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The Three-Dimensional Tracking Pattern of the Patella in the Human Knee Joint and the Effects of Surgical Interventions

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Introduction

Precise causes for retropatellar chondromalacia are still unknown. It is generally believed that patellar tracking patterns, contact areas, pressure distribution, contact incongruence and cartilage deficiencies play a role in its aetiology [2, 3, 5, 9, 18]. Fundamental research concerning the patello-femoral joint is still incomplete and consequently so also is the scientific basis for various surgical interventions. The kinematic behaviour of the patella versus the femur has not yet been thoroughly investigated, and data from the literature, as summarized in Table 1, are inconsistent [6, 13, 16, 17].

The first objective of the present investigation was to provide an accurate data base for the normal three-dimensional tracking pattern of the patella. Operations for chondromalacia are often based on theory, intuitional convention or empirical observations. It is unknown whether and to what extent various operations cause a rerouting of the patellar tracking mechanism. The effects on the patellar tracking patterns of two operations, that of lateral retinacular release and that of tubercle elevation, both popular treatments for chondromalacia, are presented and discussed here.

Methods

Four postmortem leg specimens were fixed onto an apparatus allowing for prescribed flexion motion, free tibial rotations following prescribed tibial rates of torque and free varus-valgus rotations (Fig. 1). The four heads of the quadriceps muscle were loaded separately with static forces. Five tantalum markers (0.8–1.0 mm) each were inserted into the patella, the femur and the tibia. The knee was flexed from 0°–150° in nine steps. At each flexion position X-ray exposures were taken. The spatial coordinates of the markers as measured from the exposures were reconstructed in each position, using a roentgen stereophotogrammetric analysis (RSA) system [10, 15]. The bones were provided with coordinate systems and their relative motions expressed in terms of translation vectors along the axes and in terms of Euler rotation angles about the axes (Fig. 2). Each test series was carried out for the neutral flexion pathway and for externally and internally rotated pathways (±3 N m tibial torque), both with total Q-forces of 110 N. These tests were repeated after lateral retinacular release and after tubercle elevations of 0.5 cm and 1.0 cm.

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Table 1. Differences in patellar rotations and patellar translation from the literature

Reference	Number of speciemens		Q-loading	Measurements		Tibial rotation	Average patellar movements		
	In vivo	In vitro		Number	Range		Shift	Rotation	Tilt
Veress et al. (1979)	4		Isometric	4	0°– 90°	Neutral	Lateral	(Unknown)	Inconclusive
Sikorski et al. (1979)	12		Isometric	3	60°– 90°	Neutral	(Unknown)	Lateral	Medial
Reider et al. (1981)		20	92 N	7	0°– 90°	Fixed	*Type I* Lateral 14 mm	Lateral 6°	Lateral 12°
							Type II Medial 7 mm	Lateral 6°	Neutral 0°
Fujikawa et al. (1983)		8	20–30 N	6	25°–130°	(Unknown)	(Unknown)	Lateral 6.2°	Medial 11°

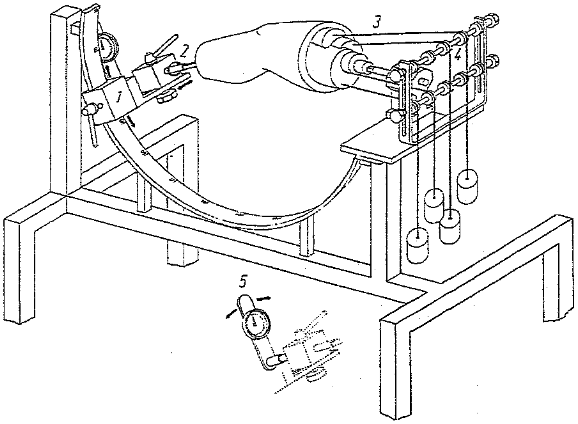

Fig. 1. Motion. *1* Clamp for flexion/extension along the rail; *2* clamp for tibial internal/external rotation and varus/valgus rotation; *3* wires, attached to the quadriceps muscle; *4* pulleys to guide the wires in the different muscle directions; *5* torque wrench

