016, by means of dynamic MRI assessment, Beckert et al. concluded that the modified lateral patellar edge measurement previously described by McDermott was a better target for surgical correction than the commonly used TTTG, which is generally obtained in a static CT examination. Recently, the authors of this review published a novel technique to assess patellar height: the quads active ratio. A dynamic MRI sequence was performed during volitional isometric quadriceps contraction, calculating the overlap among patellar and trochlear articular cartilages in a midsagittal slice: a quads active ratio of 0.12 showed good sensitivity for PFI. The feasibility of ultrafast dynamic MRI in paediatric population has also been tested, reporting compliant cooperation from a cohort aged 11–16 years; the evaluation was capable to identify differences between normal and unstable PFIs. A protocol combining data from static high resolution MRI and low resolution active sequences of MRI was reported in another paediatric cohort, with a study time close to an hour.
**Fig. 5** CT images obtained at different degrees of knee flexion and with/without quadriceps contraction\(^{19}\).

**Fig. 6** High definition 4DCT tracking pattern of a PFI knee by Forsberg et al.\(^{21}\).

### TABLE 3 MRI modalities in PFJ assessment

| MRI Modality     | Description                                                                 |
|------------------|-----------------------------------------------------------------------------|
| Conventional MRI | Static image acquisition under isometric quadriceps contraction              |
| Motion-triggered cine MRI | Originally designed for cardiac studies, evaluates cyclic movement of the knee. Dependent on patient compliance, as multiples cycles have to be performed over several minutes at a certain pace. |
| Ultrafast MRI    | Allows for image obtainment during slow motion of the knee. This avoids repetition of cyclic movements, decreasing study time and the need for specific patient collaboration and training. |
Ultrasound (US)

The development of high definition US devices and techniques has allowed for a more precise evaluation of musculoskeletal anatomy, and the PFJ has not been an exception. Shih et al. modified a standard articulated knee brace with the addition of an US probe and a goniometer (Fig. 9). They evaluated PF tracking during several active knee movements (sitting, stepping, squatting) and found significant differences in lateral tracking. The system was validated with MRI and proved good inter and intra-rater reliability and complies with most of the ideal features listed by Muhle et al., but as the study only included healthy individuals, its clinical utility should be considered with caution.

Herrington’s research group employed US to measure the distance between the lateral border of the patella and the edge of the lateral femoral condyle, while the quadriceps were contracted by means of electrical stimulation. Measurements were reported as reliable and reproducible, but PFI cases were excluded from the cohort.

Combined Imaging Techniques

A recurring approach in the study of the PFJ biomechanics has been the combination of data obtained by different imaging modalities. Most studies blend CT/MRI static data with the tracking patterns obtained with continuous fluoroscopy. Fernandez et al. pioneered in 2008 with a method fusing 3DMRI, dynamic 2D fluoroscopy, and video recording (Fig. 10). The paper described a pilot investigation in a healthy volunteer, with over 6 hours of processing time, but the accuracy is reported of less than 2 mm and 1° of error. Shortly later, Nha published a larger study applying a combination of static 3DMRI and 2D fluoroscopy during full range of movement WB squatting on 8 knees, validating the accuracy of the system with a cadaveric study. This work produced a broad list of normal angles and measures, which probably have a better utility in the research field rather than in clinical practice.

More recently, an optimized protocol to join data from 3DMRI and 2D fluoroscopy was published, improving success rates and processing time with fewer errors. The processing time ranged from 48–177 min, a significant reduction compared to previous works. In 2018, a new trial was conducted comparing the PFJ biomechanics of patients with anterior knee pain and volunteers, by a computerized combination of static CT images and dynamic fluoroscopy.

Other Modalities

Additionally, distinct alternatives have been wielded in the dynamic study of the PFJ. Laprade and Lee conducted research on volunteers, assessing PFJ kinematics by means of a non-invasively magnetic tracking system, attaching sensors to the skin; this device potentially allows for evaluation during any action (Fig. 11). Another interesting device was presented by Wilson et al.; by means of a custom-made thermoplastic patellar clamp attached to a goniometer, patellar motions were recorded by an optoelectronic capture system. This allowed obtaining data from real-time squats.

Fig. 7 Inflatable device to allow for continuous isometric contraction during a range of knee flexion, by McNally.

Fig. 8 Proximal migration of the patella between conventional (left) and quadriceps contracted (right) sagittal MRI sequences, from Barroso et al.26.
patellar extension, spin, tilt, and shift, with <1.2 and <1.1 mm error according to the cadaveric validation tests.

