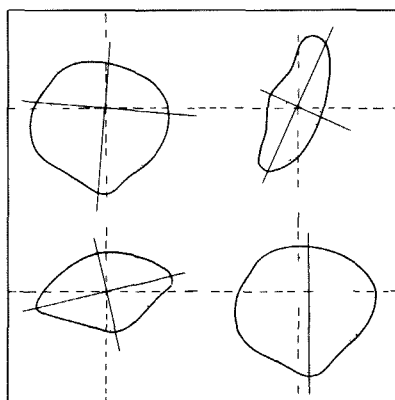


THE THREE-DIMENSIONAL TRACKING PATTERN OF THE PATELLA



A VAN KAMPEN

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THE THREE-DIMENSIONAL TRACKING PATTERN OF THE PATELLA

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THE THREE-DIMENSIONAL TRACKING PATTERN OF THE PATELLA IN VITRO ANALYSIS

PROEFSCHRIFT

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DOCTOR IN DE GENEESKUNDE
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To the memory of Theo van Rens

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INTRODUCTION

Orthopaedic research has progressed and improved tremendously during the last 25 years. The knee joint has always been an important subject of this research, as a challenge to investigators because of its kinematic complexity. Assisted by biomechanical studies, knowledge of the tibiofemoral articulation (e.g. motion, contact areas and stresses, ligament function and stresses) has increased.

In 1977, the patellofemoral joint was described by Ficat and Hungerford as "The forgotten compartment of the knee joint". Ten years later, reviewing the literature, this is still partly true. In the last decade more research has been carried out concerning the biomechanical behaviour of the patellofemoral joint, with special emphasis on contact zones and pressure distribution. This research has been partly initiated by the clinical problem of chondromalacia, often assumed to be related to disturbances of the physiological pressure distribution and contact zones.

The phrase "forgotten compartment" is still justified where the kinematics of the joint is concerned. Although patellar movements partly determine the contact zones and the pressure distributions, fundamental research concerning the kinematic behaviour of this joint is still scarce.

Evidently, influences on patellar tracking by several surgical procedures are also unknown. This lack of knowledge was stimulating enough to start a project to measure the precise three-dimensional tracking patterns of the patella. In the biomechanical section of the Laboratory for Experimental Orthopaedics of the University of Nijmegen, experience with a high precision measuring system (roentgenstereophotogrammetric analysis, RSA) was available for such experiments.

Chapter II contains a brief description of the anatomy of the patellofemoral joint, because the bony landmarks of the joint partly determine the patellar movements. A survey of the literature concerning contact patterns, contact stresses and kinematics is also presented, to be related to the results of the present experiment. The methods used and the results obtained for the normal tracking patterns of the patella are presented and discussed in Chapter III.

Chapter IV discusses the pathophysiology, the etiology and the different forms of treatment of chondromalacia, as mentioned in the literature.

In Chapter V, the changes in patellar tracking after two types of operations, performed in our experiments, are examined and discussed.

In 1984, Bentley and Dowd pleaded for further research concerning biomechanics, biochemistry and healing properties of the articular cartilage of the patella, in

order to increase our knowledge and ability to distinguish the different causes of the anterior knee pain syndrome.

The aim of this study was to contribute to a better understanding of the patellofemoral joint.

The objectives of the present study were:

- Accurate determination of the full 3-dimensional tracking patterns of the human patella during flexion/extension of the knee joint.
- Evaluation and interpretation of the effects of internal/external tibial rotations on the tracking patterns.
- Observation and interpretation of changes in tracking patterns by surgical interventions.

FUNCTIONAL ANATOMY AND BIOMECHANICS

II.1 EMBRYOLOGY

The patella is the largest sesamoid bone in man. Its sesamoid nature has been subject of discussion in the literature. Bernays (1878) and Brooke (1937) have described the patella developing behind the quadriceps tendon. It was Walmsley, in 1940, who examined a series of human knee joints in embryos and young foetuses, indicating the development of the patella in the quadriceps, stating: "Where the quadriceps is in relation to the lower end of the femur there is an aggregation of rounded cells in the deeper three-fifths of its substance in a 20 mm embryo. This is the early representative of the patella; and, though its margins are indefinite, it is obviously confined to the substance of the quadriceps and there is a gradual transition of its cells into those of the quadriceps network".

In the first six months of foetal life, the patella grows relatively fast (de Vriese, 1908; Walmsley, 1940). During the development of the patellofemoral joint, the knee joint is in a flexed position of about 90 degrees (Bernays, 1878; Herzmark, 1938; Walmsley, 1940).

Differences in size between the medial and lateral articular facets of the patella are visible already in the seventh month (192 mm embryo; Walmsley, 1940). Development of the supracondylar patellar surface of the femur, initiated by the developing suprapatellar pouch, takes place in the same period, with an already visible, more prominent, part of the lateral femoral condyle (Walmsley, 1940). Thus, the form of the patella is defined and determined in an early stage, independently of the femoral surface to which it is to be opposed after birth. Details of the functional form (e.g. articular ridges) are acquired when its function is established (Walmsley, 1940; Gray and Gardner, 1950; Ficat and Hungerford, 1977). After birth, the patella is completely cartilaginous. The ossification usually starts after the second year and is complete at maturity (Köhler and Zimmer, 1982). The post-natal development of the condyles is characterised by a relative overgrowth of the posterior parts, contributing to the reposition of the femoral condyles in respect to the load axis (Von Lanz and Wachsmuth, 1972).

II.2 FUNCTIONAL ANATOMY OF THE PATELLOFEMORAL JOINT

II.2.1 Anatomy of the distal femur

The knee joint is the largest joint in the body. It consists of two articulations, the tibiofemoral and the patellofemoral one, with a common articular cavity. With respect to the patellofemoral articulation, the femoral condyles are not parallel, but diverge posteriorly and inferiorly. The inclination of the medial femoral condyle is more pronounced as compared to the lateral one (Fig. II.1).

The medial condyle reaches further caudally than the lateral one, to such an extent that, despite the obliquity of the femoral shaft, the lower surface of the femur is practically horizontal. The lateral condyle reaches further anteriorly than the medial one, causing the lateral patellar surface of the femur to be more prominent than the medial part. The sagittal curves change from circles of large radii anteriorly to ones of smaller radii posteriorly, resulting in spiral curves (Morris, 1953). The articular surface of the patellofemoral joint of the femur extends over the anterior surface of both condyles, the larger part of it on the lateral condyle.

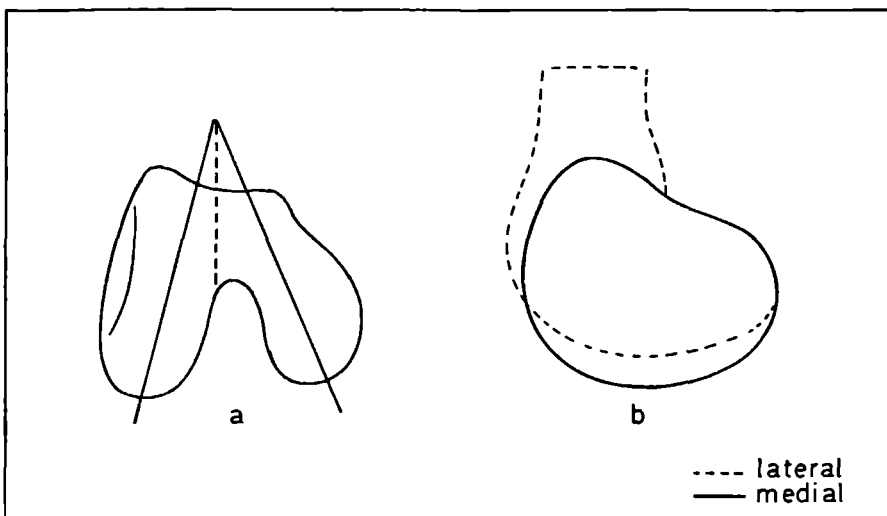


Fig. 11.1: Schematic representation of the distal femur (right knee). a: transvers view, showing the difference in inclinations of both condyles, and the further anteriorly reaching wall of the lateral one. b: the sagittal view shows the further caudally reaching medial condyle.

11.2.2 Anatomy of the patella

The patella consists of cancellous bone, covered by a thin compact lamina. It is triangular on the lower side (the apex patellae) and curved on the upper (the basis patellae). The anterior surface is convex and roughened by many longitudinal striae.

Its axial length is about 4-4.5 cm and its maximum thickness about 2-2.5 cm (Anglietti et al., 1975; Reider et al., 1981). At its superior, lateral and medial borders, the patella is attached to fibres of the m. vastus femoris and m. vastus intermedius, the m. vastus lateralis and the m. vastus medialis respectively, forming a trilaminar expansion over the patellar tendon, continuing below in the

patellar ligament (Last, 1948). The contribution of the different muscle tendons to the expansion is variable (Reider et al., 1981).

The patella is embedded in the fibrous continuation of the quadriceps muscle and also stabilised at the sides by the medial and lateral retinaculum. The medial and lateral stabilization is augmented by an epicondylar patellar band and a patellotibial band deep to the superficial retinaculum on both sides (Fick, 1904; Braus, 1954; Fulkerson and Gossling, 1980).

The patellar tendon length is about 4.5-6 cm, slightly converging from the patellar apex to its insertion on the tuberositas tibiae (the tibial tubercle).

The articular cartilaginous surface of the patella can be divided, by a vertical ridge, in a medial and a lateral facet. Close examination reveals, that the articular surface can further be divided in several different facets (Fick, 1904; Wiberg, 1941) of which the most medial facet (the odd facet) is probably the only one of clinical importance (Goodfellow et al., 1976). The cartilage thickness reduces from the vertical ridge to the lateral and medial borders. The blood supply of the patella is provided by an anastomotic ring surrounding the patella, with contribution of the superior genicular, medial genicular, lateral genicular and anterior tibial recurrent artery (Scapinelli, 1967).

II.2.3 Patellar function

The patella is an important functional component of the extensor mechanism of the knee joint. Kaufer (1971) designed a mechanical study to define and quantify the extensor function of the patella and the effect of its removal. His results contradicted the, now regarded as obsolete, ideas of Brooke (1937) and Watson-Jones (1945), who believed that the patella was only a morphological remnant and that its removal probably even increases the knee movement and quadriceps power. Kaufer (1971) showed that the patella contributes to the knee extension moment arm through the entire range of motion, which increases with progressive extension. Excision of the patella led up to a maximum of 30 percent decrease in quadriceps force moment. Many authors have later supported Kaufer's views.

Besides increasing the moment arm and centralising the forces of the different muscles, the patella provides a smooth gliding mechanism for the quadriceps muscle with little friction by its hyaline cartilage coverage (Ficat, 1970; Larson et al., 1978). Some authors (Fick, 1904; Freehafer, 1962) emphasize the protective function of the patella for the cartilage of the distal femoral condyles when the knee is flexed.

II.3 KINEMATICS OF THE KNEE JOINT

II.3.1 Introduction

Neither of the two articulations of the knee joint act as a simple hinge. The tibiofemoral articulation has two degrees of rotational freedom, of which apart from flexion/extension, exo-/endorotation plays an important role. Varus/valgus

rotations occur during flexion, but are coupled to the flexion and tibial rotations (Blankevoort et al., 1987). In the same manner, the patellofemoral joint can in principle display rotations around three axes; these rotations may be mutually coupled, or coupled to those in the tibiofemoral joint.

The patellofemoral joint shows a rolling-gliding mechanism in which the direction of gliding, expressed as tendencies of articular surface motion, is opposite to that of rolling, while in the tibiofemoral joint the directions of gliding and rolling are equal (Müller, 1983). In order to describe the motion patterns of the patellofemoral joint, knowledge about the tibiofemoral joint motion is essential and must be taken into account, because patellar movements are particularly influenced by tibial rotations, as will be shown in Chapter III.

II.3.2 Tibiofemoral motions

II.3.2.1 Exo-/endorotation

The total amount of rotational freedom depends on knee-flexion angle, the torque on the tibia and the axial loading. The exo-/endorotation component is illustrated by the so called "screw-home" mechanism, the obligatory exorotation of the tibia during the last phase of extension. This "obligatory" rotation, described by several investigators (Hallen and Lindahl 1966, Markolf et al., 1981), is probably due to the function of active stabilisers in combination with geometric and ligamentous constraints, but is not a property of the passive knee structure (Blankevoort et al., 1987).

II.3.2.2 Varus/valgus rotation

In contrast to exo-/endorotation, varus/valgus rotation is not a degree of freedom, but occurs as an obligatory motion, kinematically coupled to flexion and exo-/endorotation by the passive joint structures. Very little has been published relative to the amount of varus/valgus rotation. Van Dijk (1983) found a synchronous abduction or valgus movement of the tibia, independently of an exo- or endorotation moment. These findings were only partly supported by Blankevoort et al. (1987), who found a tendency towards valgus rotation with an endorotation moment and towards varus rotation with an exorotation moment on the tibia. This difference is probably caused by a lack of control of the external knee forces in the experiments of van Dijk (1983).

II.3.3 Patellofemoral motions

Although several investigators (Fick, 1904; Wiberg, 1941; De Sèze et al., 1951; Bouillett and Van Gaver, 1961; Brattström, 1964; Ficat, 1970) paid attention to patellar flexion and patellar shift during flexion of the tibia, quantification of these movements was not made until 1979, when Veress et al. measured patellar tracking patterns by analytical X-ray photogrammetry.

In the same year Sikorski et al. (1979) developed a measuring system whereby

patellar rotations could be measured in two planes with two roentgenexposures. Reider et al. (1981) used an orthogonal grid system to measure the position of the patella in three dimensions during flexion/extension of the knee joint. Finally, using patellar and femoral replica's, Fujikawa et al. (1983) measured two rotational movements of the patella during knee flexion.

The nomenclature given to the different rotations of the patella is confusing and not generally consistent. For example, Fujikawa et al. (1983) describe the rotatory movement of the patella about the antero-posterior axis as the frontal rotation, whereby the lateral (frontal) rotation was defined as the patellar apex moving towards the fibular head. Reider et al. (1981) call this movement medial rotation (or clockwise rotation in right knees).

For the present investigation, coordinate systems are used, introduced in the distal femur, the proximal tibia and the patella (Fig. II.2).

The origin of the femur coordinate system is located in the highest point of the intercondylar notch, at the cartilage border. The origin of the tibial coordinate system is located in the centre of the tibial plateau, just behind the insertion of the anterior cruciate ligament. The origin of the patellar coordinate system is in the centre of the patella. The axes of the three systems are parallel in extension, in which case the x-axes point medially, perpendicular to the sagittal plane; the

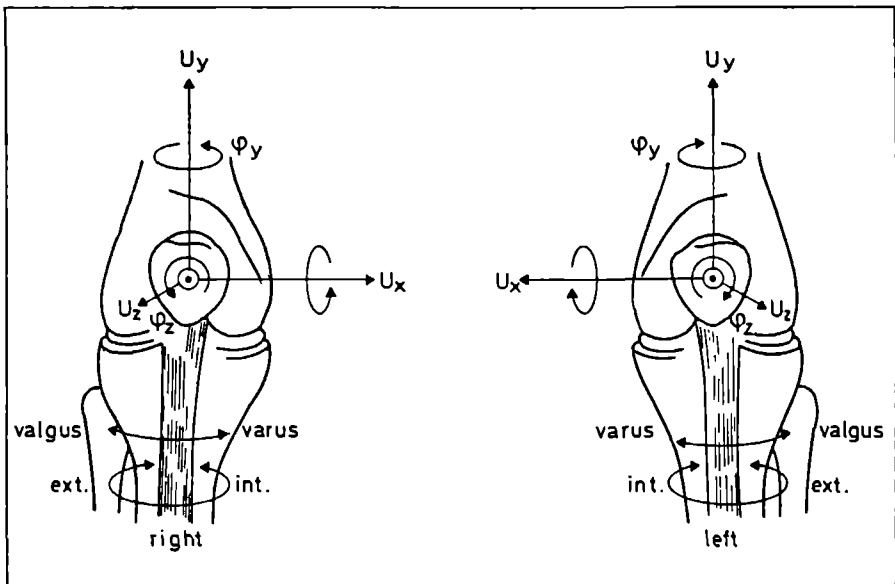


Fig. II.2: The orientation and location of the coordinate axes of the patella for left and right knee specimens, as introduced for the present investigation. Subsequent rotations around the axes represent patellar flexion (x-axis), patellar tilt (y-axis) and patellar rotation (z-axis). Translation along the x-axis represents patellar shift. For reasons of clarity, the coordinate systems of the femur and the tibia are not shown.

y-axes point proximally, perpendicular to the horizontal plane; the z-axes point anteriorly, perpendicular to the frontal plane.

During knee motion, the femoral system is considered as the space-fixed system, relative to which the tibial and patellar motions are described. Tibial rotations around the femoral x-axis describe flexion/extension. Tibial rotations around the tibial y-axis and z-axis describe exo/endorotation and varus/valgus rotation, respectively. Patellar rotations around the femoral x-axis describe patellar flexion (positive) or extension (negative). Rotation around the patellar y-axis describes medial tilt (positive), when the medial patellar facet rotates towards the medial femoral condyle; or lateral tilt (negative), when the lateral patellar facet rotates towards the lateral femoral condyle. Rotation around the patellar z-axis represents medial patellar rotation (positive), when the patellar apex turns towards the medial condyle; or lateral patellar rotation (negative), when the patellar apex turns towards the lateral condyle. Translation along the femoral x-axis will be described as patellar shift, medial positive and lateral negative. (See also Fig. II.3).

In the following description of data from the literature, the nomenclature of patellar rotations used by the different authors have been transformed, if necessary, to the above mentioned convention, for reasons of clarity.

Veress et al. (1979) measured patellar tracking patterns by analytical X-ray photogrammetry in four patients with degenerative joint disease of the knee, who had undergone a high tibial osteotomy. The tracking patterns were determined from four measurements, from extension to 90 degrees of knee flexion, with an unknown isometric contraction of the quadriceps. The overall results showed a progressive lateral shift with increasing knee flexion and an inconclusive tilt movement (subject 1: lateral, 2: mediolateral, 3: medio-lateral, 4: medial). Tibial rotations were not taken into account. The rotations of the patella were measured relative to the femur.

Sikorski et al. (1979) introduced a radiological technique, in which by serial axial radiographs of the patellofemoral joints, patellar rotation (tilt and rotation) could be measured in two planes. Measurements were taken from 12 adult volunteers, not suffering from chondromalacia patellae, with isometric quadriceps contractions. The results showed a progressive lateral rotation of the patella from 60 degrees to 120 degrees knee flexion (3 measurements), and a slight medial tilt. These motions were not quantified.

The first study quantifying patellar motions in an in vitro situation was undertaken by Reider et al. (1981). Their experiments were performed with a fixed tibia and moving femur from 0-90 degrees flexion, with a standard traction of 92 N applied to the quadriceps muscle. Measurements were taken with 15 degrees flexion increments, using an orthogonal grid system. The patellar movements were reported relative to a fixed tibial reference point (the tibial tubercle). They observed two basic tracking patterns in 20 cadaver knees. The first tracking pattern (in 17 knees) showed a lateral shift, a lateral tilt and a lateral rotation of the patella with progressive knee flexion, in respect to the tibia. The second tracking pattern (in 3 knees) showed a lateral shift up to 30 degrees of knee flexion, a medial shift with further flexion, no tilt, and a lateral rotation of the patella.

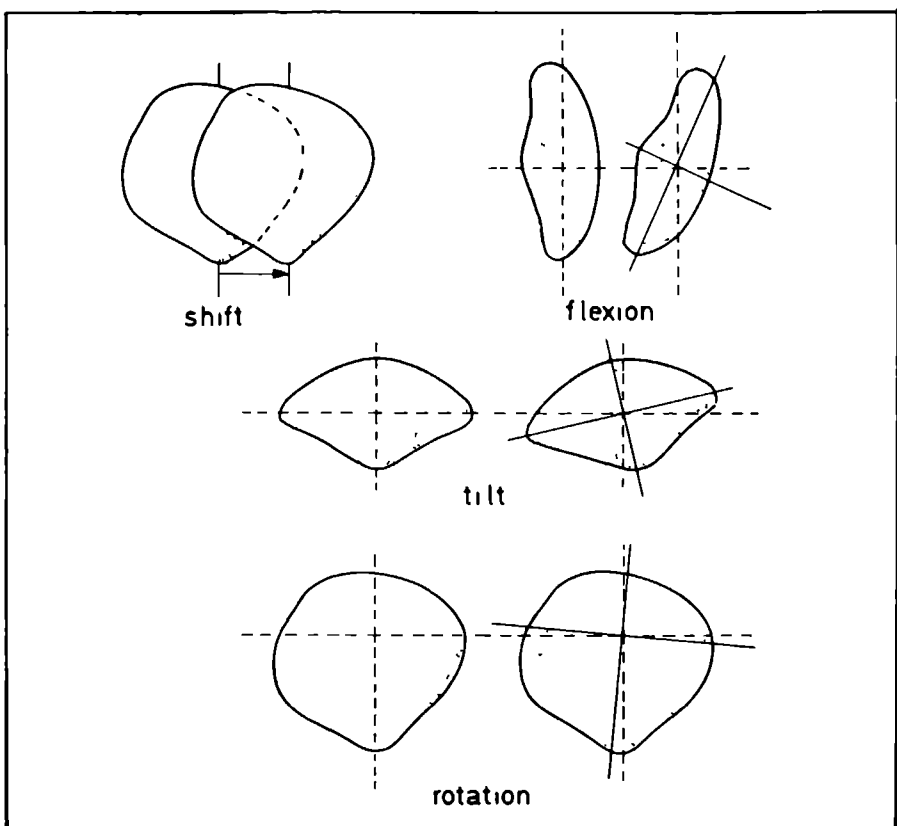


Fig. 11.3: Illustration of the patellar rotations and patellar shift.

The investigators assume that the latter group may represent asymptomatic knees, with an underlying tendency to abnormal tracking. In their article, Reider et al. (1981) describe only the direction of the patellar movements and quantify the total excursions. The different patella positions at different flexion angles are not presented, and no tibial rotations were taken into account.

Fujikawa et al. (1983) published their experimental work on the patellar movements on eight human cadaver knee joints. They studied the patellar rotation and the patellar tilt, from replica's of both the patella and distal femur, from 25 degrees flexion to full knee flexion (6 measurements). The results show a lateral progressive rotation of the patella with increasing knee flexion, with a total average excursion of 6.2 degrees. The patellar tilt is determined by the lateral patellofemoral angle as defined by Laurin et al. (1978). This implies that the

degree of tilt measured is not precisely in relation to the supero-inferior femur axis, but to the femoral trochlea. The patella showed a progressive medial tilt, averaging up to a maximum of 11 degrees.

The conclusion of the few data from the literature must be that the kinematic behaviour of the patella in relation to the patellofemoral joint is not precisely known. The available data, as summarized in table II.1, are inconsistent. The most important objective of this study was to provide a precise and complete data base of patellar tracking patterns.

Authors	Nr Specimen		Q-loading	Measurements		Tibia rotation	Average Patellar movements		
	in vivo	in vitro		number	range		shift	rotation	tilt
Veress et al '79	4		isometric	4	0-90°	neutral	lateral	unknown	not conclusive
Sikorski et al '79	12		isometric	3	60-90°	neutral	unknown	lateral	medial
Reider et al '81		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 '83		8	20-30 N	6	25-130°	unknown	unknown	lateral 6.2°	medial 11°

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

II.4 PATELLOFEMORAL CONTACT AREAS AND FORCES

II.4.1 Introduction

Different methods for determining patellofemoral contact areas have been used by several investigators, e.g. methyl-methacrylate prints (Shoji, 1974), dyes (Goymann et al., 1974; Matthews et al., 1977; Goodfellow et al., 1976), silicon rubber prints (Seedhom et al., 1979; Fujikawa et al., 1983), pressure distribution transducers (Ahmed et al., 1983) and pressure sensitive films (Huberti et al., 1984; Hille et al., 1985).

Differences in established contact areas among the various investigators do exist and are partly due to the different techniques used and to influences of patellar shape. Magnitude, direction and duration of patellofemoral loading also plays a role.

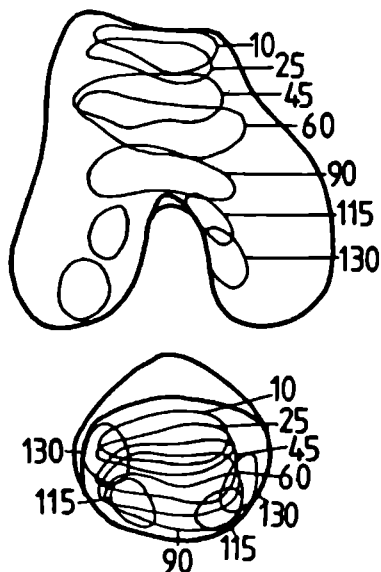


Fig. 11.4: Contact areas on both femur and patella at different angles of knee flexion (right knee), (from Fujikawa et al. 1983, by courtesy of the publisher of Engng. in Med.).