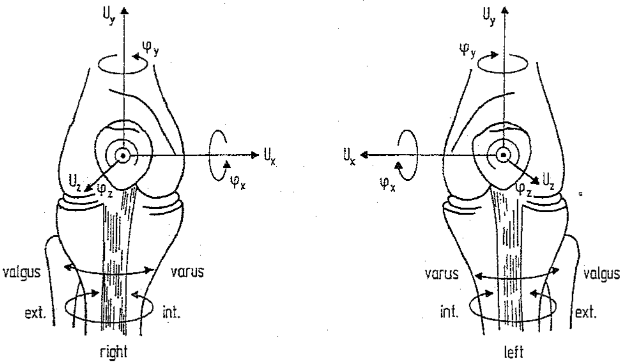

Fig. 2. Orientation and location of the coordinate axes of the patella. Subsequent rotations $(Q_{x,y,z})$ around the axes $(U_{x,y,z})$ represent patellar flexion (Qx), patellar tilt (Qy) and patellar rotation (Qz). Translation along the x-axis (Ux) represents patellar shift. For reasons of clarity, the coordinate systems of the femur and the tibia are not shown (see text)

In Fig. 3 the nomenclature of the different patellar movements is presented. Patellar rotation around the femoral x-axis describes patellar flexion (positive) or extension (negative). Rotation around the patellar y-axis describes medial tilt (positive) as the medial patellar facet rotates towards the medial femoral condyle, and lateral tilt (negative) as the lateral patellar facet rotates towards the lateral femoral condyle. Rotation around the patellar z-axis describes medial patellar rota-

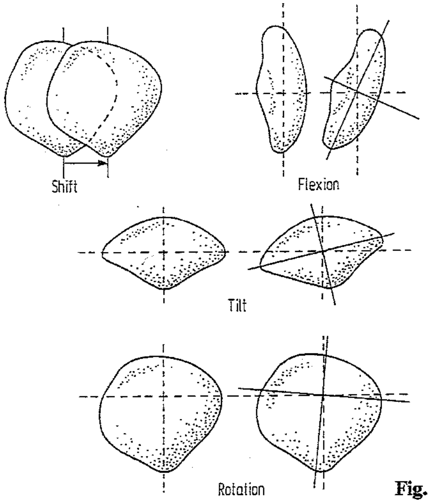

Fig. 3. Patellar rotations and patellar shift

tion (positive) as the patellar apex turns towards the medial condyle, and lateral patellar rotation (negative) as the patellar apex turns towards the lateral condyle. Translation along the patellar x-axis will be described as patellar shift: medial (positive) and lateral (negative).

Results

The precision of three-dimensional reconstruction was higher than 50 μm, resulting in rotation precisions of approximately 0.1°. Retesting one specimen resulted in maximal deviations of 5%, indicating excellent reproducibility per specimen. Effects from variation in quadriceps force magnitude were negligible. Although varying in absolute magnitudes, all specimens showed the same trends in tibial and patellar movements with increasing flexion. An example is shown in Fig. 4, in which tibial exo-endorotation, tibial varus/valgus rotation, patellar flexion, rotation, tilt and shift are shown as a function of tibial flexion, for both the internally and the externally rotated motion pathways.

Maximum tibial exo-/endorotatory laxity (approximately 35°) is reached after approximately 30° knee flexion and declines only in very high knee flexion (above 130°) due to reduced exorotation. Tibial flexion is accompanied by a slight tibial varus rotation, which mechanism is increased by external rotation of the tibia. Patellar flexion occurs in concert with knee flexion, as expected, but lags by about 20%. The flexion lag is more pronounced after approximately 105° knee flexion, as established for all specimens.