In 2016, Fujita et al. described an accessible method to qualitatively register PFJ tracking patterns by means of a conventional video camera and processing software.55

It is worth mentioning a paper by Liu et al. regarding the utility of diffusion tension imaging (DTI).56 This MRI-based technique is mainly employed in neuroimaging, as it provides information about location, orientation, and anisotropy of neural tracts, but can also evaluate microscopic changes in muscular fibers. Comparing the data obtained from the vastus oblique medialis in a PFI cohort and in healthy controls, DTI was capable of detecting changes in muscular quality, even with no differences in muscle cross-section volume. This could be considered as a screening test to detect early changes in PFI-prone patients.
Recently, several research teams have employed wearable devices to study real time biomechanics of various anatomical segments, such as the lumbar spine\(^c\) or the knee\(^b\). There is great availability of these wireless devices, generally synchronized to mobile phones, and with accessible prices. They allow for long, unsupervised observation periods, as the subjects carry them during their usual activities within the community, which has proved useful to monitor adherence and performance in exercise and rehabilitation protocols\(^59\). These devices may become an interesting source of data for the dynamic evaluation of the PFJ in the near future, providing information during strenuous activities and sports practice.

**Conclusion**

We believe future efforts should be pointed towards standardizing research protocols in order to obtain larger series of comparable data. Our impression is that the accuracy of many techniques cited in this paper, especially dynamic/kinematic MRI and DKCT, would warrant conclusive evidence to better understand the PFJ, but this should come from large series, including clinically affected PFI patients. Theoretically, dynamic assessment of the PFJ should be superior to the still established static methods. Many disparate publications point towards this direction, but the evidence is still insufficient to challenge current clinical practice. As seen in this review, most dynamic assessment modalities are not restricted to highly specialized centers and should be accessible and affordable in the utmost health settings. Stronger evidence on the clinical relevance of these investigations is warranted to advocate for their standardization in the study of clinically relevant PFI.

**Fig. 11** Non-invasive sensor setting in Laprade and Lee’s article\(^{53}\).

**References**

1. Diduch DR, Kandill A, Burnus MT. Lateral patellar instability in the skeletally mature patient: evaluation and surgical management. J Am Acad Orthop Surg, 2018, 26: 429--439.
2. Liu J, Steinhaus M, Klabian I, et al. Patellar instability management: a survey of the International Patellofemoral Study Group. Am J Sports Med, 2018, 46: 3299--3306.
3. Bollier M, Fulkerson JP. The role of trochlear dysplasia in patellofemoral instability. J Am Acad Orthop Surg, 2011, 19: 8--16.
4. Ries Z, Bollier M. Patellofemoral instability in active adolescents. J Knee Surg, 2015, 28: 265--277.
5. Loeb AE, Tanaka MJ. The medial patellofemoral complex. Curr Rev Musculoskel Med, 2018, 11: 201--208.
6. Phillips CL, Silver DAT, Schranz PJ, Mandalia V. The measurement of patellar height: a review of the methods of imaging. J Bone Joint Surg Br, 2010, 92: 1045--1053.
7. Yanokopoulos CK, Mataragas E, Antonogiannakis E. The effect of quadriceps contraction during weight-bearing on four patellar height indices. J Bone Joint Surg Br, 2006, 90: 670--673.
8. Muhle C, Brosnann J, Heller M. Kinematic CT and MR imaging of the patellofemoral joint. Eur Radiol, 1999, 9: 508--518.
9. Beckert MW, Albright JC, Zavala J, Chang J, Albright JP. Clinical accuracy of J-sign measurement compared to magnetic resonance imaging. Iowa Orthop J, 2016, 36: 94--97.
10. Witowski D, Goraj B. Patellar motion analyzed by kinematic and dynamic axial magnetic resonance imaging in patients with anterior knee pain syndrome. Arch Orthop Trauma Surg, 1999, 119: 46--49.
11. Lubowitz JH, Bernadini BJ, Reid JB. Current concepts review: comprehensive physical examination for instability of the knee. Am J Sports Med, 2008, 36: 577--594.
12. Türkmen F, Aكار MA, Kacira BK, et al. A new diagnostic parameter for patellofemoral pain. Int J Clin Exp Med, 2015, 8: 11563--11566.
13. Zimmermann F, Liebensteiner MC, Balcarek P. The reversed dynamic patellar apprehension test mimics anatomical complexity in lateral patellar instability. Knee Surg Sports Traumatol Arthrosc, 2019, 27: 204--610.
14. Brossman J, Muhle C, Bull R, et al. Evaluation of patellar tracking in patients with suspected patellar malignment: cine MR imaging vs arthroscopy. Am J Roentgenol, 1994, 162: 361--367.
15. Baroso Rosa S, James D, Matthews BD. Is knee arthroscopy under local anaesthetic a patient-friendly technique? A prospective controlled trial. Eur J Orthop Surg Traumatol, 2016, 26: 633--638.
16. Suganuma J, Mochizuki R, Inoue Y, Kitamura K, Honda A. Arthroscopic evaluation of patellofemoral congruence with rotation of the knee joint and electrical stimulation of the quadriceps. Arthroscopy, 2014, 30: 214--221.
17. Martinez S, Korobkin M, Fondren FB, Hedlund LW, Goldner JL. Diagnosis of patellofemoral malalignment by computed tomography. J Comput Assist Tomogr, 1983, 7: 1050--1053.
18. Standford W, Phelan J, Katoh MH, et al. Patellofemoral joint motion: evaluation by ultrafast computed tomography. Skeletal Radiol, 1988, 17: 487--492.
19. Pinar H, Aksei D, Karaoglan O, Genç I. Kinematic and dynamic axial computed tomography of the patello-femoral joint in patients with anterior knee pain. Knee Surg Sports Traumatol Arthrosc, 1994, 2: 170--173.
20. Guzzanti V, Gigante A, Di Lazzaro A, Fabbriciani C. Patellofemoral malalignment in adolescents. Computerized tomographic assessment with or without quadriceps contraction. Am J Sports Med, 1994, 22: 55--60.
21. Forsberg D, Lindblom M, Quick P, Gauffin H. Quantitative analysis of the patellofemoral motion pattern using semi-automatic processing of 4D CT data. Int J Comput Assist Radiol Surg, 2016, 11: 1731--1741.