11.4.2 Patellar contact areas

In full extension, there is no contact area between patella and femur, or a very slight one, located at the lower margin of the patellar cartilage. With progressive flexion, the contact area, mostly bean-shaped, increases over both the lateral and medial facets and migrates proximally, reaching the upper pole of the patella between 90 degrees (Seedhom et al., 1979) and 120 degrees of knee flexion (Huberti et al., 1984; Ahmed et al., 1983). A contact area between the medial odd facet of the patella and the medial femoral condyle is found by most authors after 90 degrees, or even after 120 degrees of knee flexion. The contact areas in the last part of flexion differ between investigators and between investigated specimens. Some authors (Hehne et al., 1981; Hungerford and Barry, 1979) found that with increasing flexion angles, the contact area is divided in two parts and shifting distally again, while others (Huberti et al., 1984; Hille et al., 1985) found a persisting dome shaped contact area at the proximal edge of the articular cartilage. Using a mathematical model of the patellofemoral joint, van Eijden (1985) supports the first opinion; namely that the upper part of the patella is used twice during the flexion movement of the knee.

11.4.3 Femoral contact areas

The contact area on the femoral trochlea moves distally from full extension to flexion and initially forms a wide band, that divides into two separate contact areas over both condyles after reaching the top of the intercondylar notch at about 90 degrees of knee flexion. An example of contact areas, from the study of Fujikawa et al. (1983), is shown in fig. 11.4.

From about 90 degrees of knee flexion there is an increasing contact area between the femoral trochlea and the quadriceps tendon, which may reduce the pressure on the patellar surface (Henne et al., 1981; Huberti et al., 1984). The magnitudes of the contact areas differ remarkably between investigators (Ahmed et al., 1983). The contact areas vary from about two square centimeters in 20 degrees of knee flexion to about four square centimeters in 90 degrees of knee flexion and reduce in the last part of flexion to about three square centimeters. Most authors describe larger contact areas over the lateral facet in comparison to the medial one. Assuming the average retropatellar surface area to be about twelve square centimeters, approximately one-fifth of the total patellar articular area in slight flexion, and roughly one-third at 90 degrees knee flexion is in direct contact with the femur.

II.4.4 Patellofemoral forces

Controversies about patellofemoral compression forces and contact pressures are even more extensive than those about contact areas.

Because measuring patellofemoral compression forces in vitro is difficult, many investigators have previously calculated these forces, based on the assumption that the force through the quadriceps muscle is equal to the force through the patellar ligament (Reilly and Martens, 1972; Matthews et al., 1977; Seedhom et al., 1979). The resultant force represents the compression force, depending on the angle (β) between the quadriceps muscle and the patellar ligament (Fig. II.5). According to this model the compression force increases from extension to flexion, caused by a decrease of the angle β . More recently, several investigators have shown that this model is not entirely correct (Ellis et al., 1980; Huberti et al., 1984; van Eijden, 1985). By in vitro measurements (Ellis et al., 1980; Huberti et al., 1984) as well as with a mathematical model of the patellofemoral joint (van Eijden, 1985) it has been shown that the ratio between the force in the patellar ligament (F_p) and the force in the quadriceps tendon (F_q) varies with flexion. The force ratio (F_p/F_q) was found to range from about 1.1 in extension to about 0.7 at 90 degrees flexion, due to variable locations of the patellar contact areas.

The calculations also assume a specific patellofemoral contact point, which is not true in the real situation, where a contact area or two contact areas occur (Henne et al., 1981; Fujikawa et al., 1983). Finally, in the fore-mentioned calculations of the forces, the contact between the quadriceps tendon and articular surface of the femur, which transfers a considerable amount of the contact forces in greater flexion, is not taken into account (Huberti et al., 1984). A more realistic approach to patellofemoral forces and pressure determination became possible with the introduction of pressure-sensitive films (Prescale, Fuji), which permit the direct determination of the pressure patterns and the contact areas within the joint.

The results of two recent studies (Huberti et al., 1984; Hille et al., 1985) show remarkably uniform patellofemoral contact pressures over the entire contact surface. The pressures are usually maximal between 60 and 90 degrees of flexion.

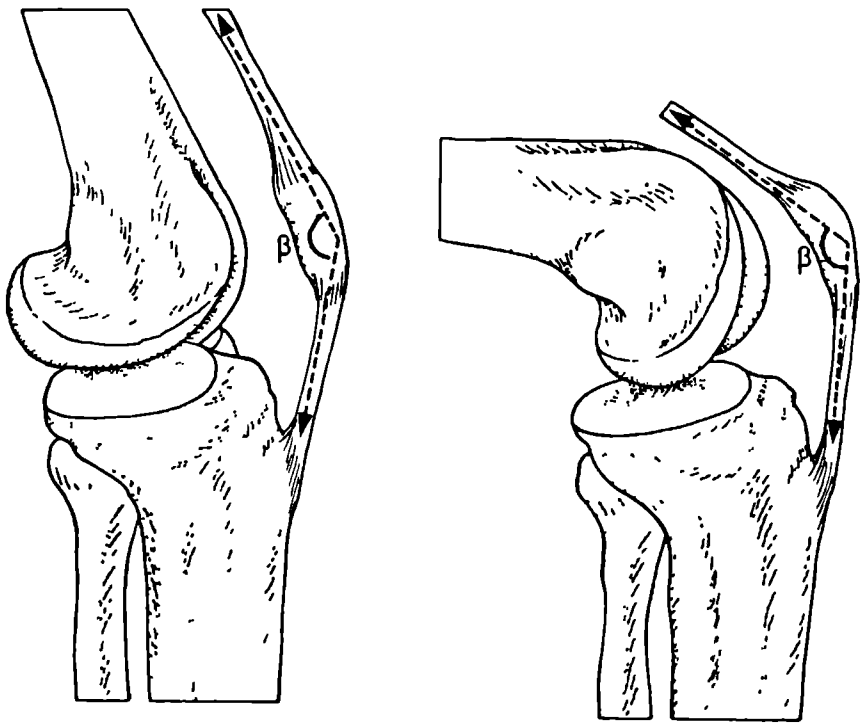


Fig II 5 Illustration of the decrease of the angle β between quadriceps tendon and patellar ligament by the increase of knee flexion

Although, beyond 90 degrees, a higher contact pressure is sometimes found over the medial patellar facet

II 5 SUMMARY AND CONCLUSIONS

The information from the literature shows that the kinematic behaviour of the patella in relation to the femur is not precisely known and the available data are inconsistent. The effects of tibial rotations, which may influence the patellar tracking patterns, were not studied. The most important objective of the present study was to provide a data base of precise and complete patellar tracking patterns. More is known about the patellofemoral contact behaviour, although inconsistencies are found here, too. Differences in size of patellofemoral contact patterns, as well as controversies on magnitudes of patellofemoral compression forces and contact pressures are partly due to different laboratory conditions for the in vitro measurements reported. At the present time such characteristics as patellofemoral contact areas, forces and pressures cannot be measured in vivo. Therefore the significance of the results have to be considered only indicative of the situation in dynamic functional activities.

TRACKING PATTERNS OF THE NORMAL PATELLA

III.1 THE SELVIK MEASURING SYSTEM

The kinematic measuring system, introduced by Selvik in 1974, is based on roentgenstereophotogrammetric analysis (RSA). This system has been used for several years in our biomechanics section for a number of applications in human-joints kinematics (Van Dijk, 1983; De Lange et al., 1985; Huiskes et al., 1985; Blankevoort et al., 1987). RSA offers a three-dimensional technique, high accuracy and minimal damage to the object measured. RSA is built upon the reconstruction of spatial coordinates of markers, or object points, from their two-dimensional projections from two roentgentubes (Fig. III.1). The position of a rigid body in space is determined by the positions of three non-collinear points in this object. Because bones in general, and the skeleton of the knee joint in particular have no precise bony landmarks, markers are implanted into the cortex of the bones, with an especially developed insertion instrument (Aronson, 1974). Tantalum pellets of 0.5 to 1.0 mm diameter, which can be clearly depicted from roentgenexposures, are used for this purpose (Fig. III.2).

For reasons of accuracy, 5 to 6 tantalum pellets are placed in each bone, thereby

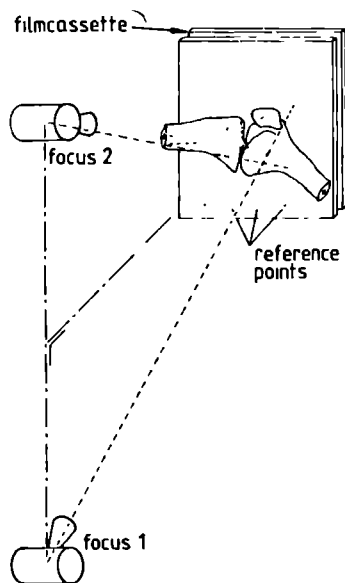


Fig. III.1: Schematic representation of the experimental set-up for RSA. At each flexion position the specimen is exposed by two roentgentubes (focus 1 and 2).

creating a redundant landmark system, by which the measurement error can be reduced to a minimum. The two-dimensional coordinates of these markers on the X-rays are measured with a coordinate digitizer and the data are transferred to a computer. The computer calculates the spatial coordinates of the markers (computer program X ray), and a second computer program (Kinema) calculates the positions of the bones (e.g. femur, tibia and patella) in relation to each other in terms of translations and Euler rotations. To describe joint motion, Cartesian coordinate systems are applied to the femur, tibia and patella as described in chapter II. In the initial or reference position of the knee (extension) the coordinate systems are parallel.

The accuracy of the acquired data depends on several factors, for example the already mentioned number of markers, the relative positions of these markers in the object, and the accuracy of the film digitizing procedure (Woltring et al., 1985; Huiskes et al., 1985). The precision of 3-D marker reconstruction was better than 50μ , resulting in Euler rotation precisions of appr. 0.1 degrees. The reproducibility of the experiments was tested by re-measuring one specimen.

III.2 MATERIALS

Using the experience of a pilot-study (van Gulick et al., 1983) a special motion rig was constructed to perform the experiments (Fig. III.3). To this motion rig the



Fig. III.2: Double roentgenexposures of a knee specimen in 30 degrees flexion. The two-dimensional coordinates of the visible tantalum pellets can be measured with a coordinate digitizer.

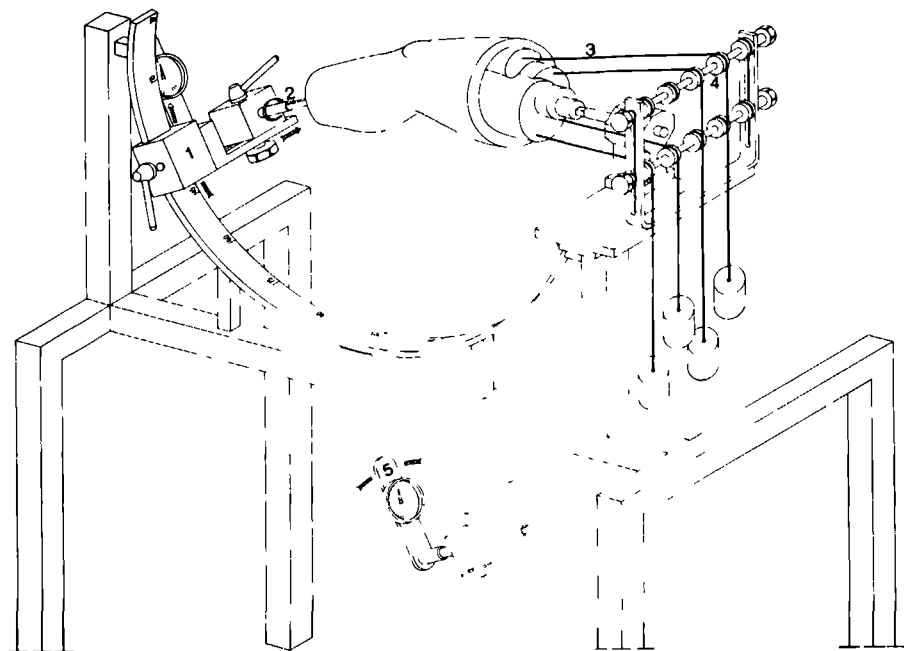


Fig. III.3: Schematic drawing of the motion rig.

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. The torque-wrench.

femur is fixed horizontally with an intramedullary rod, fixed with acrylic cement. The rod is rectangular on the femoral side, to avoid rotation in the cementlayer. In the intramedullary canal of the tibia a rod is cemented as well. This rod is placed in a clamp, allowing prescribed rotations (internal and external) of the tibia, and prescribed tibiofemoral flexion/extension motions along the circular rail. Along the circumference of this rail a scale from 0-150 degrees is engraved. During normal flexion-extension movements of the knee, the varus-valgus position of the tibia changes. Therefore, the tibia fixation clamp is constructed in such a way, that such movements are free to occur during a flexion step. The clamp can be fixed in a specific position afterwards. Torques for internal and external rotation of the tibia are manually applied, using a torque-wrench fixed to the tibia-rod. Torques of zero and ± 3 Nm were routinely applied during the flexion-motion steps. These torques give a good description of the exo/endo rotation freedom of motion. The increase of freedom-of-motion ranges with increasing torques, is relatively small, due to the relatively high stiffness of the knee ligaments (Blankevoort et al., 1987), see Fig. III.4. The rotatory laxity at ± 3 Nm is defined as the limit of exo-/endorotations.

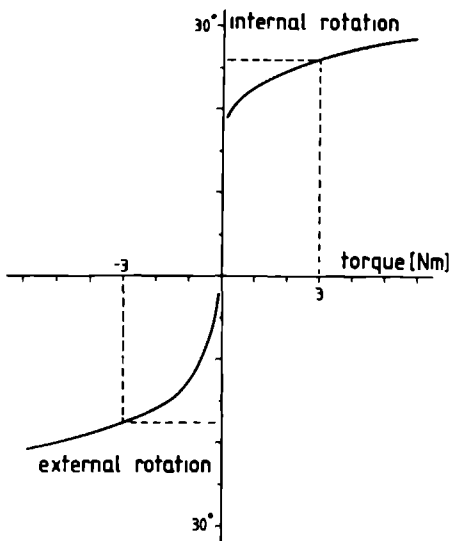


Fig. III.4: Torque-rotation curve of a knee joint specimen at 25 degrees flexion. The increase of tibial exo-/endorotation is relatively small for torque increases above the level of ± 3 Nm (Blankevoort et al., 1987).

The pulleys on the femoral side of the rig are used to guide the wires by which the quadriceps muscle is loaded in a specific direction.

Traction to the extensor apparatus could be applied in two different manners. Either traction to the patella itself, or traction to the four separate muscle components. The latter method was chosen for the present investigation, because of the resulting more natural and smooth distribution of forces over the patella. However, traction on the muscle-bellies provides an important limit to the force magnitudes exerted. Experimentally, the following method for exerting traction was found to be the most reliable: forces were applied through perforated aluminum strips, which were moulded and stiched around the muscle-bellies, at right angles to the direction of the fibres, at about 20 cm proximal from the joint-line (Fig. III.5). Tearing of the strip from the muscle was observed when a force greater than 50 Newton was applied to one muscle-belly. A force of 28 N per muscle-belly was chosen to just align the patella in the patellofemoral groove, similar to the forces used by Goodfellow et al. (1976), Seedhom et al. (1979), Ferguson et al. (1979) and Nakamura et al. (1985).

In one knee specimen the experiments were also performed with a force of 7 N per muscle-belly. Thus, patellar movements with total quadriceps forces of 112 N (Q high) and 28 N (Q low) could be compared.

To reduce the number of parameters, the traction was divided equally over the four components of the quadriceps muscle. This choice was arbitrarily, although consciously made. There are several studies concerned with quadriceps function, both mechanically and electromyographically (Hallen and Lindahl, 1966; Lieb and Perry, 1968, 1971; Basmajian et al., 1971). Although small differences do exist at various flexion degrees, the overall results seem to indicate an equal contribution of the four heads of the quadriceps muscle in extending the knee.

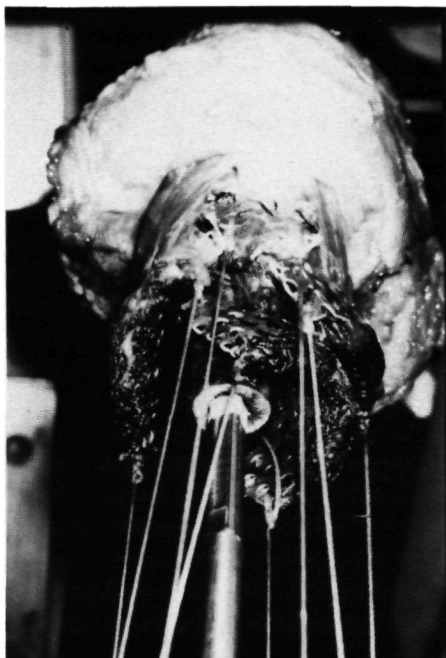


Fig. III.5: View of a knee specimen from proximally, showing the perforated aluminium strips attached to the four heads of the quadriceps muscle, the wires for traction exertion, and the intramedullary rod on the femoral side.

Four knee joints were investigated from patients who underwent an above-knee amputation for peripheral vascular disorders. Although at preselection knees with roentgenological evidence of patellofemoral arthritis or scars around the knee joint were excluded, the investigated knees showed at the time of preparation some form of retropatellar cartilage damage (see table III.1). This damage was probably age-related, in accordance with the findings of Emery and Meachim (1973). They found in 105 necropsy specimens these cartilage damages normally after the second decade. The femoral groove cartilage was normal in all knees. Grading of cartilage damage was performed according to Bentley and Dowd (1984). In three

Specimen	Age	Right/ Left	tib. fem. angle	Odd facet	Cartilage degeneration*)	
					Medial	Lateral
102	70	left	3°		1	2-3
103	80	right	8°	x	1	0
104	65	left	7°	x	1	0
105	57	right	5°	x	0	1

TABLE III.1 Data on four specimens.

*) Cartilage damage grading according to Bentley and Dowd (1984).

out of four patellae an odd facet could be established (Goodfellow et al., 1976). All knees showed intact menisci and cruciate ligaments.

III.3 EXPERIMENTAL METHODS

The amputated leg specimens were kept in a freezer until the time of use. After thawing, the bones were transected approximately 20 cm above and below the knee joint. The four parts of the quadriceps muscle (m. vastus lateralis, m. vastus medialis, m. vastus intermedius and m. rectus femoris) were dissected over a length of 10 cm, taking care not to open the knee joint. Around the different musclebellies the perforated aluminum strips were molded for the traction wires. In the femur, the tibia and the patella 5 tantalum markers were inserted, divided around the proximal tibia and the distal femur and along the border of the patella. To simplify identification of markers on the two roentgenexposures, tantalum pellets placed medially were 1.0 mm in diameter, pellets placed on the lateral side were 0.8 mm in diameter.

After cementing the rods in the intramedullary canals of the femur and the tibia, the specimen was placed in the motion rig. The long axis of the femur was positioned parallel to the roentgencassette. The joint line was placed approximately in the centre of the circular rail and the traction wires to the quadriceps muscle bellies were placed over the pulleys in the principal muscle orientations (Fig. III.5). During the preparation and the experimentation the specimens were kept moist with a Ringer solution. The experiments were carried out at room temperature.

The experiments included the following steps:

Step 1:

Stereo-roentgenexposures taken of the intact knee with the tibia extended (reference position) and after subsequent flexion steps of 15 degrees up to maximal flexion. This part of the experiment was repeated three times with:

1. the tibia in neutral rotation (zero torque),
2. a tibial external torque of 3Nm,
3. a tibial internal torque of 3Nm.

Step 2:

Performance of two different operations (see Chapter V) on the specimens, after which step 1 was completely repeated.

Step 3:

Dissection of the knee joint for inspection. Insertion of a tantalum pellet central in the patella, in the middle of the tibial plateau and in the intercondylar notch of the distal femur, to serve as origins for the three different coordinate systems.

A final stereo-roentgenexposure was made, to calculate the positions of the origins relative to the primary implanted pellets. For the reproducibility of the results on patellar movements between the four specimens, it was tried to insert the tantalum

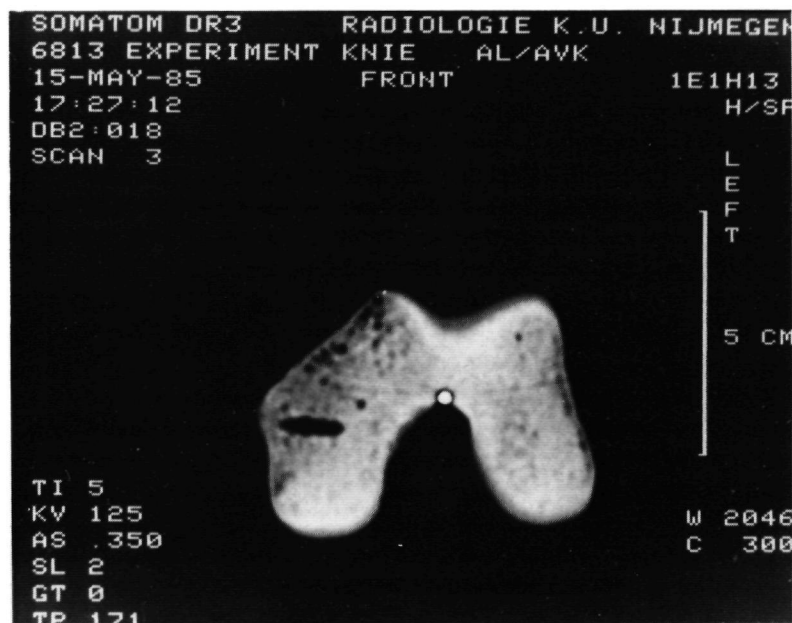
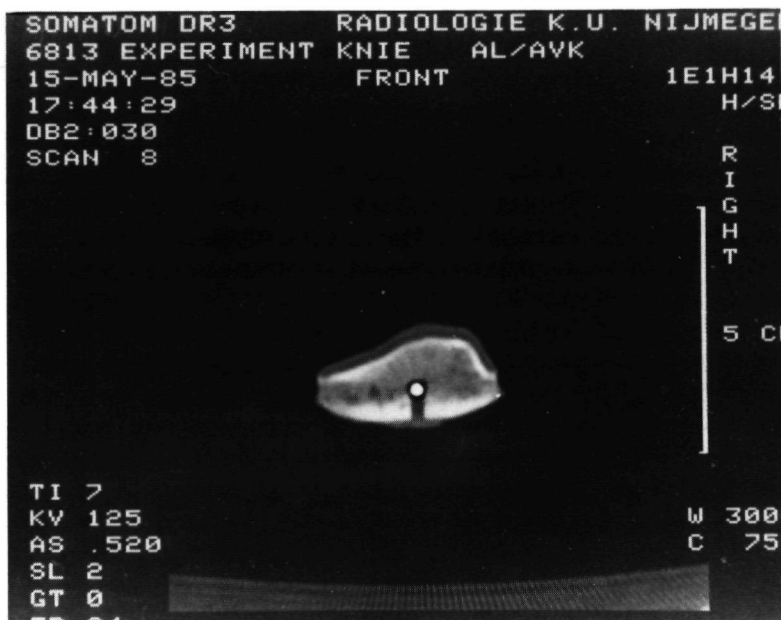


Fig. III.6: CT-scan of specimen 104, which shows the tantalum pellets, the localisations of the origins of the coordinate systems, in the femur and the patella.

pellet in -or near to- the centre of gravity. The more-or-less central position was checked with an AP and a lateral roentgenexposure. In one case a CT-scan was performed afterwards, giving a good impression of the location of the pellets in the femur and the patella (Fig. III.6).

In one specimen (104) the complete experiment was carried out with low (Q-low) and high (Q-high) quadriceps loading.

In another specimen (105) the three complete flexion series were repeated, in order to evaluate the reproducibility of the measurements.

The total number of double roentgenexposures for a single specimen varied, depending on how much flexion could be reached, from 72 to 90.