Patellar rotation is directed medially; the patellar apex moves towards the medial femoral condyle. Significant rotation occurs above 40° knee flexion. Internal ti-

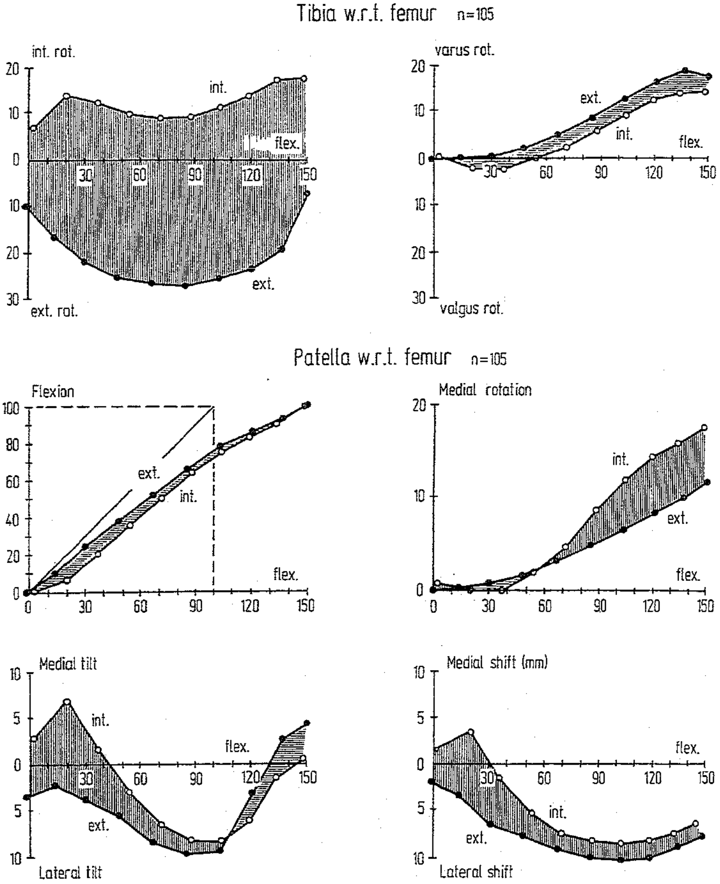

Fig. 4. An example of tibial and patellar rotations and shift versus the femur in one specimen. *Open circles,* internal tibial rotation pathways; *closed circles,* external tibial rotation pathways (±3 Nm); w.r.t., with respect to

bial rotation increases the medial patellar rotation. The tilt movement of the patella can be described as "wavering", for during flexion the patella wavers from a medially to a laterally tilted position and vice versa. The patellar tilt is highly influenced by tibial rotations, especially towards full extension. This is understandable when one considers the clinically movable patella in extension, which becomes stuck in its patellofemoral groove with further knee flexion. Along the external rotation envelope (the limit of patellar rotation induced by tibial rotation) medial tilt is converted to lateral tilt or, at least, to less pronounced medial tilt. A possible explanation for this phenomenon is that by tibial exorotation, lateral knee structures and especially the more laterally oriented patellar ligament pull at the patella, which causes the patella to tilt laterally.

At approximately 100° knee flexion the patella exhibits a sudden jerk towards a medially tilted position, probably caused by loading of the most medial (odd) patellar facet. Translation of the patella in the frontal plane, the patellar shift, is pointed laterally and is progressive upon further knee flexion. Along the tibial exorotation motion pathway the patellar lateralisation is more pronounced.

The patellar motions relative to the femur, along the envelope of tibiofemoral flexion, did not show very significant changes in flexion, tilt, rotation or shift, after performance of a lateral retinacular release, as illustrated in Fig. 5. These trends were found in all specimens. After a tubercle elevation of 1.0 cm, according to Bandi [1], the changes in patellar flexion, tilt and shift were minimal. However, patellar rotation is evidently increased, both along the internal and the external rotated pathways (Fig. 6). Although the other specimens also showed changes in patellar tracking after the tubercle elevation, no consistent trend could be established.