...
22. Gobbi RG, Demange MK, Rodrigues de Avila LF, et al. Patellar tracking after isolated medial patellofemoral ligament reconstruction: dynamic evaluation using computed tomography. Knee Surg Sports Traumatol Arthrosc, 2016, 24: 1–9.

23. Sheehan FT, Drace J. Quantitative MR measures of three-dimensional patellar kinematics as a research and diagnostic tool. Med Sci Sports Exerc, 1999, 31: 1399–1405.

24. Draper CE, Besier TF, Santos JM, et al. Using real-time MRI to quantify altered joint kinematics in subjects with patellofemoral pain and to evaluate the effects of a patellar brace or sleeve on joint motion. J Orthop Res, 2009, 27: 571–577.

25. Teng HL, Chen YJ, Powers CM. Predictors of patellar alignment during weight bearing: an examination of patellar height and trochlear geometry. Knee, 2014, 21: 142–146.

26. Barroso Rosa S, Bahzo Z, Dona K, et al. The quadriceps active ratio: a dynamic MRI-based assessment of patellar height. Eur J Orthop Surg Traumatol, 2018, 28: 1165–1174.

27. Shih YF, Bull AMJ, McGregor AH, Amis AA. Active patellar tracking measurement: a novel device using ultrasound. Am J Sports Med, 2004, 32: 1209–1217.

28. Nha KW, Papannagari R, Gill TJ, et al. In vivo patellar tracking: clinical motions and patellofemoral indices. J Orthop Res, 2008, 26: 1067–1074.

29. Sarkar A, Razdan S, Yadav J, Bansal N, Kuar SU, Pahuja P. Effect of isometric quadriceps activation on ‘Q’ angle in young females. Indian J Physiol Pharmacol, 2009, 53: 275–278.

30. Brossman J, Muhle C, Schröder C, et al. Patellar tracking patterns during active and passive knee extension: evaluation with motion-triggered cine MR imaging. Radiology, 1993, 187: 205–212.

31. Freedman BR, Sheehan FT. Predicting three-dimensional patellofemoral kinematics from static imaging-based alignment measures. J Orthop Res, 2013, 31: 441–447.

32. Katchburian MV, Bull AMJ, Shih YF, Heatley FW, Amis AA. Measurement of patellar tracking: assessment and analysis of the literature. Clin Orthop Relat Res, 2003, 412: 241–259.

33. Kejriwal R, Annear P. Arthroscopic assessment of patella tracking correlates with recurrent patellar instability. Knee Surg Sports Traumatol Arthrosc, 2019. https://doi.org/10.1007/s00167-019-05532-0.

34. Sasaki T, Yagi T. Subluxation of the patella: investigation by computerized tomography. Orthop Clin North Am, 1986, 10: 115–120.

35. Schutzer SF, Ramsby GR, Fullkerson JP. Computed tomographic classification of patellofemoral pain patients. Orthop Clin North Am, 1986, 17: 235–248.

36. Dupuy D, Hangen D, Zachazewski J, Boland A, Palmer W. Kinematic CT of the patellofemoral joint. Am J Roentgenol, 1997, 169: 211–215.

37. Elias JJ, Canino JA, Saranathan A, Guseilla LM, Tanaka MJ, Cosgarea AJ. Variations in kinematics and function following patellar stabilization including tibial tuberosity realignment. Knee Surg Sports Traumatol Arthrosc, 2014, 22: 2350–2356.