III.4 RESULTS

The results are arranged as follows:

1. Relative to the Cartesian coordinate system, tibial rotations around the x-axis (flexion-extension), the y-axis (endo-exorotation) and the z-axis (abduction-adduction) are determined. The tibial rotation patterns and the varus/valgus rotation patterns are presented as function of flexion.
2. Description of the patellar motions as function of knee flexion and tibial rotations. The coordinate system introduced in the centre of the patella defines patellar flexion-extension (rotation around the x-axis), patellar tilt (rotation around the y-axis) and patellar rotation (rotation around the z-axis).

In addition, the translation of the patella along the x-axis, relative to the femur, is determined (medial-lateral patellar shift).

These three patellar rotations and the shift are presented as function of the tibiofemoral flexion.

The first measurement of a particular specimen (extension, neutral tibial rotation) represents the reference position for all subsequent positions determined.

For reasons of clarity, the neutral rotation pathway of tibia and patella will not be included after the first figure. The neutral rotation pathways are normally situated between the motion pathways generated by the exerted torques on the tibia.

III.4.1 Tibial internal/external rotation

The envelope of internal and external tibial rotations with torques of ± 3 Nm, as a function of knee flexion is represented in Fig. III.7.

In the neutral motion pathway (zero torque) the tibial rotation alternated around neutral in specimen 105 with increasing knee flexion. The tibial rotations tended to move towards internal rotation with increasing knee flexion in the other three specimens.

The so called "screw home" rotation effect, the obligatory exorotation of the tibia towards full extension was present in the four specimens, in the neutral tibial rotation pathway. It is evident, however, that this mechanism disappears when external rotation torques are applied to the tibia, indicating that it is not a property of the passive joint structures.

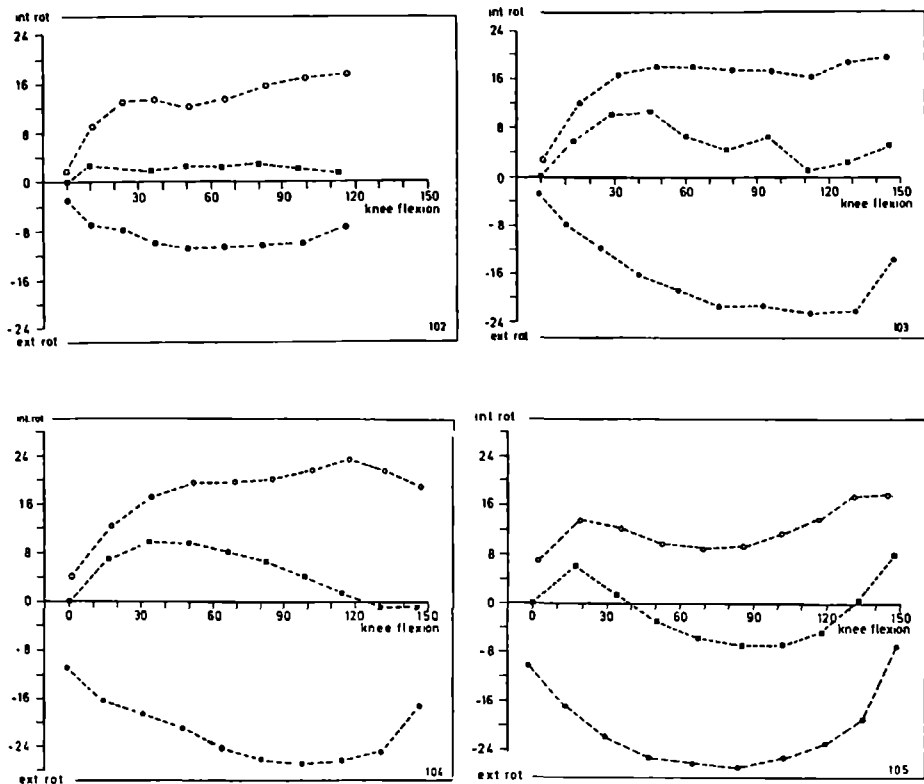


Fig. III.7: The limits of internal (open circles) and external (closed circles) tibial rotation (± 3 Nm torque) as function of flexion, measured in four specimens. The neutral rotation pathways are represented by the black squares.

The total rotatory laxity ranges from 24-46 degrees between the different specimens, probably depending on the tightness of the ligaments (Fig. III.8). The amount of rotational freedom does influence the amount of patellar movements, as will be shown later. Remarkable is the decrease of exorotation laxity in higher knee flexion, noticed in all specimens except 102.

III.4.2 Tibial ab- and adduction

Tibial rotations around the z-axis (Fig. III.9) show a slowly progressive positive direction, becoming obvious after 50 degrees of knee flexion, being more pronounced along the exorotation envelope of motion in three specimens. Thus, in anatomical terms, knee flexion is accompanied by a slight varus rotation of the tibia, which mechanism is increased by external rotation of the tibia. Except for the first 20 degrees of knee flexion, the tibial rotation influence is almost constant. The trends of the curves in three specimens (103, 104, 105) are remarkably similar,

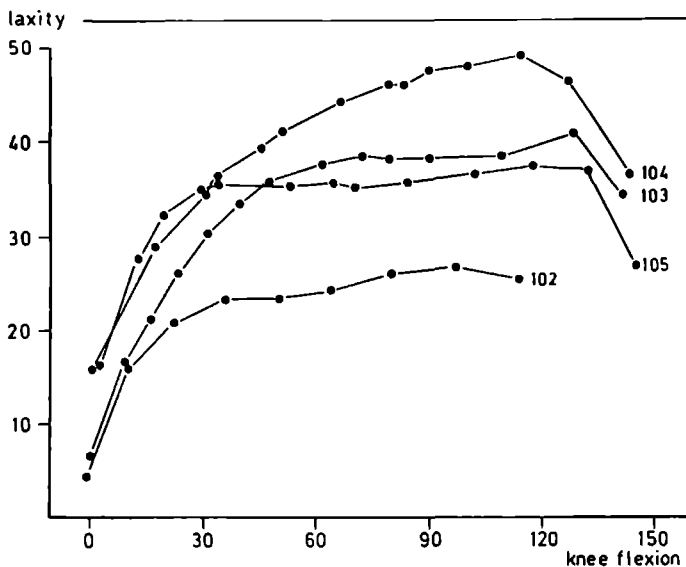


Fig. III.8: Total tibial rotatory laxity as function of knee flexion in four specimens. The rotatory laxity of specimen 102 is evidently the smallest.

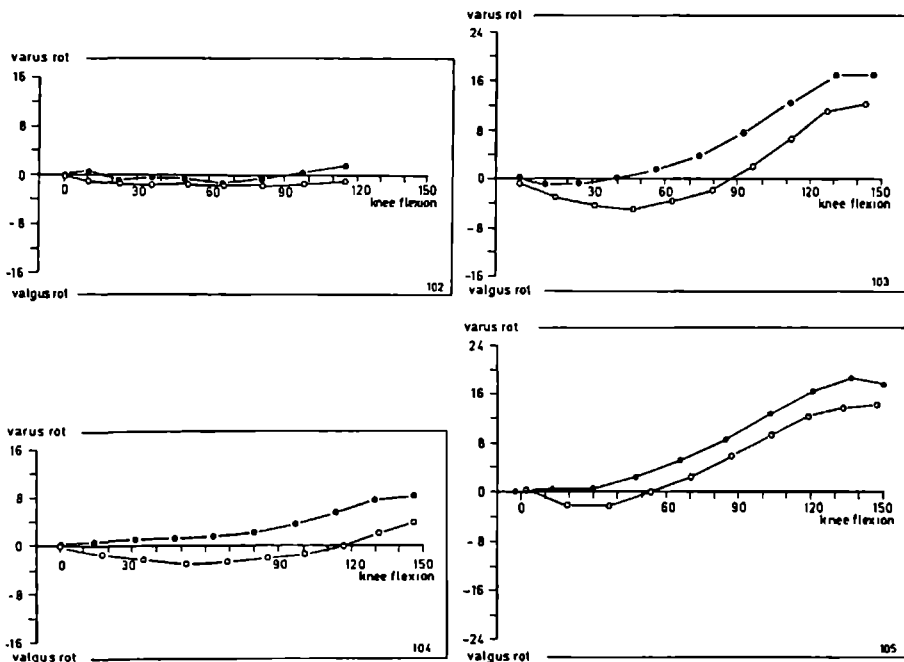


Fig. III.9: Varus/valgus laxity as function of flexion, for the internal (open circles) and external (closed circles) pathways (± 3 Nm), measured in four specimens.

Specimen	Maximal varus rot. (degrees) (flexion angle)		
	Endorot. pathway	Neutral pathway	Exorot. pathway
102	-1.8 (82)	-0.3 (112)	1.5 (115)
103	12.2 (144)	14.0 (145)	17.0 (145)
104	3.7 (145)	5.6 (145)	8.2 (145)
105	14.2 (148)	15.6 (134)	18.7 (136)

TABLE III.2 Maximal varus rotations of the tibia. Between brackets the knee flexion angle is presented at which the maximal varus rotations along the different pathways occur.

although absolute maximal values showed significant differences, as shown in Table III.2. In specimen 102 the varus/valgus rotation is almost negligible. It is interesting to note that this specimen stands apart also relative to the rotatory laxity (Fig. III.8).

III.4.3 Patellar motions

Patellar flexion (rotation around the x-axis), patellar tilt (rotation around the y-axis), patellar rotation (rotation around the z-axis), and patellar shift (translation along the x-axis) will be subsequently described. Patellar movements are described relative to the femur, around the body fixed axes of the patella.

III.4.4 Patellar flexion

Patellar flexion occurs in concert with knee flexion, as expected, but lags behind about 20 percent (Fig. III.10). The patellar flexion lag is more pronounced after about 105 degrees of knee flexion. Along the external rotation pathway, the patellar flexion lag is reduced to about 10 degrees per measurement. Maximal patellar flexion is reached simultaneously with maximal knee flexion. Overall, the influence of tibial rotations on patellar flexion is small.

III.4.5 Patellar tilt

The tilt movement of the patella can be described as wavering: during flexion the patella wavers from a medial to a lateral tilted position and vice versa (Fig. III.11). The patellar tilt is highly influenced by tibial rotations, especially towards full extension. This is understandable when thinking of the clinically moveable patella

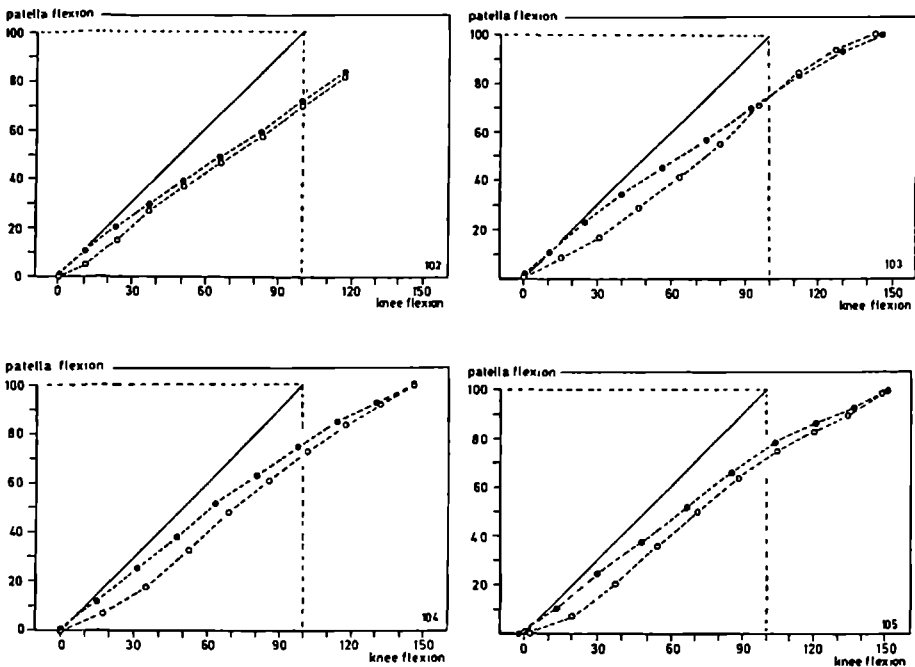


Fig. III.10: Patellar flexion as function of knee flexion. The open circles represent the internal tibial rotation pathways, the closed circles represent the external tibial rotation pathways (± 3 Nm), measured in four specimens.

in extension, which gets stuck in its patellofemoral groove with further knee flexion.

Influences of tibial exorotation, especially in the first part of knee flexion, are more pronounced than the influence of tibial endorotation. Along the external rotation envelope medial tilt is converted to lateral tilt, or at least a less pronounced medial tilt. A possible explanation for this phenomenon would be that by tibial exorotation, lateral knee structures and especially the more laterally orientated patellar ligament pull at the patella, which cause the patella to tilt laterally. The influence of tibial endorotation can be explained in the same manner. During rotation, the patella follows the direction of tibial rotation.

The trends of the curves in three specimens are remarkably similar (103, 104, 105). Specimen 102 again behaves somewhat differently, the wavering tilt being less pronounced. An interesting phenomenon, observed in three specimens (103, 104, 105), occurs at greater knee flexion, at the average of 100 degrees. The patella shows a sudden jerk towards a medially tilted position, together with a crossing-over of the exo- and endorotation pathways, changing the relative positions of the curves. This effect will be discussed later.

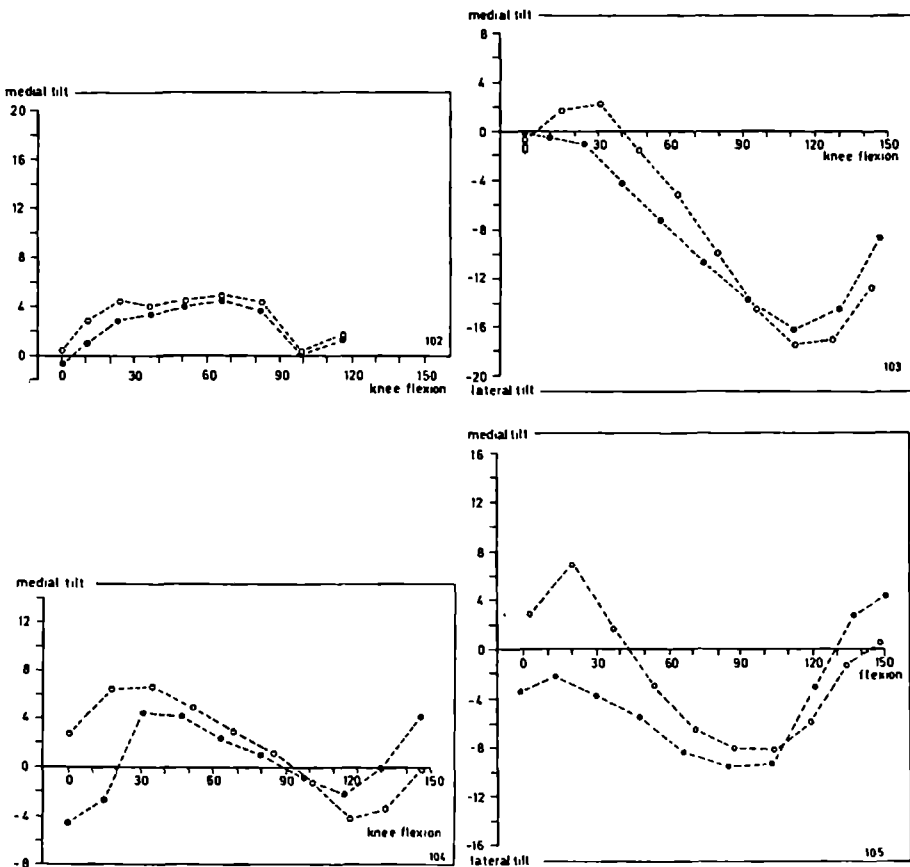


Fig. III.11: Patellar tilt, medial/lateral, as function of knee flexion. The open circles represent the internal tibial rotation pathways, the closed circles represent the external tibial rotation pathways (± 3 Nm), measured in four specimens.

III.4.6 Patellar rotation

Patellar rotation is defined as rotation around the z-axis. By definition, lateral patellar rotation implies movement of the patellar apex towards the fibula. Medial patellar rotation implies movement of the patellar apex from the fibula.

In the first 40 degrees of knee flexion there is no significant patellar rotation (Fig. III.12). With further flexion the patella rotates medially. Along the internally rotated pathway, the medial patellar rotation is more pronounced. Maximal values of medial patellar rotation are reached in greater knee flexion, but differ between specimens (Table III.3).

External rotation of the tibia reduces the medial patellar rotation. In one specimen (104) the external tibial rotation leads to a lateral patellar rotation. Relative to each

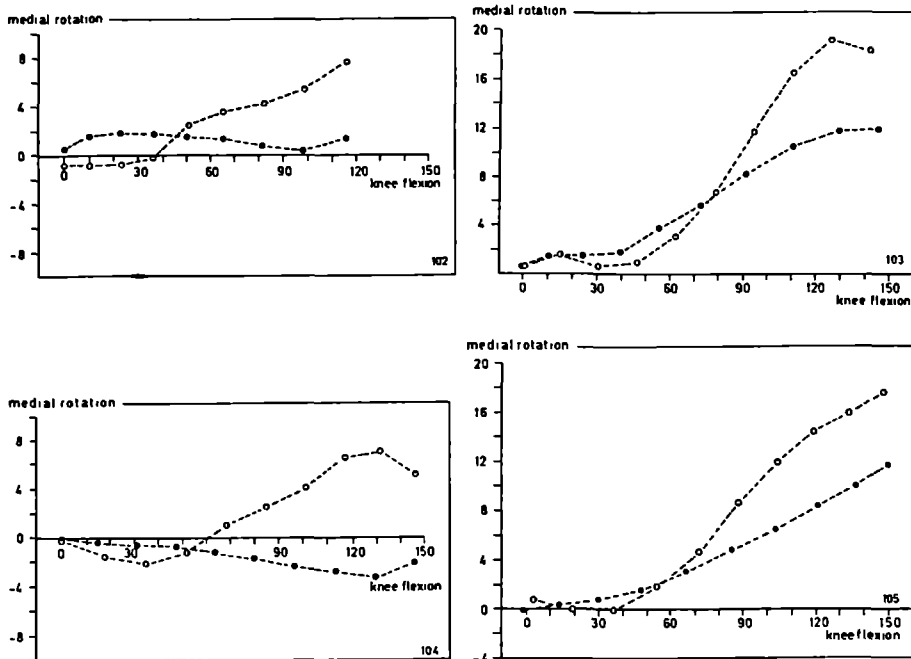


Fig. III.12: Patellar rotation, medial/lateral, as function of knee flexion. The open circles represent the internal tibial rotation pathways, the closed circles represent the external tibial rotation pathways (± 3 Nm), measured in four specimens.

Specimen	Maximal medial rotation (degrees) (flexion angle)		
	Endorot. pathway	Neutral pathway	Exorot. pathway
102	7.6 (115)	2.9 (64)	1.3 (115)
103	18.3 (145)	14.6 (145)	11.8 (145)
104	7 (130)	1.3 (80)	-3.2 (130)
105	17.5 (148)	14.7 (148)	11.7 (150)

TABLE III.3 Maximal medial patellar rotations. Between brackets the knee flexion angle, at which the maximal medial patellar rotations along the different pathways occur.

other, however, not regarding the reference axes, the trends of the curves of the four specimens are again remarkably similar. It is interesting to note that the tibial rotations have a progressive influence on the patellar rotations in the second part of knee flexion, opposite to the tibial rotation influence on the patellar tilt.

III.4.7 Patellar shift

Translation of the patella along the x-axis, the patellar shift, shows a progressive lateralisation with further knee flexion (Fig. III.13). Along the tibial exorotation motion pathway, patellar lateralisation is more pronounced, here again in the first part of knee flexion, similar to the tibial exorotation influence on the tilt.

The tibial exorotation influence on the patellar shift is more pronounced than the tibial endorotation influence. In the neutral pathway there is an initial patellar medialisation. The maximal lateral shift of the four specimens is represented in Table III.4.

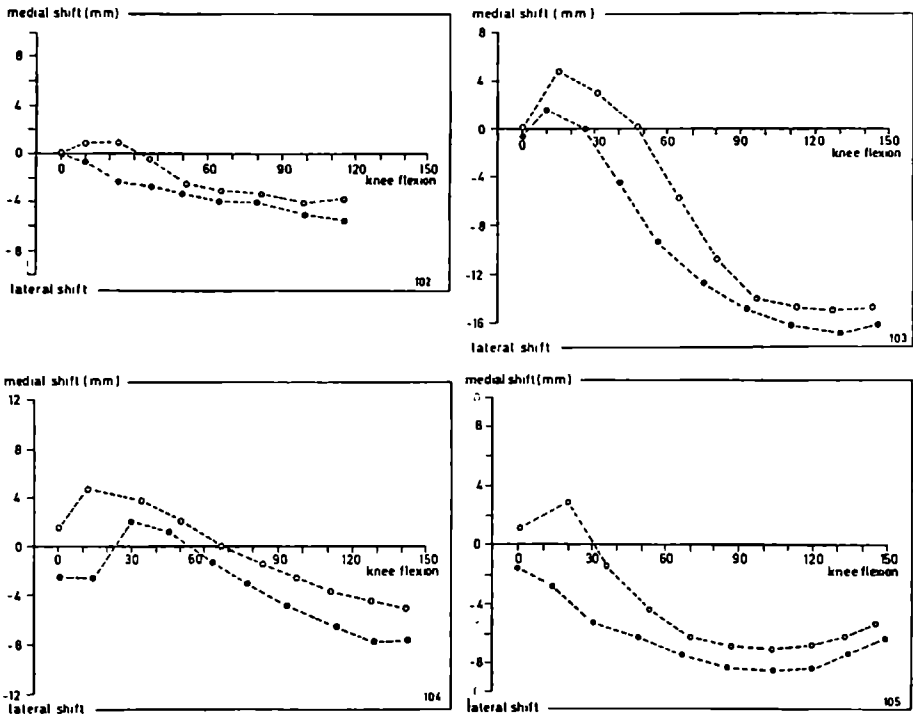


Fig. III.13: Patellar shift, medial/lateral, as function of knee flexion. The open circles represent the internal tibial rotation pathways, the closed circles represent the external tibial rotation pathways (± 3 Nm), measured in four specimens.

Specimen	Maximal lateral shift (mm) (flexion angle)		
	Endorot. pathway	Neutral pathway	Exorot. pathway
102	3.8 (112)	4.9 (112)	5.6 (115)
103	15.3 (128)	16.2 (128)	17 (130)
104	4.9 (145)	7.2 (145)	7.9 (145)
105	8.4 (104)	9.7 (103)	10.2 (103)

TABLE III.4 Maximal lateral patellar shift. Between brackets the knee flexion angle, at which the maximal lateral patellar shifts along the different pathways occur.

III.4.8 Influence of different quadriceps loading

After performance of the subsequent flexion steps of 15 degrees from extension until maximal flexion with tibial torques zero and ± 3 Nm and a total quadriceps loading of 112 N (Q-high), this part of the experiment was repeated with a total quadriceps loading of 28 N (Q-low).

For the tibial rotations the influence of this reduction is small, as could be expected (Fig. III.14). Only in the first part of flexion, the external rotation pathway is more pronounced with less quadriceps loading. On patellar rotations and translations the effect of different quadriceps loading is also small. Changes are visible in patellar tilt in the first part of flexion, and in patellar rotation in the second part of knee flexion, both along the external rotation pathway. These changes are very insignificant and do not cause differences in the overall 3-D tracking pattern of the patella.

III.4.9 Reproducibility of the measurements

One specimen (105) was used to test the reproducibility of the measurements. Directly after the test procedure in which roentgenexposures in eight flexion steps were taken, the test procedure as described in section III.4.8, was repeated.

The results of this repetition of the test procedure are shown in Fig. III.15. For tibial rotations, patellar rotations and patellar shift alike the differences in the curves are negligible, indicating that the measuring system used offers a highly accurate measurement. These results also indicate that the tibial torques (± 3 Nm) could be reproducibly prescribed.