Discussion

For the determination of three-dimensional tracking patterns of the patella a high precision measuring system (RSA) was used. Because of its high precision and the high reproducibility found here, the results represent true patellar motions, and general conclusions on the patellar tracking pattern may be drawn, although the number of investigated specimens was relatively small. The motions found in the four specimens varied in terms of absolute rotation and translation excursions, but the tendencies and relative motion patterns were remarkably similar. The differences that do occur can be explained by anatomical variability.

The three-dimensional patellar tracking patterns are characterised by a progressive patellar flexion, a wavering patellar tilt, a medial patellar rotation and a lateral patellar shift during knee flexion. The patellar movements can be partially explained by the bony configuration of the femoral groove. The anterior wall of the lateral femoral condyle causes in extension and during the first stage of flexion a medial patellar tilt. In the second stage of flexion a lateral patellar tilt is induced by the further caudally reaching medial condyle. The patellar tilt inversion towards a medial tilt in higher knee flexion represents the medial femoral condyle – the patellar odd-facet contact – in accordance with the results of studies on the contact patterns of the patello-femoral joint [6, 7, 14].

The medial patellar rotation and the lateral patellar shift are induced by the direction of the femoral groove, slightly laterally oriented, as seen from proximal to distal. By the pull of the patellar ligament the patella rotates medially with further knee flexion. This also explains the increment of medial patellar rotation caused by internal tibial rotation as an effect of further medialisation of the patellar tendon. In the same manner the reduced lateral patellar shift along the internal tibial rotation pathway is explained.

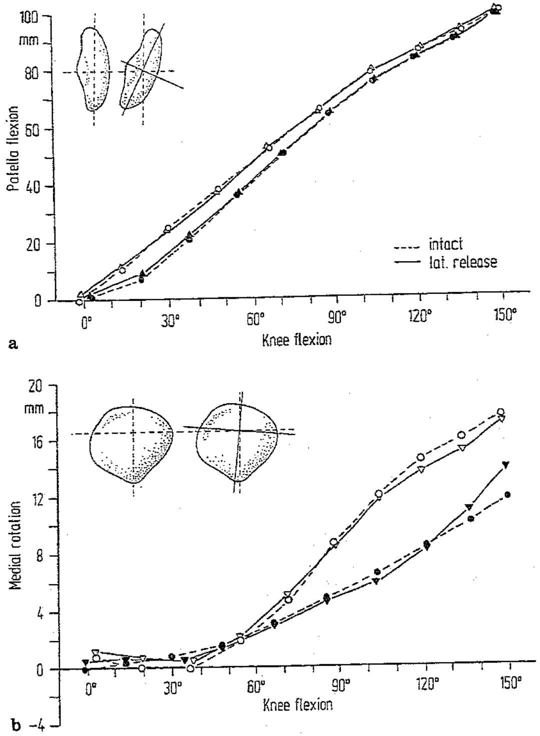

Fig. 5 a–d. Effect of lateral retinacular release on patellar rotations and shift. **a** Patellar flexion, **b** patellar rotation, **c** patellar tilt, **d** patellar shift. *Open circles, triangles,* internal tibial rotation pathways; *closed circles, triangles,* external tibial rotation pathways; *broken lines,* before lateral release; *solid lines,* after lateral release

The three-dimensional tracking patterns are greatly influenced by tibial rotations: patellar tilt and shift more in the first stage of knee flexion and patellar rotation more in the second. At examination the patellar shift and tilt seem to be a coupled movement. Patellar rotation seems to follow the varus/valgus rotation of the tibia.

Lateral retinacular release for chondromalacia is intended to alter and reduce the pressure distribution in the patellofemoral joint through a medialisation of the resultant quadriceps force. This should result in a rerouting of the patellar tracking mechanism. The present results on the three-dimensional tracking pattern of the patella after lateral release, however, indicate that the patellar tracking pattern mechanism is determined mainly by the bony constraints and by the pull of the patellar ligament. It is not influenced by a lateral retinacular release, once it is