38. Williams AA, Elias JJ, Tanaka MJ, et al. The relationship between tibial tuberosity-trochlear groove distance and abnormal patellar tracking in patients with unilateral patellar instability. Arthroscopy, 2016, 32: 55–61.

39. Tanaka MJ, Elias JJ, Williams AA, Demehri S, Cosgarea AJ. Characterization of patellar maltracking using dynamic kinematic CT imaging in patients with patellar instability. Knee Surg Sports Traumatol Arthrosc, 2016, 24: 3634–3641.

40. McKoy FG, Mink JC, Fox JM. Patellofemoral joint: kinematic MR imaging to assess tracking abnormalities. Radiology, 1988, 168: 551–563.

41. McNally EG, Ostlere SJ, Pai C, Phillips A, Reid H, Dodd C. Assessment of patellar maltracking using combined static and dynamic MRI. Eur Radiol, 2000, 10: 1051–1055.

42. O’Donnell P, Johnstone C, Watson M, McNally E, Ostlere S. Evaluation of patellar tracking in symptomatic and asymptomatic individuals by magnetic resonance imaging. Skeletal Radiol, 2005, 34: 130–135.

43. Gold GE, Besier TF, Draper CE, Asakawa DS, Delp SL, Beaufour GS. Weight-bearing MRI of patellofemoral joint cartilage contact area. J Magn Reson Imaging, 2004, 20: 526–530.

44. Carlson VR, Sheehan FT, Shen A, Yao L, Jackson JN, Boden BP. The relationship of static tibial tubercle-trochlear groove measurement and dynamic patellar tracking. Am J Sports Med, 2017, 45: 1856–1863.

45. Burke CJ, Kaplan D, Block T, et al. Clinical utility of continuous radial magnetic resonance imaging acquisition at 3T in real-time patellofemoral kinematic assessment: a feasibility study, Arthroscopy, 2018, 34: 726–733.

46. Regalado G, Lintula H, Eskelinen M, et al. Dynamic KINE-MRI in patellofemoral instability in adolescents. Knee Surg Sports Traumatol Arthrosc, 2014, 22: 2795–2802.

47. Blyani R, Elias J, Saranathan A, et al. Anatomical factors influencing patellar tracking in the unstable patellofemoral joint. Knee Surg Sports Traumatol Arthrosc, 2014, 22: 2334–2341.

48. Herrington L, Pearson S. The applicability of ultrasound imaging in the assessment of dynamic patella tracking: a preliminary investigation. Knee, 2008, 15: 128–127.

49. Fernandez JW, Akbarshahi M, Kim HJ, Pandy MG. Integrating modelling, motion capture and x-ray fluoroscopy to investigate patellofemoral function during dynamic activity. Comput Methods Biomech Biomed Engin, 2008, 11: 41–53.

50. Bey MJ, Kline SK, Tashman S, Zauel R. Accuracy of biplane x-ray imaging combined with model-based tracking for measuring in vivo patellofemoral joint motion. J Orthop Surg Res, 2008, 3: 1–8.

51. Ohnishi T, Suzuki M, Kobayashi T, et al. Robust 2D/3D registration for fast-flexion motion of the knee joint using hybrid optimization. Radiol Phys Technol, 2013, 6: 170–179.

52. Esfandiarpour F, Lebrun CM, Dhillon S, Boulanger P. In-vivo patellar tracking in individuals with patellofemoral pain and healthy individuals. J Orthop Res, 2018, 36: 2193–2201.

53. Laprade J, Lee R. Real-time measurement of patellofemoral kinematics in asymptomatic subjects. Knee, 2005, 12: 63–72.

54. Wilson NA, Press JM, Koh JL, Hendrix RW, Zhang LQ. In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain. J Bone Joint Surg Am, 2009, 91: 558–566.

55. Fujita Y, Tsuda E, Yamamoto Y, et al. Quantitative analysis of dynamic patellar tracking in patients with lateral patellar instability using a simple video system. Knee, 2016, 23: 604–609.

56. Liu LS, Zheng ZZ, Yuan HS. Significance of diffusion tensor imaging of vastus medialis oblique in recurrent patellar dislocation. Chin Med J (Engl), 2017, 130: 642–646.

57. Mjösund HL, Boyle E, Kjaer P, et al. Clinically acceptable agreement between the VMotion wireless motion sensor system and the Vicon motion capture system when measuring lumbar region inclination motion in the sagittal and coronal planes. BMC Musculoskelet Disord, 2017, 18: 124.

58. Papi E, Bo YN, McGregor AH. A flexible wearable sensor for knee flexion assessment during gait. Gait Posture, 2018, 62: 480–483.

59. Argent R, Sievin P, Bivallacqua A, Neligan M, Daly A, Caulfield B. Wearable sensor-based exercise biofeedback for orthopaedic rehabilitation: a mixed methods user evaluation of a prototype system. Sensors (Basel), 2019, 19: E432.