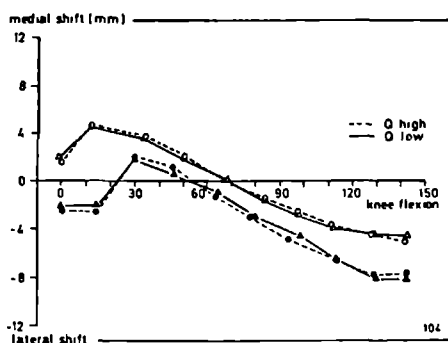
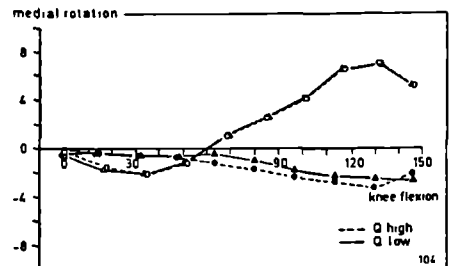
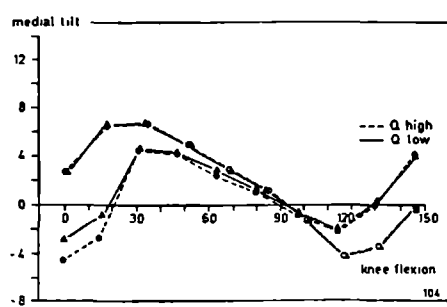
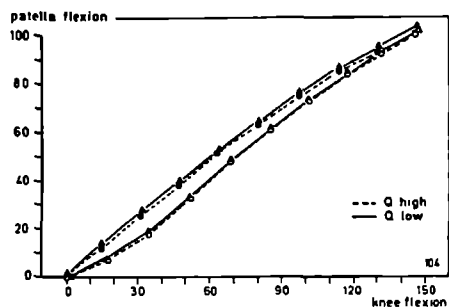
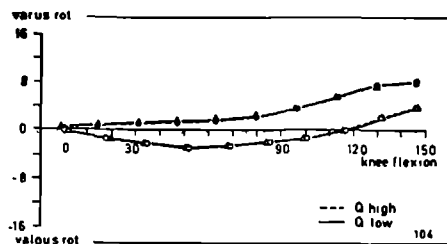
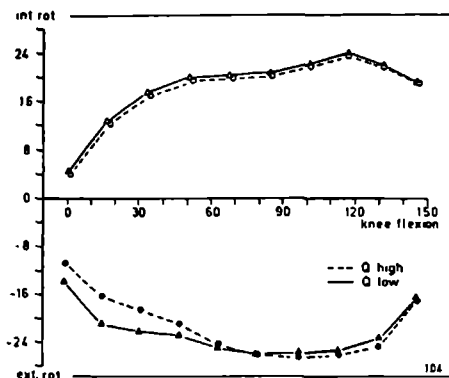


Fig. III.14: The influence of different quadriceps loadings (Q-high, Q-low), on the tibial and the patellar rotations and the patellar shift, respectively, in specimen 104.

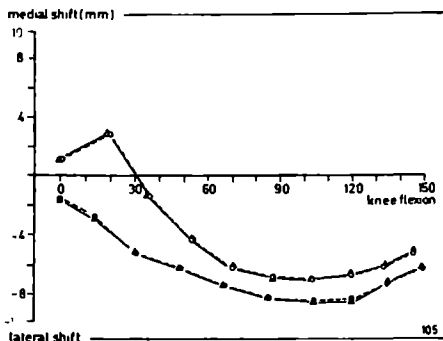
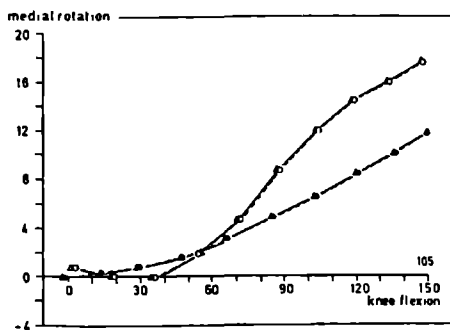
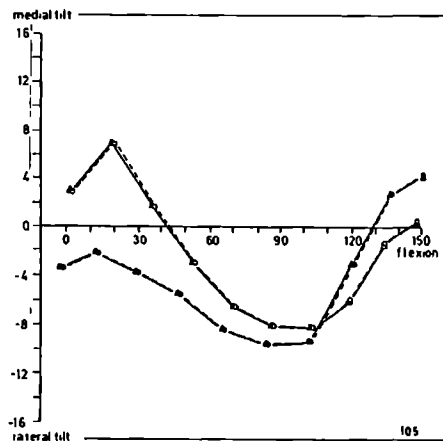
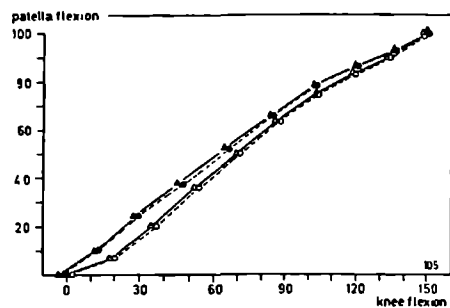
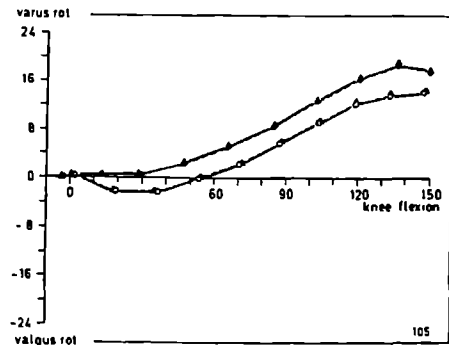
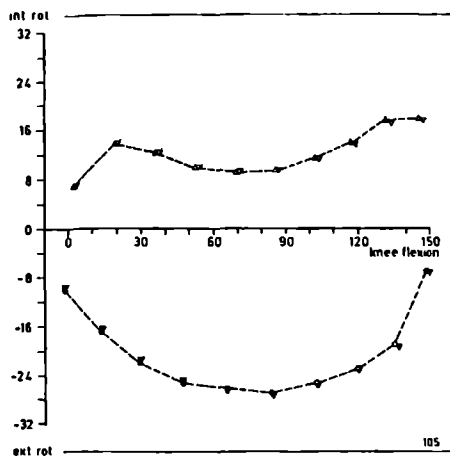


Fig. III.15: Reproducibility of the measurements for specimen 105. The dotted lines in the graphs represent the first measurements. The continuous lines represent the second measurements.

III.4.10 Helical axis representation

Besides describing the motion of a rigid body in terms of rotations around perpendicular axes and translations of a base point, displacements of a rigid body can also be described by subsequent positions and orientations of a screw axis, or helical axis. The helical axis or, to be precise, the finite helical axis, is a three-dimensional analog to the "instant center of rotation" in planar motion (Frankel et al. 1971). The latter method is based on the fact that the displacement of a rigid body over a plane from one position to another can be assumed as if it occurred as a pure rotation around one specific point. A motion can be divided into small motion steps, and for each step this point can be determined. The smaller the steps, the more the pattern of the subsequent motion centers approximates a description of the motion as it occurred in reality (Woltring et al. 1985). In the 3-D analog, the helical axis describes the change in position of a rigid body as if it occurred as a pure rotation around and a translation along one single axis. To describe a complete motion pathway, e.g. extension to flexion in the knee, the total motion is divided in small steps and for each step the helical axis is determined. If the motion was purely circular, for instance in the case of an ideal hinge, the axes for each step would coincide or, in other words, one single helical (or motion) axis would be found for the full excursion. Since the knee is not an ideal hinge, a pattern of axes is found, which together represent and illustrate the motion patterns (Blankevoort et al. 1986). With the same computer program as used before (Kinema), a finite helical axis can be calculated for each subsequent position. These axes were determined for all flexion steps of the tibia relative to the femur and of the patella relative to the femur. The helical axis representation illustrates the joint motion more directly as compared to the rotation angles and translation representation. The subsequent helical axes for tibial and patellar motions were determined for specimen 104. Each helical axis describes a flexion step of about 15 degrees, along the neutral tibial pathway (zero torque).

Fig. III.16 and Fig. III.17 represent the helical axis patterns of the tibia vs. the femur, and the patella vs. the femur, respectively, as seen from two different viewpoints. In the centre of the cubes the coordinate system of the femur is represented by the dotted lines. The same axis patterns are shown again in Fig. III.18 (tibia vs. femur) and Fig. III.19 (patella vs. femur), in a different way. In these last two figures, the axes are projected on the mid-transversal (x-z) and mid-frontal (x-y) planes, relative to the coordinate system of the femur. In these figures (III.18-19), the first axis (1) describes the first 15 degrees flexion step, and the subsequent axes (2-9) the next flexion steps.

When comparing the axis patterns of tibia vs. femur and patella vs. femur, there is an obvious similarity. Most of the helical axes run roughly in the medial-lateral direction, parallel to the x-axis, because for both bones, flexion is the largest rotational component. Oblique courses of the axes occur in both cases in particular during the first flexion step. This indicates the relatively large tibial endorotation component, and the relatively large patellar tilt component, respectively, during this initial flexion motion. The oblique course of the final axis of the patella (nr. 9)

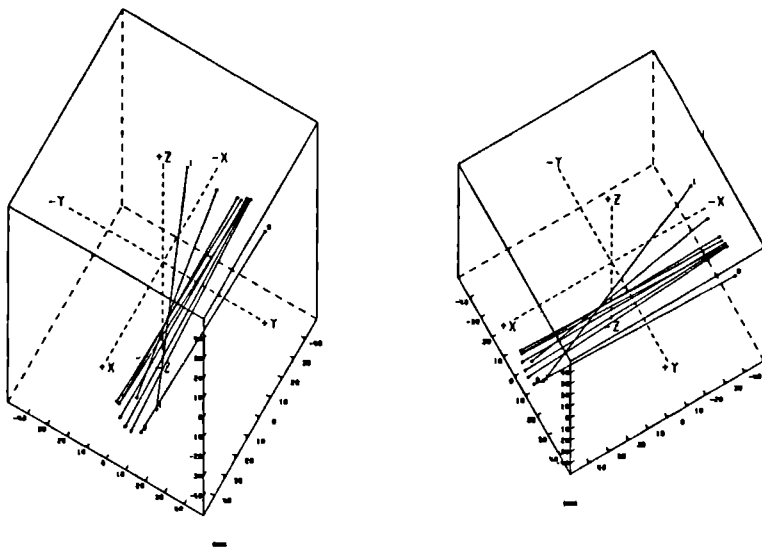


Fig. III.16: 3-Dimensional representation of the helical axes of the tibia vs. the femur for subsequent steps of flexion (spec. 104, neutral rotation pathway), as seen from two different viewpoints.

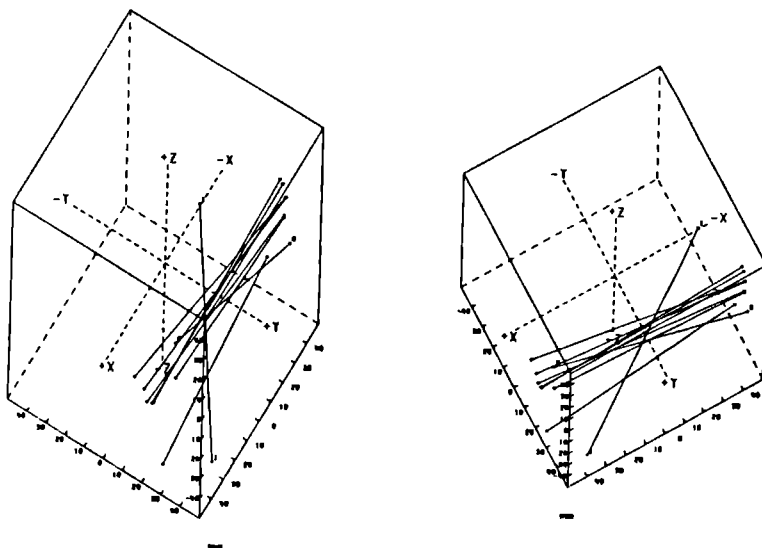


Fig. III.17: 3-Dimensional representation of the helical axes of the patella vs. the femur for subsequent steps of flexion (spec. 104, neutral rotation pathway), as seen from two different viewpoints.

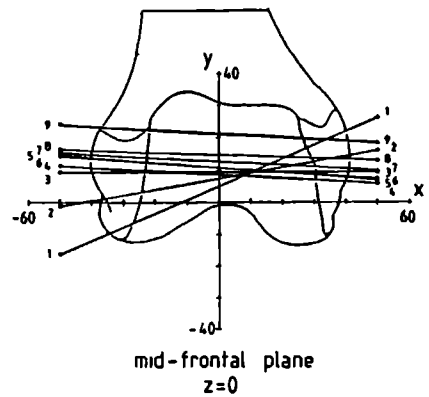
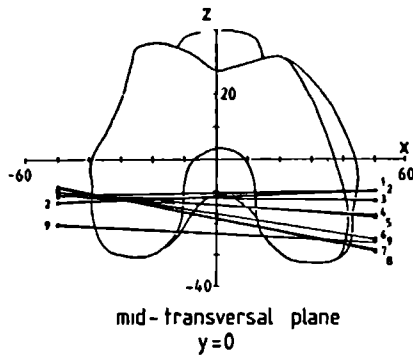


Fig. III.18: The helical axis projections on the frontal (xy) plane and the transversal (xz) plane for the tibia vs. the femur (spec. 104, neutral rotation pathway).

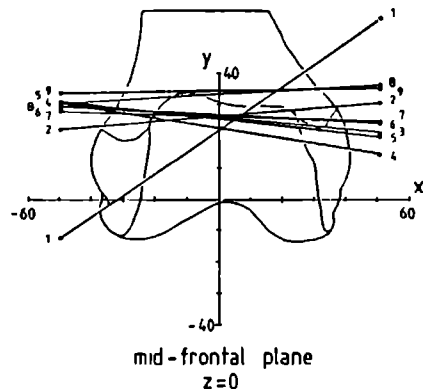
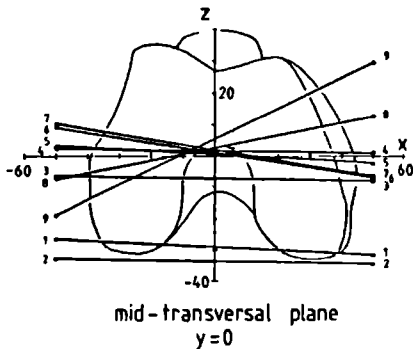


Fig. III.19: The helical axis projections on the frontal (xy) plane and the transversal (xz) plane for the patella vs. the femur (spec. 104, neutral rotation pathway).

in the transvers plane, represents the relatively large patellar tilt during the final flexion step.

It is quite evident from these graphs, that neither the tibiofemoral, nor the patellofemoral motions can be characterized as occurring about a single axis. However, the axes are located relatively close together in each case. Moreover, in the frontal projection, the axis patterns of the patella, and their general locations, are quite similar to those of the tibia. In the transvers plane, however, we see that the patellar axis shifts anteriorly over approximately 3 cm after about 30 degrees of knee flexion. This shift indicates the flexion angle at which the patella is pulled into the femoral groove, which can be seen as a transition of its bearing surface. For the remaining part of knee flexion, the patellar axes are located more anteriorly in

Viewpoint by angles: $\varphi = -180.0$ degrees.
 $\theta = 0.0$ degrees.
 Radius = +24 centimeters

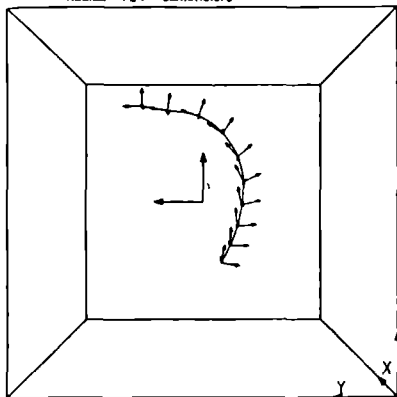


Fig. III.20

Viewpoint by angles: $\varphi = -90.0$ degrees.
 $\theta = 0.0$ degrees.
 Radius = +24 centimeters

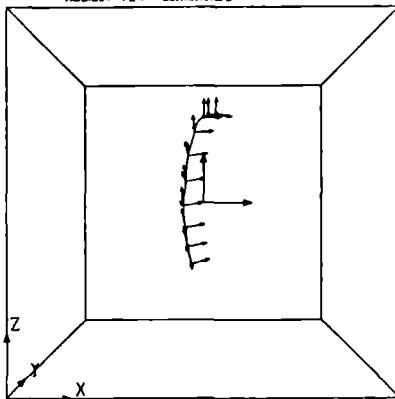


Fig. III.21

Viewpoint by angles: $\varphi = -90.0$ degrees.
 $\theta = +30.0$ degrees.
 Radius = +24 centimeters

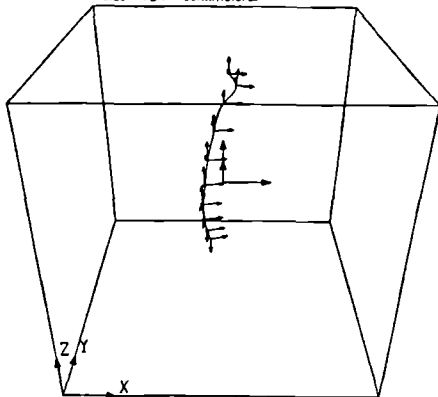


Fig. III.22

Viewpoint by angles: $\varphi = -50.0$ degrees.
 $\theta = +30.0$ degrees.
 Radius = +24 centimeters

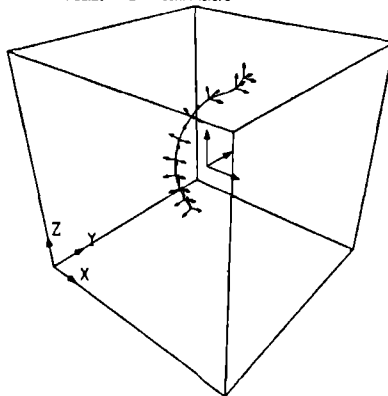


Fig. III.23

Figs III.20-23: Graphic representation of the 3-Dimensional movement of the patella vs. the femur, for subsequent flexion steps (Specimen 104, neutral rotation pathway), as seen from four different viewpoints.

the femur than the tibial axes. The helical axis pattern describing the motion of tibia vs. femur are consistent with those reported by van Dijk (1983) and by Blankevoort et al. (1986).

III.4.11 Visualisation

An attempt was made to visualise the total movement of the patella (specimen

104), relative to the femur for the neutral pathway (zero tibial torque). The results are shown in Fig. III.20-23.

In the centre of a cube the origin of the femur coordinate system, situated in the most proximal part of the intercondylar notch is shown, representing the fixed body. The patellar coordinate system at each measured position during knee flexion is shown relative to this femoral coordinate system. The cube is shown from four different viewpoints, chosen in such a way that the motion pathway of the patella origin and the subsequent orientations of the axes are optimally visualised. In the sagittal view (Fig. III.20) the sagittal pathway and the patellar flexion is clearly depicted.

In the frontal view (Fig. III.21) the medial patellar rotation, together with the lateral shift is illustrated. Rotating the cube 30 degrees around its x-axis (Fig. III.22) illustrates its medial shift and the absence of patellar rotation in the first part of knee flexion. Although difficult to illustrate, the wavering tilt can be detected at best from the viewpoint in Fig. III.23.

III.5 DISCUSSION

Many authors have investigated the exo-/endorotation motion freedom of the knee joint (Hallen and Lindahl, 1966; Markolf et al., 1976; van Dijk 1983, Nielsen et al., 1984; Blankevoort et al., 1987).

Although it was not our first purpose to study the tibiofemoral articulation, tibial rotations were taken into account because of their possible influences on the patellofemoral movements. The total rotatory laxity as function of flexion depends on the individual specimen. Comparable results in respect to tibial internal and external rotatory laxity were found by Blankevoort et al. (1987). They compared their results with the rotatory laxity data from the literature (see Fig. III.24). The reduction of total laxity in greater knee flexion, noticed in this study, was not consistently found by the fore-mentioned investigators, due to the fact that greater knee flexions (up to 140 degrees) were not always performed.

Clearly, the total amount of tibial rotation between the limits was smallest in specimen 102 (Fig. III.8). This may be the cause of the less pronounced patellar rotations observed in this specimen.

The progressive adduction or varus movement of the tibia, which in this study was found in all but one specimen does not support the results of Van Dijk (1983), who noticed a synchronous abduction or valgus movement of the tibia with increasing flexion in all test positions (mean 10.7 degrees). This can be caused by the influence of different orientations of the coordinate reference system, which are determined when the specimens are mounted in the motion rig. Moreover, in the investigation of van Dijk (1983), the tibia rotations were exerted manually, not controlled by a torque wrench, and tibial rotation was only administered in the lower flexion angles. The present results show that moving along the internal tibial rotation pathway, the varus rotation is less pronounced, or converted to a valgus rotation, which is in conformity with the results of Blankevoort et al. (1987).

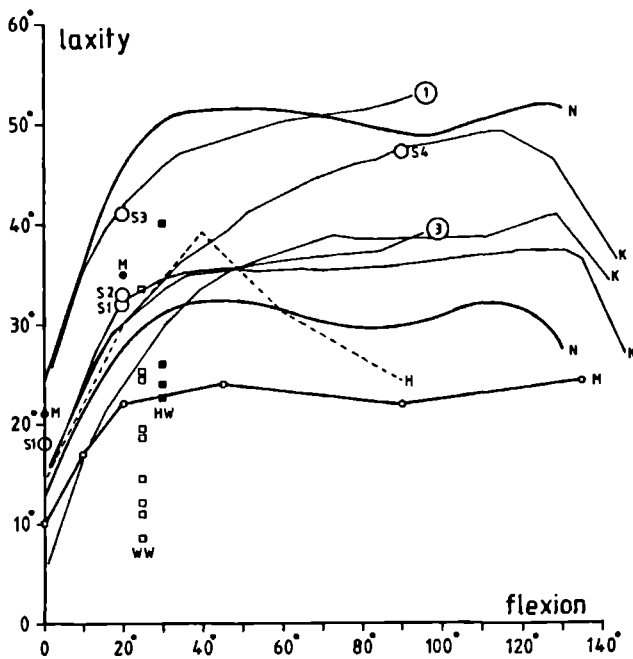


Fig. III.24: Comparison of rotatory laxity data from literature.
 WW: Wang and Walker (1974); HW: Hsieh and Walker (1976);
 M: Markolf et al. (1976, 1981); H: Hungerford et al. (1981);
 S: Shoemaker et al. (1982, 1983); N: Nielsen et al. (1984);
 K: van Kampen et al. (1985); 1,3: Blankevoort et al. (1987).

Although different in absolute values, three specimens showed the same tendencies in patellar movements. A comparison of the patellar movements between the specimens shows that specimen 103 and 105 are remarkably similar in all the different movements. Relatively, specimen 104 shows the same tendencies, with slightly different tibial varus/valgus rotation and patellar rotations. Positioning of the specimens in the motion rig can cause slight differences in the reference axes of the different specimens. From these results it seems that the reference axes of specimens 103 and 105 were quite similar, and that the orientation of the reference axes of specimen 104 was somewhat different.

In one specimen (102) patellar excursions were less pronounced, probably due to the fact that specimen 102 shows a significantly lower total rotatory laxity of the tibia vs. the femur (about 50% relative to specimen 104).

Except for the patellar flexion, the patellar movements are considerably influenced by tibial rotations. The patellar tilt and the shift are more influenced by the tibial rotations in the first part of flexion. This can be explained by the fact that in the first part of flexion, the patella is not yet confined to its femoral groove, thus giving room for patellar "play". This play is effected by the tibial rotations, through tensioning of the patellar ligament, and of the lateral and medial retinaculæ,

respectively. In the second part of knee flexion the structures around the patella are more tense, and the patella is pressed in its femoral groove, which reduces the possibilities for patellar play.

The patellar rotations, however, are more affected by tibial rotations at greater knee flexion, which can be explained as follows: In flexion, the retinaculum and especially the patellotibial bands are tense. Slight changes in tibial rotation can thus exert their influences on patellar rotations through the patellar ligament and patellotibial bands in greater knee flexion.

The pathway of patellar flexion found in the present investigation is consistent with the results of van Eijden (1985) (Fig. III.25), who determined the orientation of the patella relative to the femur by lateral radiographs of autopsy knees. Van Eijden (1985) also investigated the change in direction of the patellar ligament during flexion. The patellar ligament direction, from the tibial tuberosity to the patellar apex, changed from a relatively forward placement to a backwards position from knee extension to flexion, in the sagittal plane. The angular changes between patella and patellar ligament were negligible. Therefore, the flexion lag of the patella in respect to the tibia, as found here, is due to the change in patellar ligament direction relative to the tibia.