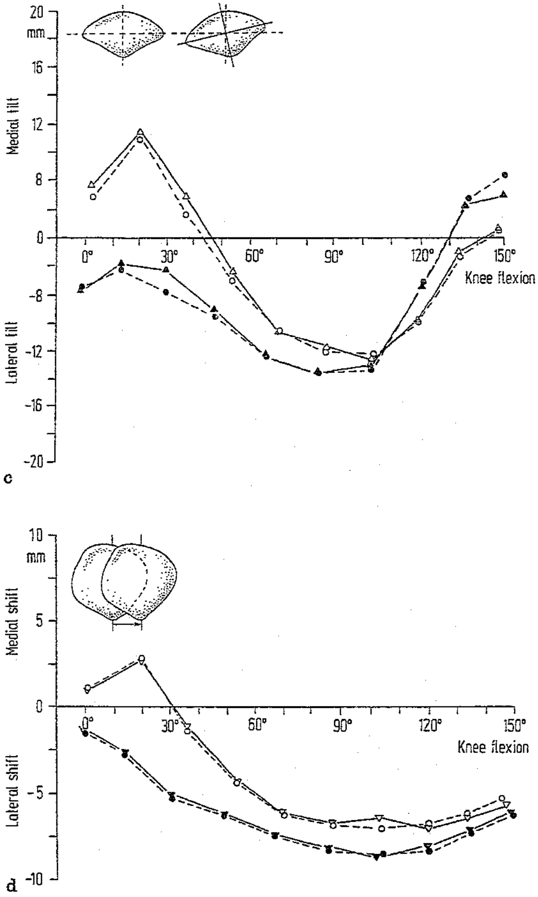

Fig. 5c, d.

pressed into the femoral groove in the greater knee flexion angles. Hence, it is likely that the shape of the contact areas, the pressure distribution and the contact area locations are not affected by this operation. This should discourage the use of this operative procedure in knees in which the lateral retinaculum is essentially normal. Loosening of the lateral retinaculum may be of value only in patients with a so-called tight retinaculum, diagnosis of which can be confirmed by axial X-ray exposures. If a beneficial effect of the lateral retinacular release in normal anatomical configuration exists, this may be explained by the cutting of the sensory nerve endings.

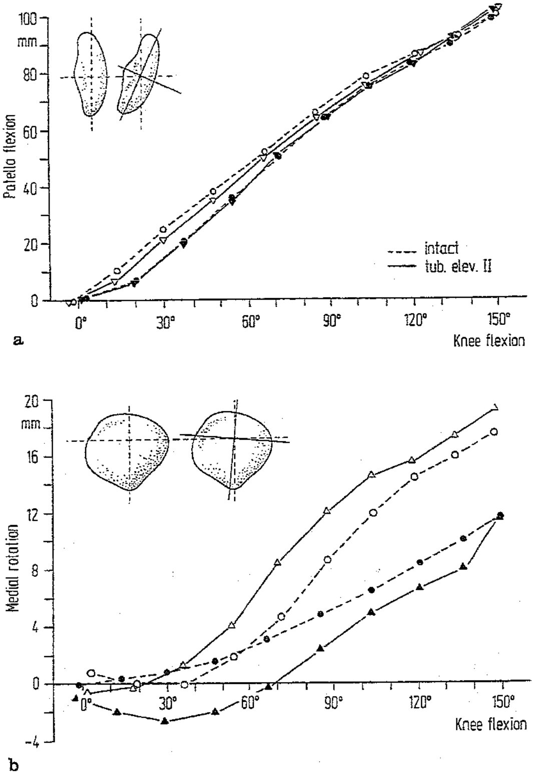

Fig. 6 a–d. Effect of tubercle elevation of 1.0 cm on patellar rotations and shift. **a** Patellar flexion, **b** patellar rotation, **c** patellar tilt, **d** patellar shift. *Open circles, triangles,* internal tibial rotation pathways; *closed circles, triangles,* external tibial rotation pathways; *broken lines,* before tubercle elevation; *solid lines,* after tubercle elevation