The present results show that by tibial exorotation the flexion lag decreases. Tibial endorotation has a negligible effect on patellar flexion, compared to the neutral tibial rotation pathway. This phenomenon is explained by the relative change in distance between the tibial tuberosity and the apex patellae, and by the position of the patellar ligament in the sagittal plane. Normally, without tibial torques, the position of the tibial tuberosity is slightly laterally orientated, relative to the patella, in the frontal view. Tibial exorotation increases the distance between the tuberosity

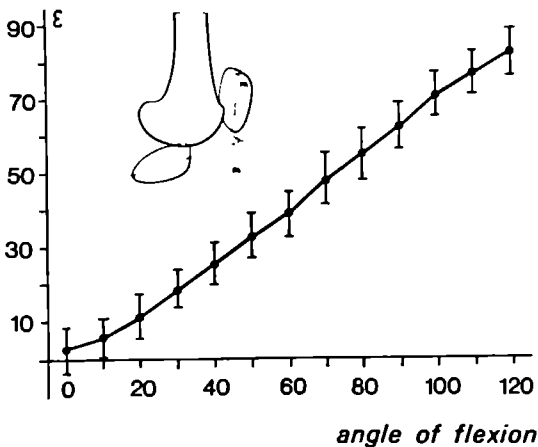


Fig. III.25: Angle between the patellar axis and the femoral axis vs. flexion angle as established by van Eijden (1985) with lateral-view radiographs (by courtesy of the author).

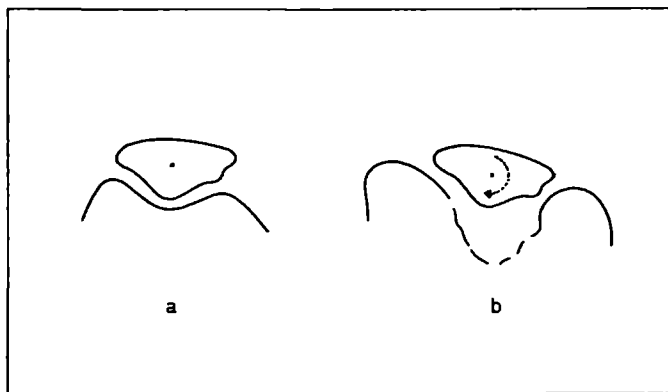


Fig. III.26: Schematic drawing of the relation between patella and femur in extension (a), and 120 degrees flexion (b). Loading of the medial odd facet occurs with a medial patellar tilt.

and the patellar apex, and the patellar ligament moves backwards, thus reducing the flexion lag of the patella relative to the tibia. By tibial endorotation, the distance between the tibial tuberosity and patellar apex remains relatively unchanged, as the position of the patellar ligament in the sagittal plane will be.

An explanation for the wavering tilt as detected here, can be found in the bony configuration of the distal femur which opposes the patella at different flexion angles. In the first part of knee flexion the patella is opposite to the anteriorly reaching wall of the lateral condyle, inducing a medial tilt. The medial condyle reaches further caudally than the lateral one, causing a lateral tilt between 50-100 degrees of knee flexion. Above 100 degrees knee flexion the patella shows a quite sudden inversion towards a medial tilt. This can be explained by the contact between the most medial part of the patella (the odd facet) and the medial femoral condyle (Fig. III.26). This is in accordance with studies, concerning with retropatellar cartilage contact areas (Goodfellow et al., 1976; Hehne et al., 1981), which show loading of the odd facet at about the same flexion angle. The direction of the patellar tilt depends partly on the knee-flexion degree and partly on the tibial rotation.

Because none of the investigators mentioned in Chapter II did take tibial rotations into account, comparison of our data with data from the literature is possible only indirectly. Veress et al. (1979) measured tilt only at 3 or 4 flexion angles, up to a maximum of 90 degrees. Yet, his figures show the same wavering tilt from medial to lateral with progressive knee flexion in three out of four measured individuals. The overall finding of a lateral tilt by Reider et al. (1981), is not supported by our results. In their experiment, the tibia was fixed, and the femur was free to flex and extend.

Although the authors mention that the apparatus was constructed to allow for the

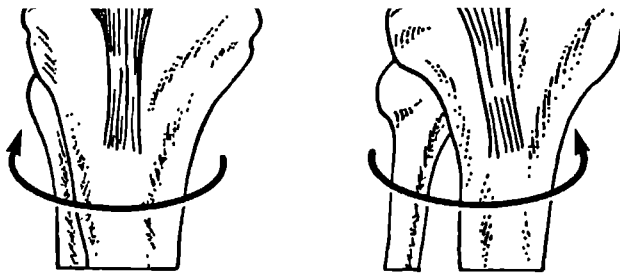


Fig. III.27: Influences of tibial rotations on patellar tilt (rotations around the y-axis). Tibial exorotation induces lateral patellar tilt (left). Tibial endorotation induces medial patellar tilt (right), both caused by the direction of the pull of the patellar ligament.

“screw-home” mechanism, further remarks in regard to femur rotation freedom are not made. The patellar movements were described in relation to the tibia, instead of relative to the femur as in the present investigation, which could explain the different patellar tilt rotations established. The results of Fujikawa et al. (1983) show a progressive medial tilt in the flexion range from 25-120 degrees.

As described above, exo- and endorotation influences on patellar tilt can be explained by stretching of the lateral/medial parapatellar structures and the pull of the patellar ligament, in combination with the articular constraints. Thus, in the first part of flexion, the tibial rotations result in a patellar tilt in the same direction (Fig. III.27). In contrast, beyond about 95 degrees of knee flexion, these tibial rotation influences lead to an inversion of patellar tilt. In greater knee flexion, with the patella deep between the femoral walls, traction on the medial side by tibial endorotation induces a lateral tilting of the patella, because the patella will ascend upon the wall of the medial femoral condyle. The flexion angle at which this crossing-over phenomenon occurs will depend on the slope and the height of the medial femoral condyle part, which forms the patellofemoral groove.

The medial patellar rotation per sé can be caused by the geometry of the femoral groove: the sulcus points slightly laterally, as seen from proximal to distal. Thus, with knee flexion, the patellar apex will rotate medially through the pull of the patellar ligament. This also explains the increment of medial patellar rotation

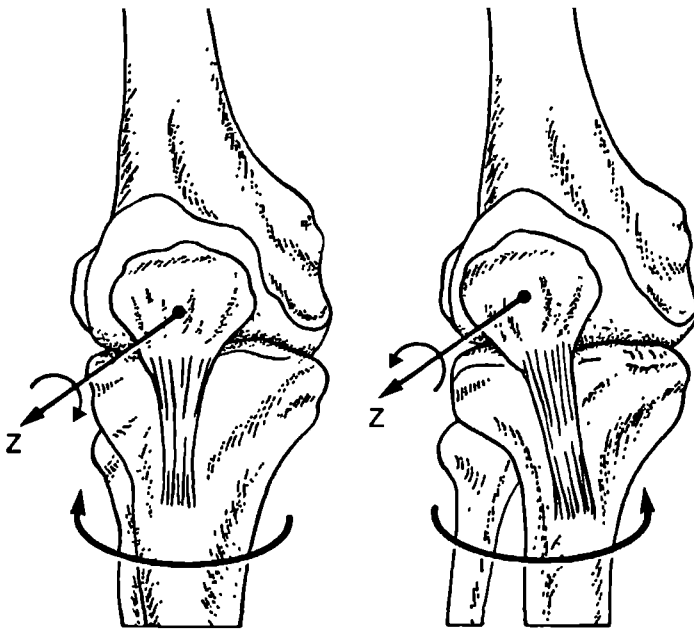


Fig. III.28: Influences of tibial rotations on patellar rotation (rotation about the z-axis). Tibial exorotation induces lateral patellar rotation (left) Tibial endorotation induce medial patellar rotation (right), both caused by the direction of the pull of the patellar ligament.

caused by internal tibial rotation, as an effect of the further medialisation of the patellar tendon (Fig. III.28). The two studies mentioned before (Reider et al., 1981; Fujikawa et al., 1983) both showed a lateral patellar rotation of about six degrees. This difference in patellar rotation direction compared to the present results can be explained partly by the lower precision in the measurements of the forementioned investigators, and partly by the different reference system used (Reider et al. 1981).

All the investigated specimens showed a lateral shift with increased knee flexion, due to the orientation of the femoral groove, as explained before. The influences of the tibial rotations can be explained by a similar mechanism as the influences of the tibial rotation on the tilt (up to 95 degrees knee flexion) and the patellar rotation (see also Fig. III.29). Hence, stretching of the lateral parapatellar structures with lateralisation of the patellar ligament by tibial exorotation will lead to a lateral patellar shift. Tibial endorotation will induce the opposite, a medial patellar shift. The direction of the patellar shift is in accordance with the results of Veress et al (1979) and Reider et al. (1981).

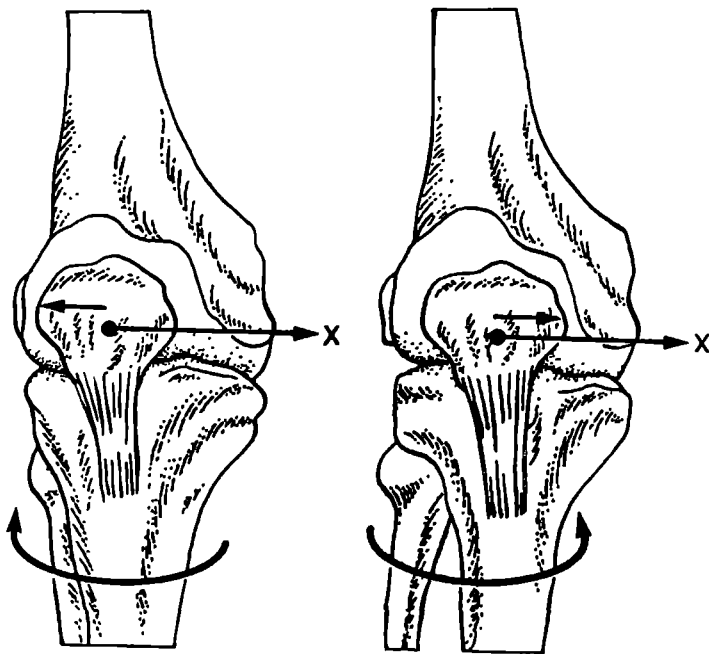


Fig. III.29: Influences of tibial rotations on patellar shift (translation along the x-axis). Tibial exorotation induces lateral patellar shift (left). Tibial endorotation induces medial patellar shift (right), both caused by the direction of the pull of the patellar ligament.

III.6 SUMMARY AND CONCLUSIONS

In order to determine the 3-D tracking patterns of the patella, a high precision measuring system (RSA) was used. Because of its high precision, and of the high reproducibility found here, the results present true patellar motions, and general conclusions on the patellar tracking patterns may be drawn, although the number of investigated specimens was relatively small.

The motions found in the four specimens were different 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 the anatomical interindividual variability and by slightly different orientations of the coordinate reference systems. The 3-D patellar tracking patterns are characterized by a progressive patellar flexion, a wavering patellar tilt, a medial patellar rotation and a lateral patellar shift during knee flexion. These patterns are highly influenced by tibial rotations. Patellar tilt and shift more in the first part of knee flexion, and patellar rotation more in the second part of knee flexion. Comparing the shift and the tilt movements suggests that the patellar shift is coupled to the tilt or vice-versa.

The patellar rotations seem to follow the varus/valgus rotations of the tibia.

The motion constraints of the patella are determined by the anatomical characteristics of the distal femur in relation to those of the patella and by the balance of forces exerted by the soft tissues. Evidently, interindividual differences in this respect will be reflected in the motion patterns.

THE ETIOLOGY, PATHOPHYSIOLOGY AND TREATMENT OF CHONDROMALACIA

"It seems likely that more has been written about the patella, relative to its size, than about any other bone in the human body".

Haxton, 1945

IV.1 HISTORICAL REVIEW

Although Büdinger (1908) is often mentioned as the first one who described changes of the retropatellar cartilage after trauma, introduction of the term chondromalacia in the literature is accredited to Aleman, who observed the posttraumatic changes of the retropatellar cartilage in 1928.

With the introduction of this term in the English literature in 1933 by Külowski, a non-traumatic origin of this pathological condition was suggested. From that time on a progressive, even overwhelming, number of articles on the subject have been published concerning etiological factors, macroscopic- and microscopic appearances, clinical presentation, radiographic investigation, classification, arthroscopic examination and treatment.

IV.2 NOMENCLATURE

Despite the numerous publications, a generally accepted definition of chondromalacia and its classification is still lacking. The terms "chondromalacia" and "chondropathia" are often interchanged, especially in the German literature. Literally, chondromalacia stands for softening of cartilage and chondropathia for cartilage disease (sickness). This would support the suggestion of Goodfellow et al. (1976) to use the term chondropathia for the clinical syndrome of anterior knee pain and to reserve the term chondromalacia for the pathological process involved, proven by arthroscopy, arthrotomy or microscopic inspection. Because it is well known that retropatellar cartilage changes, like softening and fibrillation do occur without clinical symptoms (Morscher, 1978; Abernethy et al., 1978; Insall, 1984), probably the best description of chondromalacia is given by Bentley and Dowd (1984), when they defined chondromalacia as a clear clinical syndrome of anterior knee pain, accompanied by abnormal changes of the patellar cartilage.

IV.3 CLASSIFICATION

Aleman (1928) was the first describing different stages in chondromalacia based on macroscopic aspects and graded them as follows:

Grade I: softening and swelling with an intact surface.

Grade II: a ragged surface with occasional detached flakes of cartilage.

Grade III: complete breakdown with evidence of osteoarthritis.

Outerbridge (1961) refined the above mentioned classification as follows:

Grade I: softening and swelling of the cartilage.

Grade II: fragmentation and fissuring in an area half an inch (1.27 cm) or less in diameter.

Grade III: the same as grade II, but an area of more than half an inch (1.27 cm) in diameter is involved.

Grade IV: erosion of cartilage down to bone.

Goodfellow et al. (1976) proposed a different classification, subdividing cartilage pathology in two basic categories: mainly age-dependent surface degeneration, particularly occurring on the odd facet, and basal degeneration, in which fasciculation of collagen in the middle and deep zones of cartilage occurs, without immediately affecting the surface. The first is usually painless and may be predisposing to degenerative arthritis, the second is frequently symptomatic. This classification found no general acceptance and the frequent existence of a so called basal degeneration is doubted by several authors (Bentley and Dowd, 1984; Insall, 1982).

In time, and probably by the more frequent use of arthroscopic techniques, the so-called Outerbridge-classification underwent slight modifications.

Jackson (1976) grades chondromalacia according to the following scheme:

Grade I: softening or early fibrillation of the patella, involving one or more facets. The femoral side is not involved.

Grade II: actual fragmentation or erosion, limited to the patella.

Grade III: involves adjacent changes on the femoral side of the articulation.

Insall (1982) proposed four stages, in the last of which involvement of the femoral side is commonly found. Bentley (1978, 1984), finally, modified the Outerbridge-classification, mainly relative to the defect size, as follows:

Grade I: localised softening, swelling, fibrillation or fissuring in an area of 0.5 cm or less.

Grade II: fibrillation or fissuring in an area of 0.5-1 cm diameter.

Grade III: fibrillation or fissuring in an area of 1-2 cm diameter.

Grade IV: exceeding 2 cm, with or without exposure of subchondral bone.

By introducing different or modified classifications, a comparison of the results of therapeutic measures is getting more complex. For example, a retropatellar fibrillation over the whole patellar cartilage can be classified as grade I according to Jackson (1976), grade III according to Outerbridge (1961), and even grade IV according to Bentley (1978, 1984) (see table IV.1). It would be convenient if a consensus was reached for one classification system to be used universally.

Authors	THE ASPECT OF THE CARTILAGE IN			
	Grade I	Grade II	Grade III	Grade IV
Aleman (1982)	softening swelling	ragged detached	erosion to bone	
Outerbridge (1961)	softening swelling	fragmentation fissuring < half inch	fragmentation fissuring > half inch	erosion to bone
Jackson (1976)	softening fibrillation	patellar fragmentation erosion	femoral fragmentation erosion	
Bentley and Dowd (1984)	fibrillation softening fissuring < 0.5 cm	fibrillation fissuring 0.5-1 cm	fibrillation fissuring 1-2 cm	fibrillation fissuring > 2 cm and/or erosion to bone

TABLE IV.1 The grading systems for chondromalacia, as suggested in the literature.

IV.4 ETIOLOGY

A traumatic origin is generally accepted as being the cause of chondromalacia (Outerbridge and Dunlop, 1975; Macquet, 1975; Insall, 1982). B dinger (1906) was the first to describe cartilage lesions of the patella, which he assumed to be of traumatic origin. Aleman(1928) also proposed repetitive traumas in childhood as the cause of chondral changes, for example by falls at the local "Schlittschuhbahn". Wiberg (1941) drew attention to the incongruence of the patellofemoral joint, and introduced the different types of patellae, which have since been named after him. If and how the form variations as described by Wiberg (1941) do play a role in chondromalacia is still controversial (Morscher,1978; Hehne et al., 1981; Insall, 1981).

The question "is chondromalacia caused by hyper- or hypopressure" was proposed by Wiles et al. (1956) as he stated "there is an association between pressure, or its absense and the evolution of chondromalacia". Ficat et al. (1975) extended this view in favour of hyperpressure by introducing the syndrome of excessive lateral pressure as a new entity (Syndrome d'hyperpression externe de la rotule (S.H.P.E.)), in which the cartilage changes occur on the lateral facet, due to thickening and retraction of the lateral retinaculum. They believed that the medial facet at the same time is the site of abnormal low pressure, but drew no consequences out of this statement. The diagnosis S.H.P.E. can be confirmed radiologically showing asymmetry of the joint line with lateral narrowing, loss of height of articular cartilage, lateral subchondral sclerosis and osteoporosis on the medial side.

Morscher (1978), like many others, found the medial facet to be more often affected than the lateral facet, and believed medial hypopressure, leading to

nutritional disturbance, the prime responsible mechanism for chondromalacia. Insall et al. (1976) found at arthrotomies "chondromalacia areas involving equally both medial and lateral facets; it was seldom confined to the medial facet". Outerbridge (1964) explained the etiology by the presence of an osteochondral ridge, at the upper anterior border of the medial femoral condyle, which causes "considerable friction on the medial patellar facet". Abnormal patellofemoral tracking or mal-alignment besides subluxating and luxating patellae, is thought to be responsible for chondromalacia by several authors (Heywood, 1961; Dandy and Poirier, 1975; Hughston and Walsh, 1979). In a prospective study, Insall et al. (1976), found in 50 percent of patients, operated for chondromalacia, an abnormal Q-angle and in 30 percent a patella alta. In summary, etiological factors of chondromalacia may include trauma, incongruence in geometry between the patella and the femur by form variations of the patella and/or osteochondral ridges, hypo- or hyperpressure in the patellofemoral joint and mal-alignment leading to an increased or decreased Q-angle. Hormonal factors (Morscher, 1978) and increased vulnerability of the cartilage (Outerbridge and Dunlop 1975) are also mentioned or suggested, but evidence is lacking so far.

IV.5 RELATION TO OSTEOARTHRITIS

Many authors consider chondromalacia to be a precursor of osteoarthritis (Macquet, 1976; Bandi, 1976; Chrismas, 1986), mainly because microscopic differences between patellofemoral osteoarthritis and chondromalacia have not been detected. Others (Karlson, 1939; Smillie, 1974; Bentley and Dowd, 1984) believe that chondromalacia is a separate entity and needs to be distinguished from osteoarthritis of the patellofemoral joint. Reasons in favor of the latter include: isolated patellofemoral arthritis is not a frequently found condition in elderly patients, in contrast to the many young patients with chondromalacia patellae. There is no reason why a presumed praearthrosis should disappear in time, instead of showing progression. Patients with established osteoarthritis rarely have a history of knee problems in adolescence (Insall, 1982; Bentley and Dowd, 1984).

IV.6 PAIN IN CHONDROMALACIA

Another subject of an ongoing discussion is the source of pain in chondromalacia. Because there are no pain receptors in cartilage, it is unlikely that the cartilage itself is the cause of pain in chondromalacia. The synovial capsule may be regarded as the pain producer by chemical irritation of the desintegration of cartilage (Morscher, 1978). Experimentally, a synovial inflammation can be stimulated by injection of cartilage (proteoglycans) in joints (Chrismas, 1986). Contradictory to this theory is the very rare finding of synovitis in biopsies, taken from joints with chondromalacia (Insall et al., 1976).

Abnormal pressure to the subchondral plate with its nerve ends is thought to be the source of pain by several authors (Outerbridge and Dunlop, 1975; Goodfellow et al., 1976; Insall et al., 1976; Gruber, 1979).

Cassalls (1982) questions the tight retinaculum to be responsible for pain production, suggesting that those structures should get tighter with age, instead of getting more loose. This would implicate a progressive number of patients with time and not a frequently found self-limiting disease, which is often observed. In his view the pain could rather be the result of rapid growth and stretching of soft tissues in young, active teenagers, gradually disappearing with maturity. Finally, an increased intramedullary pressure of the patella in chondromalacia is sometimes suspected to cause the pain. Björkström et al. (1980) measured the intramedullary pressure with a biopsy needle in patients with chondromalacia and control group, and registered the mean pressures in the chondromalacia group being as twice as high.

IV.7 CONSERVATIVE TREATMENT OF CHONDROMALACIA

Initially, all patients suffering from chondromalacia should be treated conservatively. Conservative measures can include isometric muscle exercises and the avoidance of obviously provoking activities (e.g. stair climbing, deep knee bending). The prescription of non-steroidal anti-inflammatory medications during several weeks may be helpful (Bentley and Dowd, 1984), as the use of patellar cut-out knee braces sometimes is.

IV.8 OPERATIVE TREATMENT OF CHONDROMALACIA

When surgical intervention is considered, the choice of treatment is almost infinite. In 1975, Madigan et al. already counted more than 96 different methods, which number has increased since then. On the one hand, this could imply criticism - searching for new methods implies discontent over existing procedures - but on the other hand this could be illustrative for the multifactorial etiology of chondromalacia.

Grossly, the operations for chondromalacia can be divided on an etiological basis as follows:

1. Cartilage deficiencies per sé
 - shaving
 - drilling
 - spongialization
 - local excision
2. Restoration of normal pressure medial
 - patella osteotomy
 - lateral release
 - re-alignment procedures
3. Restoration of normal pressure lateral
 - lateral release
 - re-alignment procedures
4. Restoration of normal pressure lat./med.

- anterior displacement of the tibial tubercle
- re-alignment procedures

5. Restoration of normal anatomy

- osteochondral ridge excision

For three reasons, it makes no sense to discuss results of operations in detail in the following overview.

- Most authors do not differentiate their patients on an etiological basis.
- The classification system of chondromalacia is not universal.
- Most studies concern a small number of patients and short-term follow-ups.

Yet, a general survey is presented, according to the above mentioned etiological bases.

By treatment of the cartilage itself, Wiles et al. (1960) reported symptom relief in 22 out of 28 patients by means of a *patella-shaving*. The average follow-up period was five and a half years. Bentley (1970) did not share this enthusiasm, recording less than 50 percent satisfactory results after an average follow-up of eight years. *Local cartilage excision* with basal degeneration, according to Goodfellow et al. (1976), leads to good results in 18 out of 23 patients with a very short follow-up period, medium 1 year. Long-term follow-up studies are not known.

Spongialization can be considered as an extension of making multiple drill holes in the subchondral bone (Pridie, 1959). In *spongialization*, a total resection of the diseased cartilage with its underlying subchondral bone is carried out.

Ficat et al. reported in 1979 on 85 patients with 79 percent good or excellent results. The same results were claimed by Ficat in 1970 with a lateral retinacular release, which is also a part of the spongialization procedure!

Under the heading "restoration of normal retropatellar pressure" the *lateral retinacular release* is undoubtedly the most popular procedure. Several authors (Merchant and Rucer, 1974; Larson et al., 1978; Ceder et al., 1979; Delgado, 1980) report good results with a *lateral release*. The follow-up periods were all short from 1 to 3 years. It is remarkable that some of these authors consider the "advantage" of lateral release to be the fact that, if it is not beneficial, other operations are still possible. Insall et al. (1976) did not support the above authors, noting slight improvements in only half of their patients.

Procedures to *re-align* the patella proximally or distally, using lateral release of the quadriceps expansion and/or reefing the medial retinaculum, sometimes in combination with medialisation and/or distalisation of the tibial tuberosity are, as stated by Hughston and Walsh (1979), difficult to perform. Success in these procedures may depend more on the experience of the surgeon involved than in any other operation for chondromalacia. Turba et al. (1974) and Insall et al. (1979) reported 70 to 80 percent satisfactory results with this procedure.