The objective of the tubercle elevation, reducing the patellofemoral contact force by increasing the moment arm of the patellar tendon, has been motivated by several studies [1, 4, 11, 12]. However, none of these studies took tibial rotations into account. Patellar rotations are greatly influenced by tibial rotations in the intact situation, and even more so after tubercle elevation. The latter is probably due to the increased medial/lateral translation of the tuberosity after elevation, as depicted in Fig. 7. The importance of a changing Q-angle on retropatellar contact areas and stresses has been emphasized by Huberti and Hayes [8], who found in an experimental study that increasing the Q-angle resulted in increased peak pressures and changes of the contact locations. Decreasing the Q-angle resulted in un-

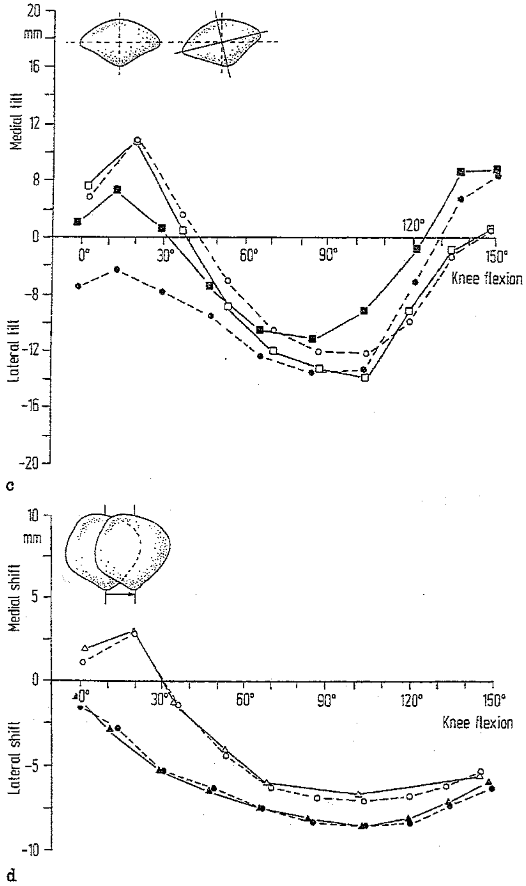

Fig. 6c, d.

loading of the vertical patellar ridge, but this was always associated with increased peak pressures at other locations. After tubercle elevation this may lead to even higher peak pressures with unpredictable contact areas due to the increased influence of the Q-angle on patellar tracking than to realising the objective of reducing the patello-femoral contact pressures.

From the present results it is evident that influences of tubercle elevation on patellar tracking pattern do exist, but their nature and extent are unpredictable. Therefore it is doubtful whether the objective of the tubercle elevation operation, the reduction of patello-femoral contact stresses, is actually accomplished.

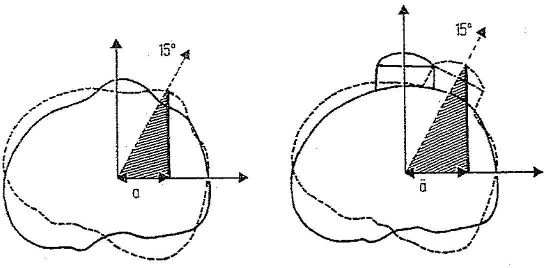

Fig. 7. Translation of tibial tuberosity (*a, left*) increases after tubercle elevation (*a'', right*) with the same tibial rotation (15°)

Summary

A data base has been offered for the normal patellar tracking pattern as established with a high precision measurement method (RSA). Normal patellar tracking is characterised by a patellar flexion, a wavering patellar tilt, a medial patellar rotation and a lateral patellar shift with progressive knee flexion. Tibial rotations have an extensive effect on the tracking pattern. The tracking pattern does not change after performance of a lateral retinacular release. After a tubercle elevation changes in patellar tracking do occur but are unpredictable in direction and magnitude. An important factor and one caused by the tubercle elevation is the change in Q-angle.

Based on the present results it is doubtful whether the objectives of both operations, rerouting the patella and/or reducing the compressive patello-femoral forces, are achieved.

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