Anterior displacement of the tibial tuberosity for relief of anterior knee pain, resulting from chondromalacia was first described by Macquet et al. in 1963. They believed that hyperpressure was the cause of the cartilage damage, which led to the

idea that by lengthening the lever arm of the patellar tendon, through forward placement of the tuberosity, the patellofemoral compressive forces could be decreased. They advised a 2 cm advancement of the tubercle. In 1976 Macquet reviewed 39 patients after tubercle elevation, with an average follow-up of 4.7 years, of which 37 had a good or excellent result. The average age of the patients at time of the operation was 56, so it is likely, that the main indication was patellofemoral osteoarthritis instead of chondromalacia.

Bandi (1972) calculated a tubercle ventralisation of 10 mm to give a pressure reduction of 20-40 percent in the patellofemoral joint.

In 1976 he reviewed hundred patients with a follow-up from 5 to 10 years. By an elevation of 10 mm, 70 percent of the patients improved and 18 percent slightly improved. In addition, in 89 patients a form of chondrectomie was performed. In this study the majority of the patients were also elderly people.

Recently, Radin (1986) reported success rates of about 90 percent by anterior tibial tubercle elevation in young adults. Elevation about 2-2.5 cm was carried out. Multiple punctate relaxing skin incisions were performed routinely to prevent skin necrosis, which is a well known complication of this operation.

At last the *patellectomie* has to be mentioned, as a surgical procedure for chondromalacia. Patellectomie is often considered to be a salvage procedure, as a final option for unbearable patellofemoral pain (Bentley, 1970; Insall, 1982). With careful patient selection, this procedure may be worthwhile.

IV.9 THE SCIENTIFIC BASIS OF OPERATIVE TREATMENT

When overlooking all these different kinds of treatments, one may wonder if the treatments have a solid scientific base, or if the treatment is merely empirically based. Empirical procedures include shaving, drilling and local excision. Patellar osteotomy and lateral release are thought to be based on reducing the retropatellar pressure on the lateral patellar facet or on restoring normal pressure medial.

Hehne et al. (1981) measured contact areas in cadaver knees before and after a sagittal osteotomy. These measurements showed after a sagittal osteotomy a decrease of the contact area of the lateral facet and occasional displacement of contact areas, whereby losses on the paramedial segment were compensated for by early loading of the odd segment. The authors believe that the non-physiological load distribution caused by this osteotomy, cannot be the cause of pain relief. Rather than by the osteotomy itself, success may be caused by the accompanying procedures, like retinacular release, shaving, or the restoration of the normal intramedullary pressure.

There are a few studies concerning retropatellar pressures before and after a lateral retinacular release, which were all performed on cadaver knees.

Huberti et al. (1983) observed no effect of a lateral release on the retropatellar pressures in 50 percent of investigated specimens. In the other specimens, pressures decreased and increased in different regions of the contact areas. The experiments were carried out with pressure-sensitive films.

Jäger and Plitz (1983) used a method of direct retropatellar pressure distribution measurements, and also found no changes in pressure distribution after a lateral release. In 1985 Hille et al. stated, after performing similar measurements as Huberti et al. (1983) with pressure sensitive films, "lateral release does not influence articular mechanics; it was at least not possible to change retropatellar pressure to any measurable extent by releasing the lateral patellar connection". Interestingly, Huberti et al. (1983) found that the average pressures in chondromalacia areas were about 50 percent less than the pressures in non-chondromalacia areas. In this respect the study of Hille and Schultz (1984) is also interesting. They established patellofemoral contact areas in relation to chondromalacia areas. In 10 out of 20 investigated specimens the chondromalacia areas were not the contact areas.

In regards to re-alignment procedures, Huberti et al. (1984) investigated the effects on the patellofemoral contact pressures by changing the Q-angle. Using cadaver knees, contact pressures were measured at three different Q-angles (physiological, increased 10 degrees, and decreased 10 degrees).

Increasing the Q-angle resulted in increased peak pressures, whereas a decrease in Q-angle led to unloading of the vertical crest and sometimes unloading of parts of the lateral facet. These findings emphasize the precise surgery needed, when performing re-alignment procedures.

The possible reduction of retropatellar pressures after tubercle elevation has been theoretically and experimentally investigated by several authors. Bandi (1972) calculated and measured a patellofemoral pressure reduction of about 20-40 percent after elevating the tubercle 10 mm.

Ferguson et al. (1979) and later Nakamura et al. (1985), also showed the relief of patellofemoral contact stresses experimentally. The first half inch tendon elevation was the most effective, further elevation was only marginally useful, because the congruity and size of the contact areas reduced drastically. Jäger and Plitz (1983) measured only at 30 degrees of knee flexion a pressure reduction after a tubercle elevation. In greater knee flexion, the pressure increased, especially at the upper pole of the patella.

IV.10 SUMMARY AND CONCLUSIONS

The etiology of chondromalacia is probably multifactorial. Whether chondromalacia is a separate entity or a precursor of osteoarthritis, is not well established. An important factor in the development of chondromalacia is probably the retropatellar pressure distribution. In this respect the question whether chondromalacia is caused by hyper- or hypopressure is still unresolved.

Two popular operations, lateral retinacular release and tubercle elevation, are based on the concepts of reallocation of pressure distribution in the patellofemoral joint or reducing the patellofemoral contact force, respectively. The pressure reallocation and/or reduction through a lateral retinacular release is not supported by several studies, with pressure measurements and contact areas measurements

before and after a lateral retinacular release (Jäger and Plitz, 1983; Huberti et al., 1984; Hille et al., 1985).

The pressure reduction by increasing the moment arm of the patellar tendon by a tubercle elevation has been demonstrated by several methods (Bandi, 1972; Ferguson et al., 1979; Nakamura et al., 1985), however only in vitro or by simple model calculations. With the introduction of pressure-sensitive films a few years ago, a new method for direct measurements of contact areas and pressures within the patellofemoral joint became available (Huberti et al., 1983, 1984). The question whether chondromalacia is caused by hyper- or hypopressure could be addressed. The data of Huberti et al. (1983) and Jäger and Plitz (1983) suggest that hypopressure is the cause of chondromalacia. This challenges operations for chondromalacia based on the concept of pressure reduction in the patellofemoral joint.

Although favourable clinical results were reported, it must be noted that the patients of both Macquet (1976) and Bandi (1976) were no adolescents but adults, with a mean age of 56 and 52 yrs. respectively. It is quite possible that these patients were suffering from patellofemoral osteoarthritis instead of chondromalacia.

EFFECTS OF OPERATIONS ON PATELLAR TRACKING PATTERNS

V.1 INTRODUCTION

Whereas the first problem for the treatment of chondromalacia is that the etiology is multifactorial and often unknown, the second problem is that, in the case of an assumed etiological factor, it is quite uncertain whether a proposed operation actually accomplishes what the surgeon had in mind. Most of the operations, meant to address specific etiological causes, are based on theory, intuition or empirical observations, and are often not supported by experimental data. One objective of many treatments is the reduction of patellofemoral contact pressures. Pressure-sensitive films have provided the opportunity to test whether this objective is obtainable with the operations proposed for this purpose. Unknown is to which extent these operations cause a rerouting of the patellar tracking mechanism, which would result in alternative locations of the patellofemoral contact regions and areas, during flexion of the knee. The RSA method, used here to investigate the three-dimensional tracking patterns of the normal patella is, owing to its extremely high accuracy, eminently suited to analyse whether this is actually the case. Two operations, popular as surgical treatment, were selected for this purpose, lateral retinacular release and tubercle elevation. The former is advocated to alter the pressure distribution in the patellofemoral joint through a medialization of the resultant quadriceps force exerted on the patella. The latter is meant to reduce the patellofemoral contact force, and thereby also the pressure, by increasing the moment arm of the patellar tendon.

V.2 METHODS

After performance of the experimental series on the intact specimens, to determine the normal tracking pattern as described in Chapter III, a lateral retinacular release was carried out according to Viernstein and Weigert (1969). The operative technique included a slightly curved incision along the lateral border of the patella (approx. 6 cm). Then the fascia lata and the retinaculum were incised, starting lateral along the m. rectus femoris, through the m. vastus lateralis, ending along the patellar tendon, approximately 1 cm from the patella. During the operation, the knee was not removed from the rig. There-after, the motion experiments were repeated, flexing the knee joint from full extension (reference position) to maximum flexion. Measurements (roentgenexposures) were taken after each 15 degrees increment of flexion. Tibial torques were applied in the same manner as during the experiment with the intact joint (± 3 Nm), and the flexion series were then repeated. The direction of the quadriceps traction was not changed.

Experience gathered from the pilot study (van Gulick et al., 1983) showed that the experiments were time-consuming. Normally, the experiment concerned with the effect of an operation was performed the day after the one of the first part of the experiment. Overnight, the knee specimen was kept moist with Ringer solution, cooled with ice-packings, and the quadriceps tension was released.

The tubercle elevation was performed according to the description of Bandi (1974). With a chisel the proximal part of the tibial tubercle was loosened, after making one or more drill holes. Elevations were obtained with wooden wedges of 0.5 cm (tub. elev. I) and 1.0 cm (tub. elev. II) height, respectively (Fig. V.1).

Because a lateral retinacular release is routinely carried out as a part of the Bandi/Macquet elevation, the effects of these surgical procedures on patellar trackings could be studied subsequently in each specimen.

V.3 RESULTS

The results of this part of the investigation are arranged as follows:

1. presentation of the influences of a lateral retinacular release on the patellar flexion, the patellar tilt, the patellar rotation and the patellar shift, respectively.



Fig. V.1: The tubercle elevation with a wooden wedge, as performed in the experiments on a left knee specimen.

2. presentation of the influences of a tubercle elevation of 0.5 cm (tub. elev. I) and 1.0 cm (tub. elev. II), respectively, on the patellar rotations and translation.

V.3.1 The influences of a lateral retinacular release on the patellar tracking

The patellar motions relative to the femur along the envelope of tibiofemoral flexion do not show very significant changes in flexion, tilt, rotation or shift, after performance of a lateral retinacular release in the four investigated specimens, as illustrated in Figs. V.2-5.

The tilt movement of the patella shows an interesting change in two specimens (103, 104) in the first part of flexion. The lateral release causes a medial tilt in extension (the reference position) which diminishes with increased flexion (Fig. V.3). In the same specimens (103, 104) a slightly increased medial patellar rotation was observed after retinacular release in full extension, also diminishing with further knee flexion (Fig. V.4). Overall, little effect of a lateral release was observed for the patellar rotation envelope. The effects of a lateral release on the patellar shift were very small (Fig. V.5). Along the external rotation pathway of the tibia, no reduced lateral shift could be detected in any of the four specimens. In one specimen (103) a reduction of the initial medial shift along the internal rotation pathway was observed.

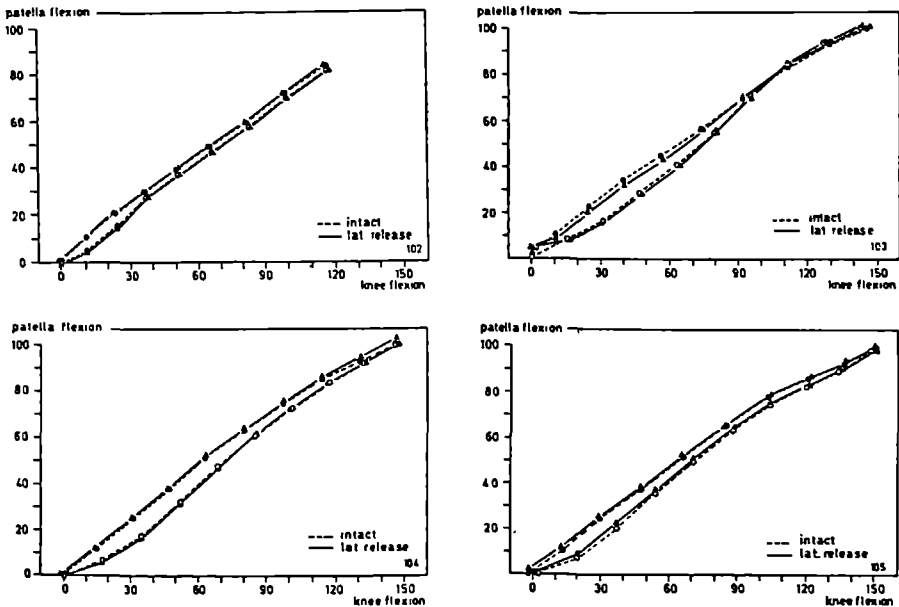


Fig. V.2: Patellar flexion, as function of knee flexion, before and after lateral retinacular release. The open symbols represent the internal tibial rotation pathways, the closed symbols represent the external tibial rotation pathways (± 3 Nm).

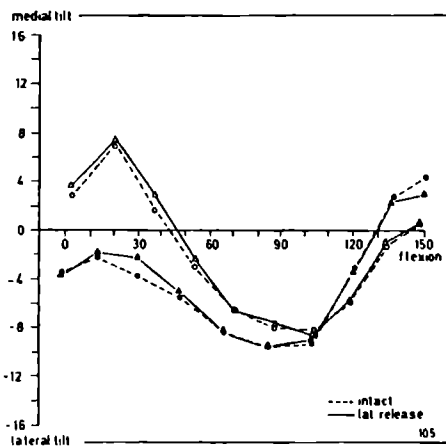
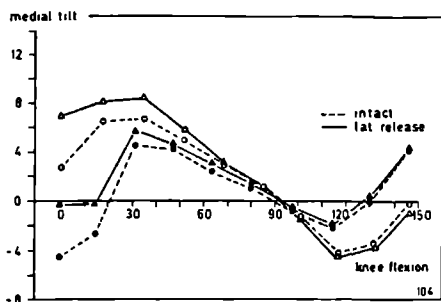
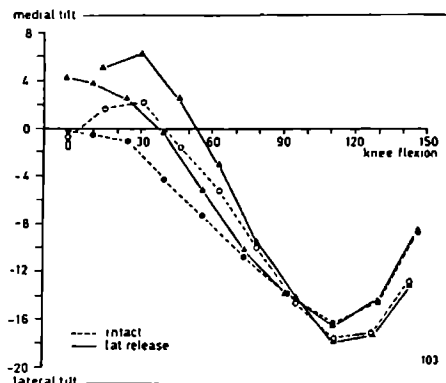
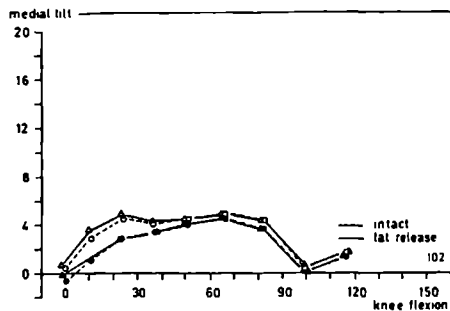


Fig. V.3: Patellar tilt, as function of knee flexion, before and after lateral retinacular release in all four specimens. The open symbols represent the internal tibial rotation pathways, the closed symbols represent the external tibial rotation pathways (± 3 Nm).

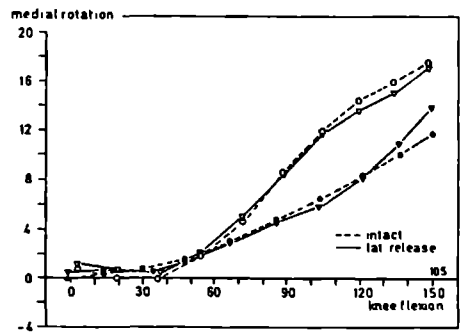
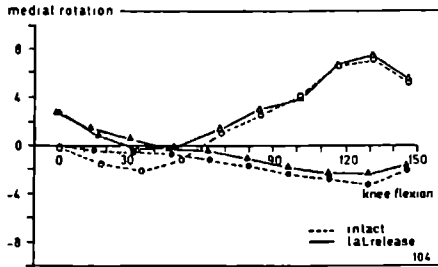
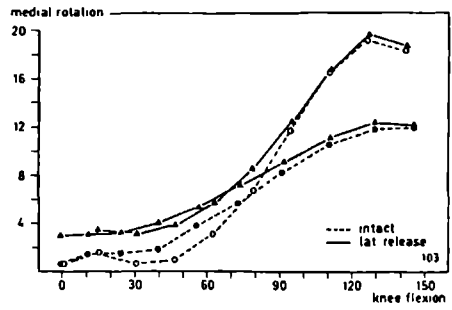
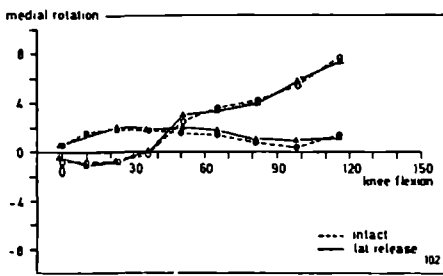


Fig. V.4: Patellar rotation, as function of knee flexion, before and after lateral retinacular release in all four specimens. The open symbols represent the internal tibial rotation pathways, the closed symbols represent the external tibial rotation pathways (± 3 Nm).

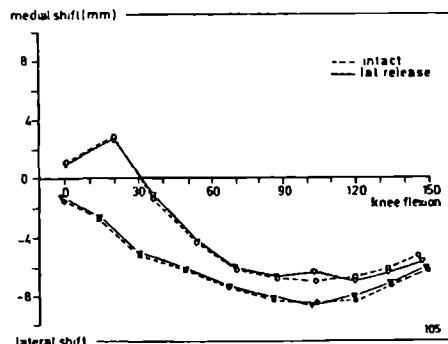
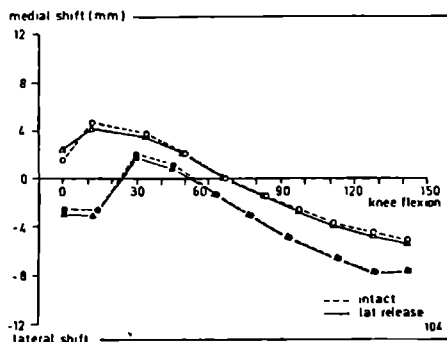
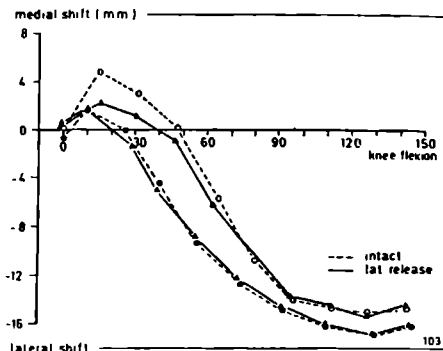
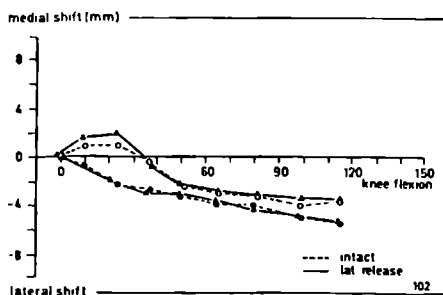


Fig. V.5: Patellar shift, as function of knee flexion, before and after lateral retinacular release in all four specimens. The open symbols represent the internal tibial rotation pathways, the closed symbols represent the external tibial rotation pathways (± 3 Nm).

V.3.2 The influences of a tubercle elevation on the patellar tracking

The patellar flexion showed a slight change after a tubercle elevation with 0.5 cm and 1.0 cm, respectively as represented in Fig. V.6 and Fig. V.7, compared to the patellar flexion before this type of operation. All specimens showed a tendency towards patellar extension in the first part of the knee flexion. The same two specimens (103, 104) which showed an initially increased medial tilt after retinacular release, showed this tilt pattern after the tubercle elevations (Fig. V.8, Fig. V.9).

The other specimens showed no significant change in tilt, relative to the intact motion patterns. Therefore, the increased medial patellar tilt in the two specimens seems to be due to the lateral release. Differences in patellar tilt between an elevation of 0.5 cm and 1.0 cm were not very significant. However, in two specimens (104, 105) a slight increase in initial tilt could be observed (Fig. V.8 and Fig. V.9). For patellar rotation the following results were found: two specimens (102, 105) showed an evident increase in patellar rotation, both along the internal and external tibial rotation pathway after a tubercle elevation of 1.0 cm (Fig. V.10). One specimen (103) showed a 4 degrees increased medial patellar rotation over the whole knee flexion range, and specimen 104 showed no change in patellar rotation at all (Fig. V.10 en Fig. V.11). Only for specimen 105 a difference in patellar rotation between tubercle elevation I (0.5 cm) and tubercle elevation II (1.0 cm) could be detected: an increase of patellar rotation along both pathways (compare Fig. V.10 and V.11). Changes in patellar shift were very small, after both tubercle elevations (Fig. V.12 and V.13). There was a slight increase in lateral shift in specimen 102, from 0.5 cm to 1.0 cm elevation (Fig. V.11 and V.12). The other specimens showed no significant differences in patellar shift as a consequence of both elevation operations. The results relative to specimen 102 were not included in Fig. V.8 and Fig. V.10, because of apparent excessive measurements errors found in the data evaluation.

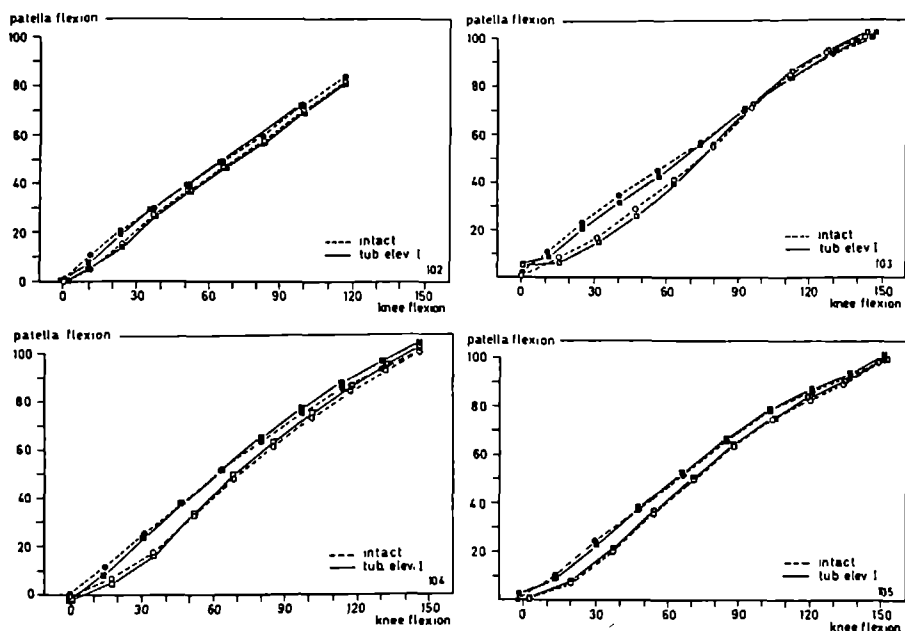


Fig. V.6: Patellar flexion, as function of knee flexion, before and after tubercle elevation I (0.5 cm). The open symbols represent the internal tibial rotation pathways, the closed symbols represent the external tibial rotation pathways (± 3 Nm), for four specimens.

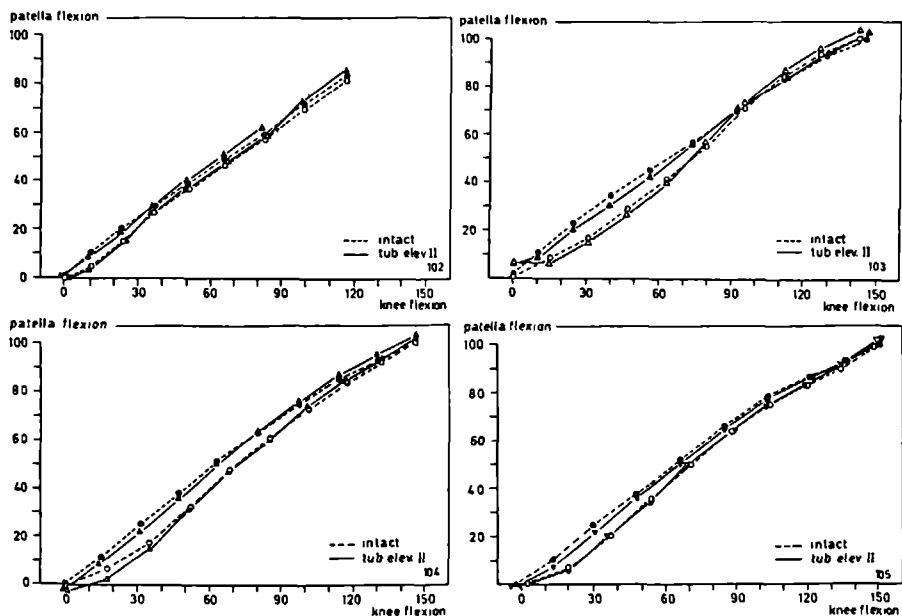


Fig. V.7: Patellar flexion, as function of knee flexion, before and after tubercle elevation II (1.0 cm) for four specimens. The nomenclature of the curves corresponds with Fig. V.6.

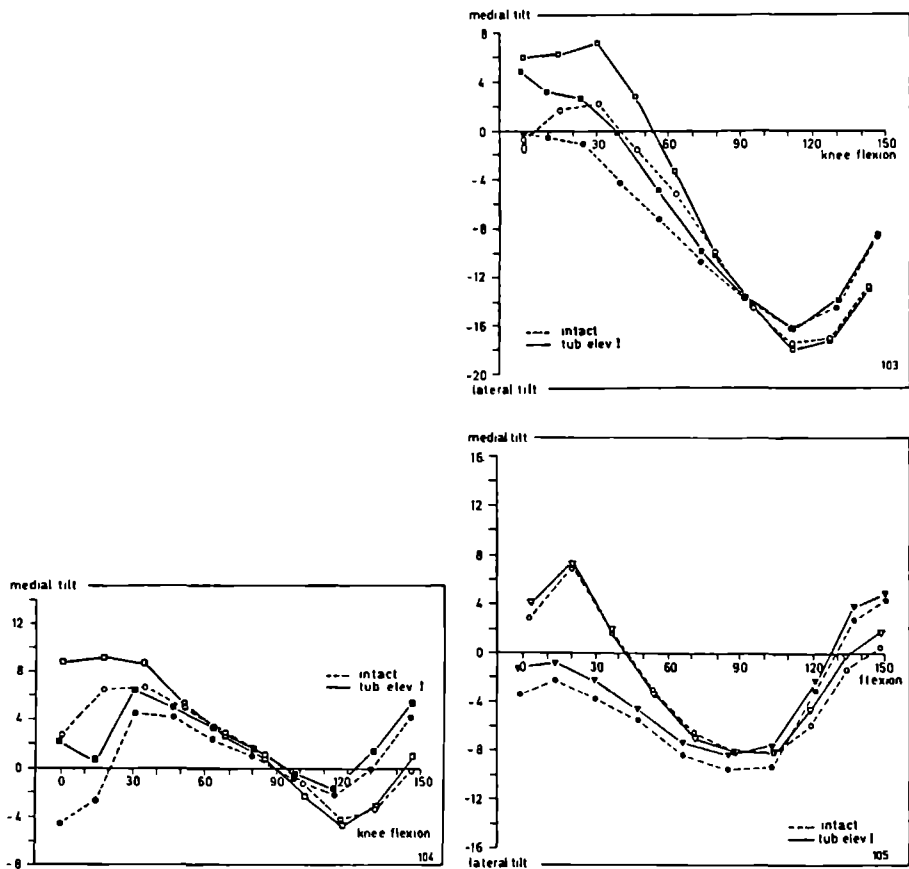


Fig. V.8: Patellar tilt, as function of knee flexion, before and after tubercle elevation I (0.5 cm) for three specimens. The nomenclature of the curves corresponds with Fig. V.6.

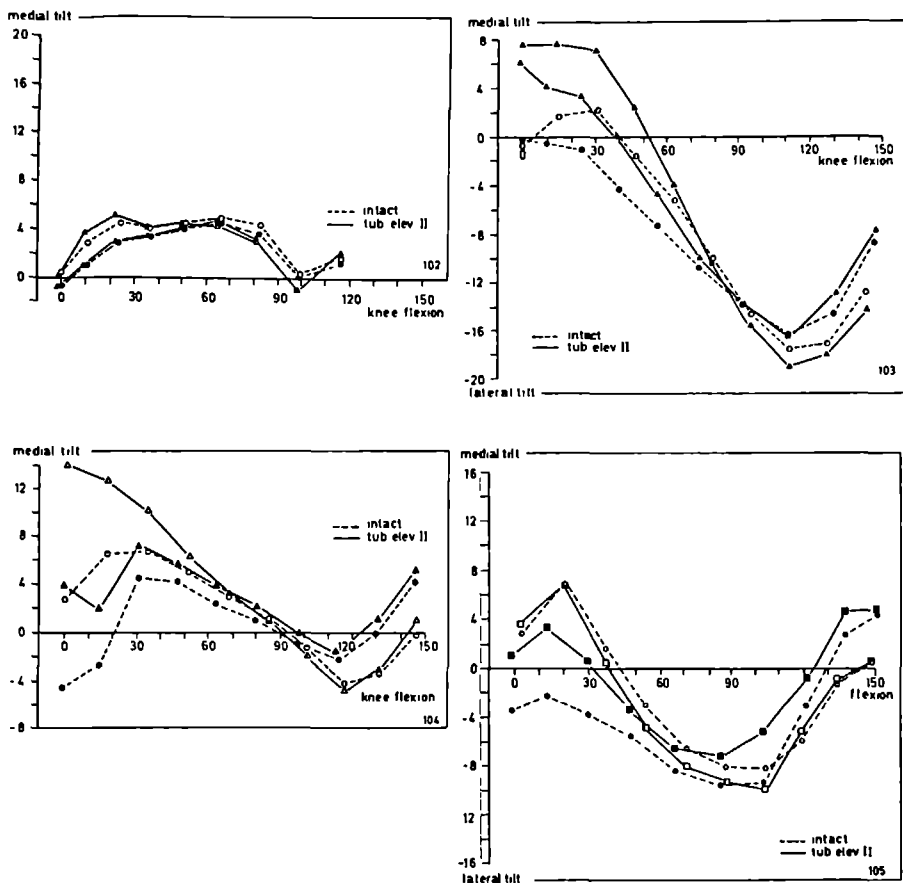


Fig. V.9: Patellar tilt, as function of knee flexion, before and after tubercle elevation II (1.0 cm) for four specimens. The nomenclature of the curves corresponds with Fig. V.6.

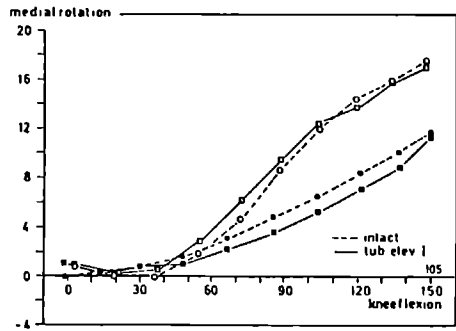
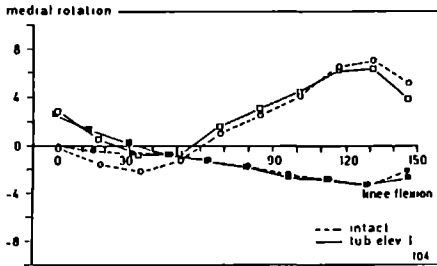
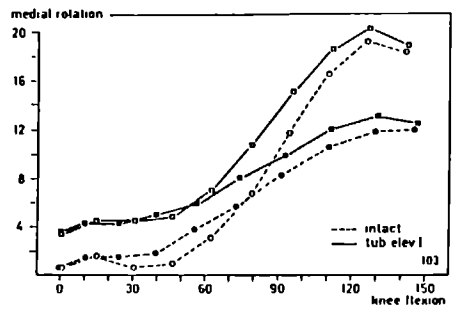


Fig. V.10: Patellar rotation, as function of knee flexion, before and after tubercle elevation I (0.5 cm) for three specimens. The nomenclature of the curves corresponds with Fig. V.6.

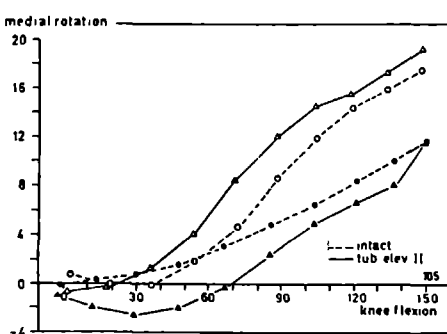
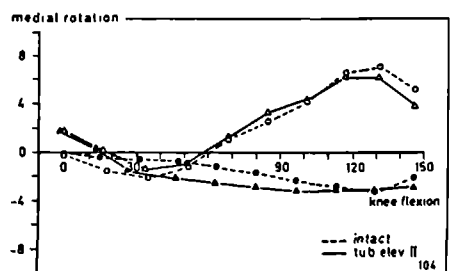
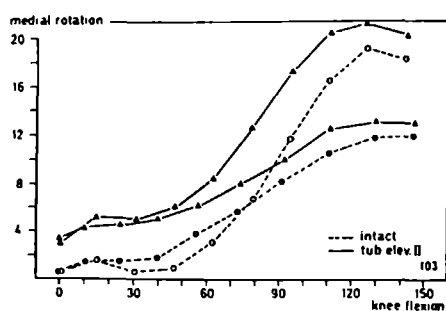
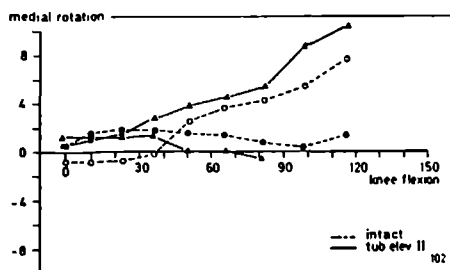


Fig. V.11: Patellar rotation, as function of knee flexion, before and after tubercle elevation II (1.0 cm) for four specimens. The nomenclature of the curves corresponds with Fig. V.6.

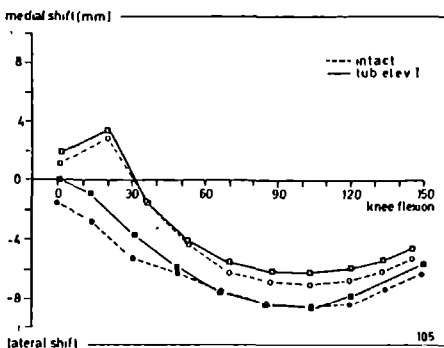
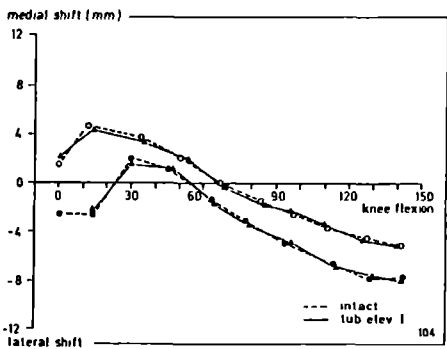
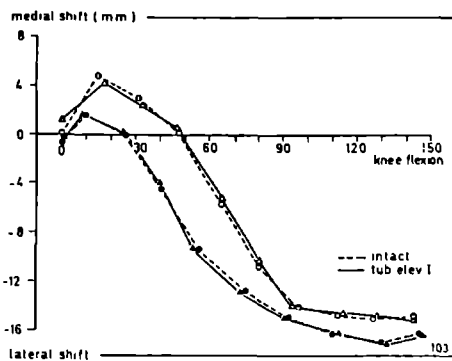
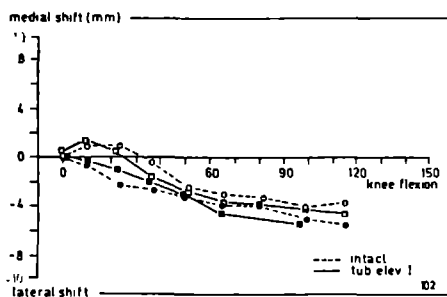


Fig. V.12: Patellar shift, as function of knee flexion, before and after tubercle elevation I (0.5 cm) for four specimens. The nomenclature of the curves corresponds with Fig. V.6.

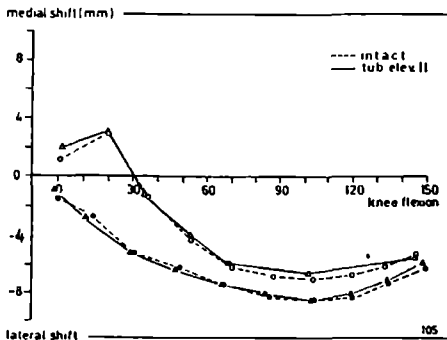
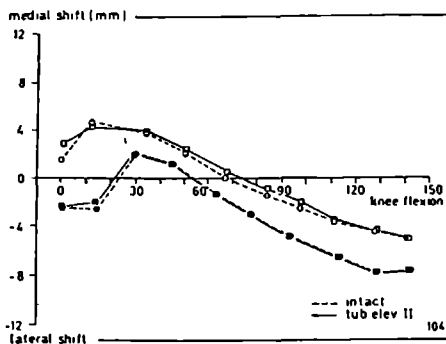
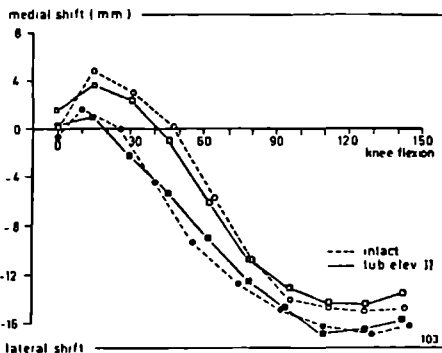
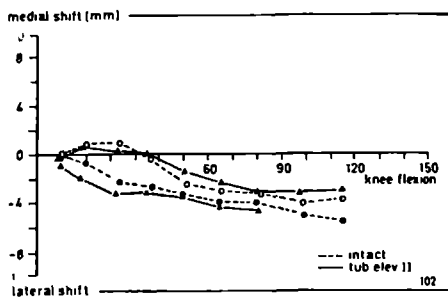


Fig. V.13: Patellar shift, as function of knee flexion, before and after tubercle elevation II (1.0 cm) for four specimens. The nomenclature of the curves corresponds with Fig. V.6.

V.4 DISCUSSION

The tibial rotations relative to the femur were again calculated after the operations and compared to the motions for the intact configuration. With the same tibial torques ($+ 3$ Nm), the envelope of motion of the tibia hardly changed, characteristic for the reproducibility (Fig. V.14).

Hence, the changes in patellar movements after the surgical interventions must be due exclusively to the operations.

Two general aspects of the patella tracking pattern can be expected to be influenced by splitting of the lateral retinaculum, due to a change in the quadriceps force direction relative to the patella.

— A turn-over from lateral to medial shift or a less pronounced lateral shift.

— A more pronounced medial tilt, or a reduction of the lateral tilt.

In fact, the latter did occur in two specimens (103, 104). In extension a medial patellar tilt occurred (mean 4 degrees) after the lateral release in these two

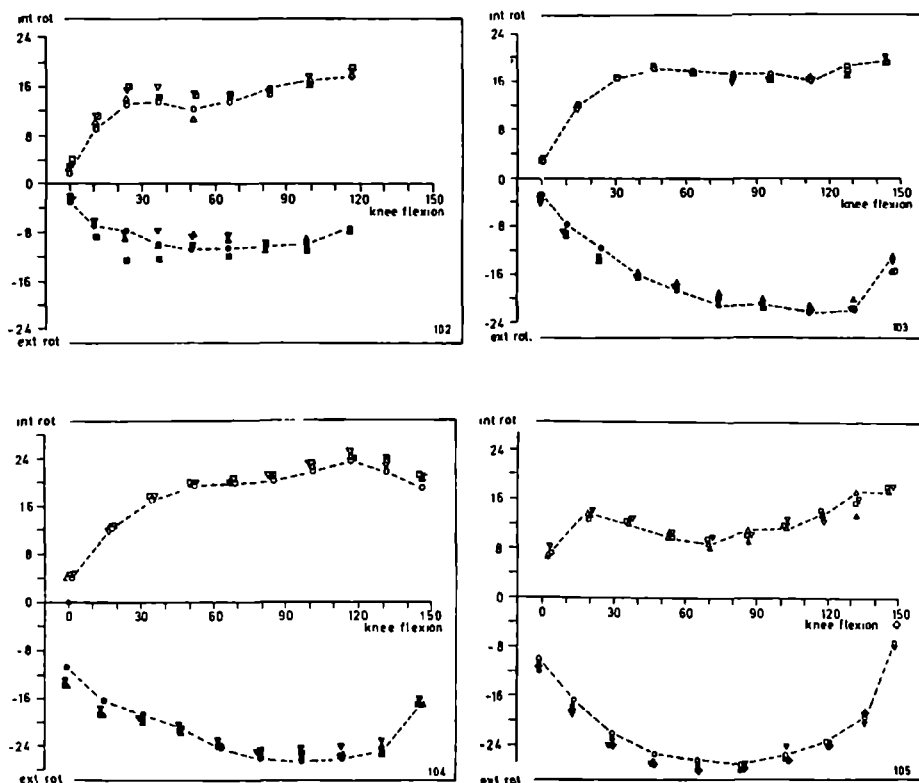


Fig. V.14: The limits of internal and external tibial rotation (± 3 Nm) as function of flexion, before and after different operations performed in the four specimens. The dotted lines represent the intact specimens (compare Fig. III.).

○ = intact knee, ▽ = lateral release, ▲ = tub. elev. I, ■ = tub. elev. II.

specimens. However, after 30 degrees of knee flexion this additional medial tilt practically diminished. In the other two specimens, no change in patellar tilt was noticed (Fig. V.3). As known from retropatellar contact and pressure studies (Chapter II), significant loading of the retropatellar cartilage normally takes place only after 20 degrees of knee flexion, initially at the lower pole of the patella. Therefore, the clinical significance of a slightly increased medial tilt from extension to 30 degrees of knee flexion can be doubted.

The two degrees of increased medial rotation observed in the same specimens is also only present in the first part of knee flexion (Fig. V.4). Hence, when the normal medial rotation in the intact specimen increases for the greater knee flexion angles, the "surgical effect" has practically disappeared.

The absence of a change in the patellar shift is in accordance with the results of Reider et al. (1981), the only in vitro investigation comparable to the present study. They showed no differences in the patellar shift before and after cutting the lateral retinaculum in 12 specimens.

Data concerning contact areas and contact pressures do not show any effective change in contact patterns and pressures before and after a lateral release.

Huberti et al. (1983) showed in their experiment, that a lateral release neither affected the patellofemoral contact pressures, nor led to increases or decreases of pressure in different regions of the contact areas.

Jäger and Plitz (1983) also measured retropatellar pressure distributions in human specimens, before and after a lateral release. They also noticed no change in the pressure distribution at 30, 60 and 90 degrees of knee flexion.

Hille et al. (1985), using pressure sensitive films, confirmed the results of the fore-mentioned investigations. In their study no changes in retropatellar pressure to any measurable extent were noticed after a lateral release. Lewallen et al. (1985) found a reduction of mean contact pressure only at 90 degrees of knee flexion, using the same pressure sensitive films. Contact areas, contact forces and contact pressures remained unchanged at lower flexion angles, after retinacular release in their experiments.

These findings on contact areas and pressures, together with the present results show, that the 3-D tracking patterns of the patella are not influenced by a lateral retinacular release.

After tubercle elevation three changes could theoretically occur:

- The patella rotates around the lateral-medial x-axis towards extension, thereby changing the patellofemoral contact regions.
- The direction of the patellar ligament changes, leading to an increased angle between the patellar ligament and the quadriceps tendon (angle β), reducing the patellofemoral contact force, which is the rationale for the tubercle elevation (Fig. V.15).
- The medial-lateral translation of the tibial tuberosity is increased during exo-/endorotation of the tibia, increasing and decreasing the normal Q-angle. This is illustrated in Fig. V.16.

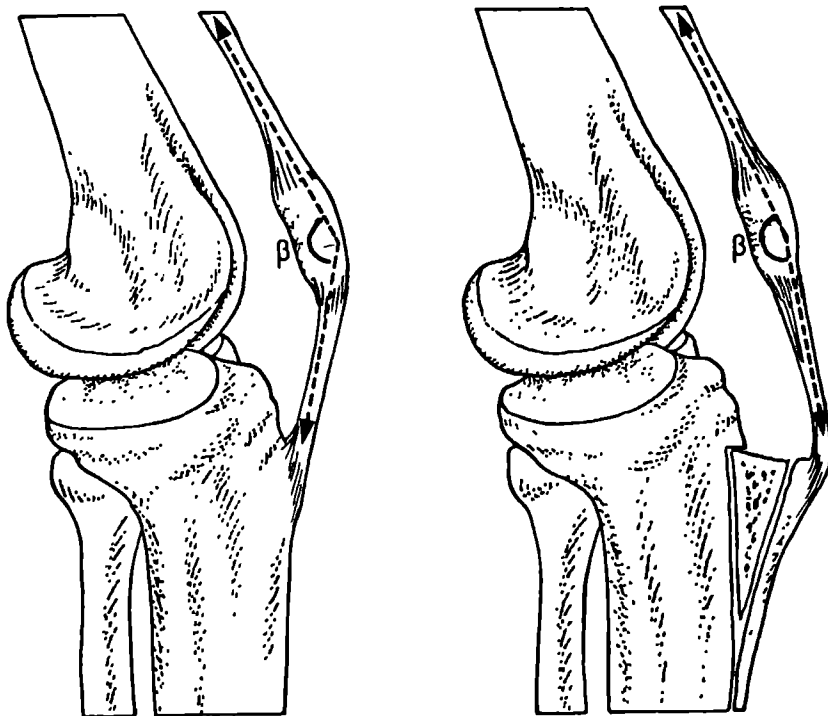


Fig. V.15: Tubercle elevation decreases the angle (β) between quadriceps tendon and patellar ligament.

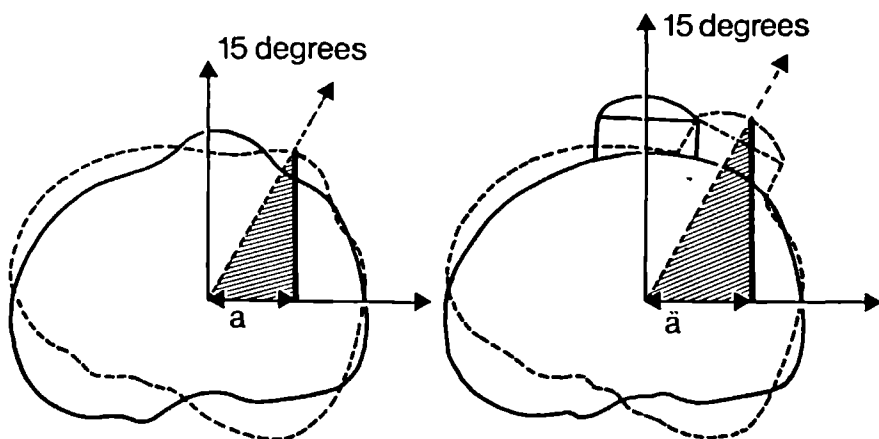


Fig. V.16: The translation of the tibial tuberosity (a , left) increases after tubercle elevation (a'' , right) with the same tibial rotation (15 degrees).

From our data it appears, that the patella indeed slightly rotates towards extension, in the first part of knee flexion (negative rotation about the patellar x-axis). This is in accordance with the results of van Eijden (1985), who investigated in a mathematical model the movements of the patella in the sagittal plane before and after a tubercle elevation. Van Eijden (1985) also calculated the changes in angles between patellar ligament and quadriceps tendon, after increasing elevations up to 2 cm. The angle β increased 10-15 degrees (1 cm elevation) especially at larger flexion angles. This effect was dominated by the angular change of the patellar ligament. The effect of a larger tuberosity translation by tibial rotation may increase patellar rotations and patellar shift in the directions as established for the patellar tracking in the intact specimens (Chapter III), through the increased excursions of the patellar ligament. In the present results on patellar movements after tubercle elevation a slight increase in patellar tilt (specimens 104, 105), in patellar rotation (specimen 105), and in patellar shift (specimen 102) was noticed, but these effects were not found consistently in all specimens. Although the changes in the rotations and translation are not spectacular, together, they contribute to alternative locations of the patellofemoral contact regions during flexion of the knee. Also, the tubercle elevation will induce an increase of the Q-angle with tibial exorotation and a decrease of the Q-angle with tibial endorotation. In this respect, notice has to be taken of the study of Huberti et al. (1984), who determined the influence of different Q-angles on the patellofemoral contact pressures. They found that an increase of the Q-angle resulted in increased peak pressures and changes of the contact locations. Decreasing the Q-angle resulted in unloading of the vertical ridge, but was always associated with increased peak pressures at other locations.

V.5 SUMMARY AND CONCLUSIONS

Lateral retinacular release for chondromalacia is meant to alter or reduce the pressure distribution in the patellofemoral joint, through a medialization of the resultant quadriceps force. It is likely that, as a result of the changing resultant force, the patellar tracking pattern changes. The present results on the 3-D tracking pattern of the patella after lateral release, however, indicate that the patellar tracking pattern mechanism is determined mainly by the bony constraints and the pull of the patellar ligament, once it is pressed into the femoral groove in the greater knee flexion angles. Lateral release only influences its 3-D position significantly in extension and in the first part of flexion. The clinical significance of this influence must strongly be doubted.

Hence, neither the shape of the contact areas and the pressure distribution, nor the contact area locations are affected, apart from some small position changes in the lower flexion angles. This pleads against this operative procedure in knees where the lateral retinaculum is essentially normal. Loosening of the lateral retinaculum may be of value only in patients with a so-called "tight retinaculum", which diagnosis can be confirmed by axial X-rays. If a beneficial effect of the lateral

retinacular release in the normal anatomical configuration exists, this may be explained by the cutting of the sensory nerve endings during the operation. The goal of the tuberosity elevation, reducing the patellofemoral contact force by increasing the moment arm of the patellar tendon has been motivated by several studies, as discussed in Chapter IV, (Bandi, 1972; Macquet et al., 1963; Ferguson et al., 1979; Nakamura et al., 1985). However, none of these studies did take tibial rotations into account. Patellar rotations are highly influenced by tibial rotations in the intact situation, and even more so after tubercle elevation. After tubercle elevation this may lead to even higher peak pressures, with unpredictable contact areas, caused by the increased influence of the Q-angle on the patellar tracking. This is in contradiction with the objective of reducing the patellofemoral contact pressures. Hence, from the present results it appears that influences of the tubercle elevation on the patellar tracking pattern do exist, but their nature and extent are unpredictable. Therefore, it is doubtful whether the objective of the tubercle elevation operation, reduction of patellofemoral contact stresses, is actually realised, especially in patients with an abnormal Q-angle.

GENERAL DISCUSSION, SUMMARY AND CONCLUSIONS

Orthopaedic surgeons are frequently confronted with patients suffering from anterior knee pain, due to chondromalacia patellae. The etiology of chondromalacia is multifactorial and often unknown, thereby creating difficulties for the choice of treatment. This can be frustrating, both for the patient and the surgeon. Methods of therapy for chondromalacia are often based on theory, intuition or empirical observations.

Fundamental research concerning the patellofemoral joint is still incomplete, and as a logical consequence of this, the scientific bases for the different surgical interventions are too. Within the limits of in vitro studies, which conclusions cannot be directly converted to the in vivo situation, some general remarks concerning pressure distributions within the normal human patellofemoral joint can be made. The locations of contact areas on the retropatellar surface are divided over both patellar facets and shift from the patellar apex towards the upper pole of the patella with further knee flexion. The retropatellar pressures on the contact areas between patella and femur are remarkably uniformly distributed over both facets, as established with the introduction of pressure-sensitive films. The quadriceps tendon contributes to a considerable extend to the load-bearing areas in greater knee flexion, thus preventing high peak-pressures on the retropatellar contact areas.

The normal kinematic behaviour of the human patella has not yet been thoroughly investigated. The few data from the literature, as summarized in Table II.I, Chapter II, are rather inconsistent. With the results presented in Chapter III, an accurate data base is offered for the normal 3-D tracking patterns of the patella.

Overall, the normal 3-D patellar tracking pattern is characterized by patellar flexion, a wavering patellar tilt, a medial patellar rotation and a lateral patellar shift, during knee flexion. The patellar rotations and the shift are basically determined by the bony constraints of the distal femur, in relation to the loads applied on the patella, as discussed in Chapter II. The anterior wall of the lateral condyle causes a medial patellar tilt in extension. The further caudally reaching medial condyle changes the direction of the patellar tilt rotation towards lateral. The medial patellar rotation and the lateral patellar shift are determined by the slightly laterally oriented femoral groove, in its course from proximal to distal.

Inclusion of tibial rotations in determining the tracking patterns of the patella has shown to be very important. Tibial rotations highly influence patellar motions: patellar tilt and patellar shift in particular in the first part of knee flexion, patellar rotation more prominently in the second part of knee flexion. Until now, none of

the investigations concerning patellar trackings, contact areas determinations or contact force measurements took tibial rotations into account, whereas in vivo, e.g. during gait, these rotations do take place. The present results emphasize the importance of tibial rotations on patellar trackings. As patellar tracking patterns will partly determine contact areas and forces, tibial rotations should be included in future investigations concerning the patellofemoral joint.

Many aspects of chondromalacia have not been resolved yet. As for example its etiology, its relation to osteoarthritis, the cause of pain and its natural course, as discussed in Chapter IV. The latter, the natural course of chondromalacia, is practically unknown. For the diagnosis chondromalacia arthroscopy of the knee is the most valuable investigation, in which articular lesions, and their extend, can be assessed. Since arthroscopy has become a routine method in orthopaedics, the diagnosis chondromalacia can be established, and its natural course followed, which is extremely important in therapeutic acting. Therefore, it is necessary to use an universal grading system, for which purpose the grading system of Bentley and Dowd (1984) seems the most usefull.

A universal grading system is also essential to judge the relative value of surgical methods in chondromalacia. Studies in which the extent of chondromalacia is not graded, or graded without mentioning the grading system, are often encountered (Ceder and Larson, 1979; Franke et al., 1980; Delgado, 1980; Bigos and McBride, 1984). The value of such studies, in which effects of operations are discussed, is limited.

Based on the assumption that chondromalacia is caused by hyperpressure, several surgical interventions aim at altering or reducing patellofemoral contact pressures. In Chapter V, the influences of two popular operations on the 3-D tracking patterns of the patella are investigated. The first, lateral retinacular release, is meant to alter the retropatellar contact pressures and locations, by rerouting the patella. Contact pressure studies with pressure sensitive films, did not show any significant changes in pressure distributions, or in contact locations. The results of the present study does not show significant changes in 3-D tracking patterns of the patella either, except in the first part of knee flexion (up to 25 degrees). The clinical significance of this effect can be doubted, because normally the patella is hardly in contact with the femur until about 20 degrees of knee flexion, as established with contact area studies. It must be emphasized that the present results are derived from essentially normal knees, without evident signs of chondromalacia or abnormal tracking. However, they do show that the biomechanical effect of a lateral retinacular release is very small. Hence, considering these and earlier data on pressure distributions and contact areas after a lateral release, the scientific basis for this operation seems to become virtually non existent.

The second operation investigated, the tubercle elevation, shows some interesting results where it concerns its effects on the 3-D tracking patterns of the patella. The increase and decrease of the Q-angle, as caused by the tubercle elevation,

through the increased tubercle translation by tibial rotations, affects the patellar rotations and the shift in an unpredictable manner. Increasing the tubercle elevation from 0.5 cm to 1.0 cm lead sometimes to increases in patellar rotations and shift. The assumed decrease of patellofemoral contact pressure, by elevating the tibial tubercle has only been calculated in simple models, mostly based on the idea that the patella acts as a simple pulley.

The present results on the 3-D tracking pattern of the patella challenges the idea that the patella acts as a simple pulley. An evident change in patellar tracking patterns after tubercle elevation was found, suggesting changes in contact patterns, both in locations and magnitudes. These changes are unpredictable and may give rise to increasing peak pressures, the opposite of the objective of this operation. Therefore, assuming the etiological factor of chondromalacia to be hyperpressure, this operation cannot be advocated unless experimental evidence of pressure reduction through tubercle elevation could be presented, taking tibial rotations into account.

CONCLUSIONS

- A universal grading system for chondromalacia patellae is required. The grading system of Bentley and Dowd (1984) is the most practical one in this respect.
- The three dimensional tracking pattern of the human patella during knee flexion is a combination of flexion, wavering tilt, medial rotation and lateral shift, determined by the anatomical configuration of the distal femur and the patella, in combination with the applied load.
- The tracking pattern is highly susceptible to tibial rotations, especially towards extension for patellar tilt and shift, and towards flexion for patellar rotation.
- Investigations considering patellar tracking, compression forces or contact areas should take tibial rotations into account.
- The influences on patellar tracking by a lateral retinacular release are negligible.
- Tibial rotations have more extensive effects on the patellar motion pattern than lateral release or tubercle elevation.
- There is no scientific basis in regard to the patellofemoral joint in favor of lateral retinacular release as a surgical treatment for chondromalacia.
- Tubercle elevation, as surgical intervention for chondromalacia, alters the 3-D tracking pattern of the patella.
- The alterations after tubercle elevation are inconsistent in regard to the kinematic behaviour of the patella, reallocation of pressure distributions and peak-pressures.

- The objective of tubercle elevation, reducing patellofemoral contact stresses, is not supported by experimental evidence.

DISCUSSIE, SAMENVATTING EN CONCLUSIES

In de dagelijkse orthopaedische praktijk komen knieklachten op basis van retropatellaire chondromalacie (kraakbeenverweking van de knieschijf), hier kortweg chondromalacie genoemd, regelmatig voor. In de literatuur worden meerdere oorzaken voor het ontstaan van chondromalacie aangegeven, echter bij vele patiënten is geen duidelijke oorzaak voor de chondromalacie aantoonbaar. De behandeling van patiënten met chondromalaciekklachten is vaak gebaseerd op theorie, intuïtie of ervaring, vooral waar een duidelijke oorzaak niet vastgesteld kan worden. Dit kan deels worden verklaard uit het feit dat fundamenteel onderzoek van het patellofemorale gewricht nog leemtes vertoont en, als een logisch gevolg hiervan, wetenschappelijke onderbouw van operatieve ingrepen ontbreekt.

In de literatuur zijn gegevens bekend over de contactoppervlakken en drukverdeling in het patellofemorale gewricht, welke in Hoofdstuk II zijn genoemd. Bij het interpreteren van deze gegevens is het van belang rekening te houden met de beperkingen van in vitro onderzoek. De krachten die in vivo op de knie worden uitgeoefend, met de consequenties voor de contactoppervlakken en de piekbelastingen in het patellofemorale gewricht, kunnen slechts bij benadering bepaald worden, omdat tot op heden dergelijk onderzoek in vivo niet mogelijk is. Met in vitro onderzoek is aangetoond dat de retropatellaire contactoppervlakken gelijkmatig verdeeld zijn over het mediale en laterale patellafacet en zich verplaatsen met toenemende kniebuiging van de patella onderpool naar de patella bovenpool. Met behulp van druk-gevoelige films is vastgesteld dat de drukverhoudingen over beide patellafacetten opvallend gelijk zijn verdeeld. De pees van de quadriceps spier draagt in toenemende mate bij aan het vergroten van het gewichtsdragende oppervlak bij toenemende kniebuiging, waardoor hoge piekbelasting op het relatief kleine retropatellaire contactoppervlak wordt vermeden.

Ten aanzien van het normale bewegingspatroon van de patella tijdens buig- en strekbewegingen van het kniegewricht is weinig onderzoek bekend. Uit de geraadpleegde literatuur blijkt dat het bewegingspatroon van de patella niet eenduidig beschreven wordt (zie Tabel II.1). Met de resultaten van het onderzoek, beschreven in Hoofdstuk III, is een nauwkeurige beschrijving van het 3-dimensionale bewegingspatroon van de patella vastgelegd. Met toenemende kniebuiging is er sprake van een toenemende patella-flexie, een golvende patella-tilt, een mediale patella-rotatie en een laterale patellaverschuiving. De patella-rotaties en de naar lateraal gerichte verschuiving worden in belangrijke mate bepaald door de configuratie van de botstructuren van het distale femur, in combinatie met de externe belasting op de patella. De naar voren prominierende

laterale femurcondyl veroorzaakt in strekstand een naar mediaal gerichte kanteling (tilt) van de patella om zijn lengte-as. Bij toenemende kniebuiging verandert de richting van de patella-tilt naar lateraal, welke deels kan worden verklaard door de verder naar caudaal reikende mediale femurcondyl. De femorale groeve, gevormd door de laterale en mediale femurcondyl, verloopt van proximaal naar distaal gezien enigszins naar lateraal. Dit verklaart de gevonden laterale verschuiving (shift) van de patella langs de horizontale as. In combinatie hiermee is de naar mediaal gerichte patella-rotatie te verklaren, om de naar voren gerichte as. Bij toenemende kniebuiging is er sprake van een lateraal gerichte patella-shift en draait de patella-onderpool naar de mediale femurcondyl, t.g.v. de trekkracht in het ligamentum patellae.

Tot op heden werden tibiारotaties (exo-/endorotaties) niet betrokken bij onderzoek naar het kinematisch gedrag van de patella, noch bij onderzoek naar retropatellaire contactoppervlakken en patellofemorale drukmetingen. Uit de resultaten van het huidige onderzoek blijkt dat de tibiारotaties de verschillende patellabewegingen in belangrijke mate beïnvloeden; de patella-tilt en -shift vooral in het begintraject van de kniebuiging, de patella-rotatie vooral bij verdere kniebuiging.

Op grond hiervan verdient het aanbeveling tibiारotaties mede te betrekken bij het bepalen van contactoppervlakken en drukmetingen omdat als gevolg van positieveranderingen van de patella door voornoemde tibiारotaties, deze tevens beïnvloed zullen worden.

Chondromalacie is een ziektebeeld met nog vele onbekende aspecten. In Hoofdstuk IV is dit onder andere besproken ten aanzien van de etiologie, de relatie met patellofemorale arthrosis, de oorzaak van de pijnklachten en het natuurlijke beloop. Een nauwelijks ingrijpende en zeer betrouwbare methode om de diagnose chondromalacie te stellen is de arthroscopie van het kniegewricht. Met behulp van de arthroscopie kunnen kraakbeenafwijkingen qua localisatie, ernst en grootte vastgesteld en vastgelegd worden. Hiermee kunnen gegevens worden verkregen die ons mogelijk op termijn meer inzicht geven in bijvoorbeeld het natuurlijk beloop van de chondromalacie. Voor het bepalen van de ernst en de grootte van de kraakbeenbeschadigingen zijn in de loop der tijd meerdere, onderling verschillende, graderingssystemen gepubliceerd (zie Tabel IV.1).

Consensus over één graderingssysteem is sterk aan te bevelen, aangezien de huidige diversiteit aan graderingssystemen verwarring schept en onderlinge vergelijking van literatuurgegevens moeilijk maakt. Dit geldt temeer daar, waar resultaten van operatieve behandelingsmethoden worden besproken. In de literatuur wordt nogal eens het gehanteerde graderingssysteem niet genoemd, waardoor de waarde van dergelijk na-onderzoek beperkt is (Ceder en Larsson, 1979; Franke et al., 1980; Delgado, 1980; Bigos and McBride, 1984).

Meerdere operatieve behandelingsmethoden voor chondromalacie hebben tot doel het verplaatsen of verminderen van de retropatellaire contactdruk, waarbij van de veronderstelling uitgegaan wordt dat chondromalacie veroorzaakt wordt

door een te hoge retropatellaire druk. In Hoofdstuk V is de verandering van het normale bewegingspatroon van de patella onderzocht, veroorzaakt door twee operaties die bovenstaande contactverplaatsing of drukvermindering retropatellaire teweeg zouden brengen.

De eerste operatie, de klieving van het laterale retinaculum, is bedoeld om de retropatellaire contactdruk en -plaats te veranderen, door het patellaspoor te wijzigen. Verandering van het patellaspoor impliceert een veranderd bewegingspatroon, wat door de resultaten in Hoofdstuk V niet wordt bevestigd. Alleen in het begintraject van de kniebuiging (tot 25°) wordt een geringe verandering in de patellabeweging waargenomen. De klinische betekenis hiervan is waarschijnlijk zeer gering, aangezien uit patellofemorale contact-oppervlakte studies bekend is, dat in extensie en geringe kniebuiging er nog nauwelijks sprake is van patellofemoraal contact. Het onveranderd blijven van het bewegingspatroon van de patella na het klieven van het laterale retinaculum wordt ondersteund door studies waarbij met behulp van druk-gevoelige films contactoppervlakken en contactdruk werden bepaald. Vóór en na het klieven van het laterale retinaculum werden hierbij geen belangrijke verschillen in contactoppervlakken en contactdruk waargenomen. Dus het klieven van het laterale retinaculum geeft geen aanleiding tot verandering van het bewegingspatroon van de patella, noch een verandering van contactoppervlakken en contactdruk. De wetenschappelijke onderbouwing die het uitvoeren van een dergelijke ingreep zou rechtvaardigen is niet aanwezig.

De ratio voor het ophogen van de tuberositas tibiae als behandeling voor chondromalacie, is het verminderen van de retropatellaire druk. Of en in hoeverre dit aanleiding geeft tot een verandering in het bewegingspatroon van de patella was tot dusver niet bekend. Uit de huidige resultaten blijkt, dat vooral de toename van de tuberositas-translatie bij ex-/endorotatie van de tibia, resulterend in het vergroten of verkleinen van de zgn. Q-angle, het bewegingspatroon op een niet voorspelbare manier beïnvloedt.

De veronderstelde vermindering van de patellofemorale contactdruk, door het ophogen van de tuberositas tibiae, is voornamelijk gebaseerd op berekeningen aan de hand van eenvoudige modellen, waarbij de patella als een katrol wordt beschouwd. Met het nu vastgelegde ingewikkelde bewegingspatroon van de patella is aangetoond dat deze aanname niet geheel correct is.

Daarnaast zijn bij bovengenoemde berekeningen tibiarotaties niet opgenomen.

Door het ophogen van de tuberositas tibiae zijn er duidelijke veranderingen in het bewegingspatroon van de patella, welke aanleiding zullen geven tot verandering in het retropatellaire contactoppervlak, zowel qua localisatie als qua druk. Deze veranderingen kunnen zelfs tot hogere retropatellaire piekbelastingen aanleiding geven, tegengesteld aan de oorspronkelijke intentie van de operatie.

Uitgaande van de veronderstelling dat te hoge retropatellaire druk één van de oorzaken van chondromalacie is, kan op grond van bovenstaande bevindingen dit type operatie niet geadviseerd worden, totdat experimenteel is aangetoond dat het ophogen van de tuberositas daadwerkelijk tot een drukvermindering in het

patellofemorale gewricht aanleiding geeft, waarbij tevens tibiartotaties in het onderzoek dienen te worden betrokken.

CONCLUSIES

- Er is behoefte aan een eenduidig, universeel te gebruiken graderingssysteem voor chondromalacie.
De indeling volgens Bentley and Dowd (1984) is goed hanteerbaar en kan als zodanig hiervoor worden aanbevolen.
- Het 3-dimensionale bewegingspatroon van de patella tijdens kniebuiging bestaat uit een combinatie van flexie, golvend verlopende tilt, mediaal gerichte rotatie en laterale shift, en wordt mede bepaald door de anatomische vorm van het distale femur en de patella, in combinatie met de externe belasting op de patella.
- Het bewegingspatroon wordt in hoge mate beïnvloed door tibiartotaties: de patella-tilt en -shift vooral in het eerste deel van de kniebuiging en de patella-rotatie vooral in het tweede deel van de kniebuiging.
- In onderzoek naar patellofemorale bewegingspatronen en druk- en oppervlaktmetingen dienen derhalve tibiale rotaties betrokken te worden.
- De invloed van het klieven van het laterale retinaculum op het bewegingspatroon van de patella is verwaarloosbaar. Er is geen experimenteel onderzoek dat het klieven van het laterale retinaculum als chirurgische behandeling voor chondromalacie ondersteunt.
- Het ophogen van de tuberositas tibiae verandert het 3-dimensionale bewegingspatroon van de patella.
- De veranderingen als gevolg van tuberositas-ophoging zijn onvoorspelbaar, zowel ten aanzien van het kinematisch gedrag van de patella als ten aanzien van de drukverdeling en piekbelastingen in het patellofemorale gewricht.
- Het doel van het ophogen van de tuberositas, te weten vermindering van patellofemorale contactdruk, wordt niet ondersteund door experimentele gegevens.

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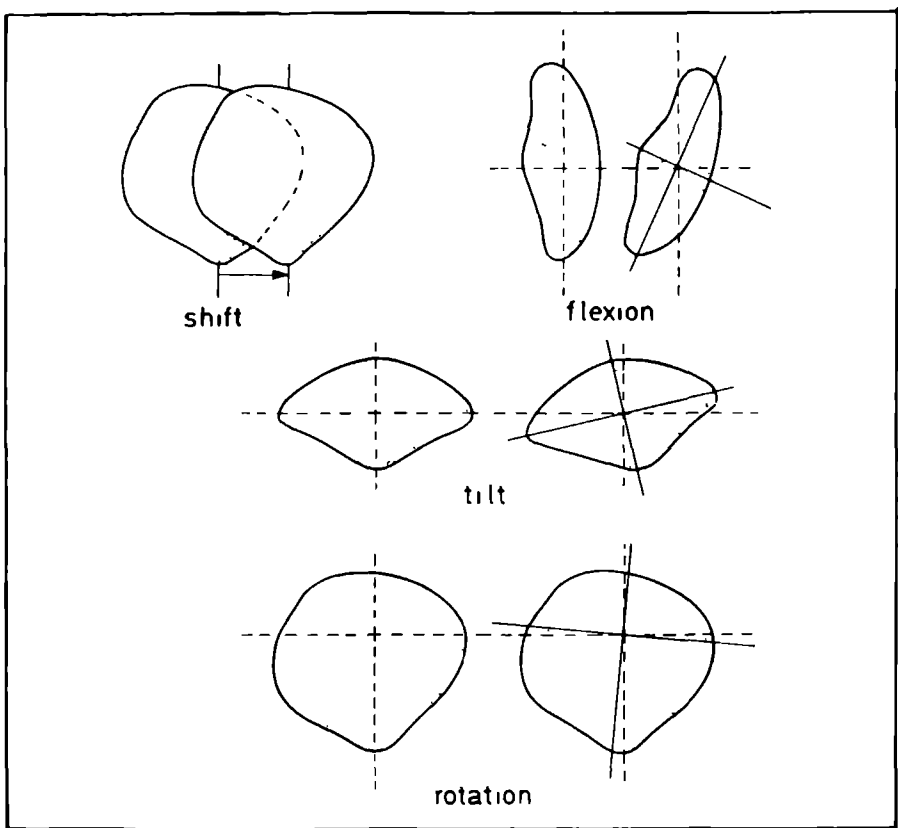
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STELLINGEN

1. De onjuiste veronderstelling dat het ophogen van de tuberositas tibiae altijd tot een retropatellaire drukvermindering leidt, is gebaseerd op berekeningen waarbij de knieschijf als een eenvoudige katrol in het sagittale vlak wordt beschouwd, en waarbij ten onrechte geen rekening wordt gehouden met de invloed van het ophogen op het ruimtelijke bewegingspatroon van de knieschijf.
2. Pijnvermindering als doel van operatieve behandelingsmethoden voor chondromalacia patellae wordt met meer zekerheid bereikt door het uitvoeren van een patellectomie dan door het klieven van het laterale retinaculum of het ophogen van de tuberositas tibiae.
3. De op zich onvriendelijk aandoende uitdrukking 'pappen en nathouden' is ten aanzien van patiënten met klachten op basis van chondromalacia patellae patiënt-vriendelijk.
4. Voor behoud van operatief bereikt functieherstel van het kniegewricht is direct postoperatief oefenen noodzakelijk. Hiertoe verdient pijnbestrijding gedurende enkele dagen met epiduraal toegediende locale anesthetica (in hoog volume en lage concentratie) de voorkeur.
5. Gezien de toename van letsels en aandoeningen van het steun- en bewegingsapparaat is een verdere reductie van het orthopaedisch onderwijs in het algemeen medisch curriculum niet acceptabel.
6. Arthroscopische chirurgie is poliklinisch onder locale anesthesie goed uitvoerbaar en kostenbesparend.
7. Een goede relatie met patiënten is gebaseerd op een maximum aan vertrouwdheid en een minimum aan vertrouwelijkheid.
Th.J.G. van Rens, 1986.
8. Bij de operatieve behandeling van een cervicale spondylogene myelopathie verdient de anterieure decompressie in combinatie met intervertebrale spondylodese de voorkeur.
9. Coronaire angioscopie biedt de mogelijkheid intra-operatieve ballon- en laser-angioplastie te ontwikkelen.

10. Wegens gebrek aan gerandomiseerd prospectief onderzoek is een gezonde twijfel bij vele aanbevolen orthopaedische behandelingsmethoden op zijn plaats.
11. De enige oplossing voor het overschotprobleem ontstaan door de Europese landbouwpolitiek is het niet produceren van deze overschotten.
12. Suriname ligt in Zuid-Amerika, al hebben wij Nederlanders dat nooit willen begrijpen.
13. Een modern gezin beschikt heden ten dage over een PC-tje en een CD-tje, in combinatie met een PL-etje.



Stellingen
 behorende bij het proefschrift van
A. van Kampen
The Three-dimensional Tracking Pattern of the Patella
 Nijmegen, 19-6-1987

